# Force-velocity profiling in jumping and sprinting actions: Exploring the utility to enhance performance in individual and team sport populations

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**ABSTRACT**

Jumping and sprinting actions are frequent in many individual and team sports such as basketball, field hockey, soccer and track and field. Both sporting actions are underpinned by the mechanical characteristics which govern human movement including force, velocity, and power. From a biomechanical perspective, to improve an athlete's performance in these actions, the mechanical characteristics contributing to performance must be quantified. One neuromuscular diagnostic assessment which can be utilized to describe mechanical characteristics of the human body is known as force-velocity (F-v) profiling, or mechanical profiling. This thesis explored field-based F-v profiling as a methodological approach to quantify and improve physical performance in previously untested team and individual population groups, plus demonstrated new and novel applications using this methodology to create greater links between mechanical data and coaching practice.

Additionally, this thesis is significant as it assesses the utility of using a macroscopic inverse dynamics approach to model biomechanical characteristics in the vertical and horizontal direction. Specifically, Samozino's field method, hereinafter known as the *SAM method*, provides indirect measures of the mechanical characteristics of jumping and sprinting actions and does not aim to replace gold standard measurement tools such as force-plate technology. Yet, the convenience to practitioners of *bringing the laboratory to the field* to provide meaningful data to inform training related practice, without the need for expensive technology warrants further validation and exploration from a theoretical, conceptual and practical perspective.

My original contribution to knowledge through this thesis comprises of five studies and two practical application chapters. Chapter 1 presents a general introduction to the thesis while providng a background to the F-v relationship. Chapter 2 is a narrative review which aims to critically appraise the literature when using field methods to determine F-

v profiles in jumping and sprinting actions. Overall, conjecture exists regarding the reliability and validity of using field-based F-v profiling methodology to determine mechanical characteristics which warranted further research. In addition, limited research exists exploring the use of mechanical profiling to inform physical preparation strategies in short and long-term intervention studies and in different population groups. Finally, the review identified and addressed a gap in the literature in translating the information obtained from the mechanical profile into how a coach could utilize the data to individualize athlete training programmes.

Chapter 3 (Study 1) established the validity and reliability of Samozino's field method to determine jump-based mechanical characteristics when compared to force plate technology. The findings showed both fixed and proportional bias between criterion and predictor, thereby raising concerns for practitioners when performing countermovement jumps with a barbell and hexbar to establish valid F-v variables using the SAM method when compared to force plate technology.

Chapter 4 (Study 2) used a cross-sectional approach to investigate differences between positional group and sex in club-based field hockey players. The results of this study identified significant differences in mechanical characteristics between sexes. Mechanical characteristics between positional groups (i.e., attackers vs defenders) further identified force or velocity dominant mechanical profiles however these were sex-specific. This suggests the physical preparation strategies to improve neuromuscular performance should be individualized by both sex and positional group.

Chapter 5 (Study 3) is another observational cross-sectional analysis which aimed to determine to relationships between matched mechanical characteristics from F-v profiles in the vertical and horizontal orientation in a field hockey cohort. The findings of this study indicate vertical and horizontal F-v profiling explain the same key lower-limb mechanical characteristics, despite the orientation of the movement task, suggesting coaches could potentially use mechanical profiling methods interchangeably and prescribe physical preparation interventions to assess neuromuscular function plus mechanical strengths and weaknesses by performing one F-v assessment only.

Chapter 6 (Study 4) investigated the influence of a short-term sprint-specific training intervention on the horizontal F-v profile in junior Australian football (AF) players. The findings indicate the F-v profile adapts to specific training stimulus with the experimental group reporting significant changes to force and power and sprint performance when compared to the control group. Furthermore, it identified practitioners could consider using a combined sprint training methodology to enhance mechanical characteristics and sprint performance in junior Australia football populations.

Chapter 7 (Study 5) used a case-study research design to longitudinally analyse changes to the horizontal F-v profile and sprint performance across a training year. The primary aim was to investigate changes to mechanical characteristics across a track and field season (~45 weeks) in two male sprint athletes (100m and 200m) who qualified for their national championships. The findings identified significant changes to maximal power and spatio-temporal variables over 30-meters coincided with improved sprint performance. Therefore, the estimated mechanical data collected across a training year may provide insight to practitioners about how the underpinning mechanical characteristics affect sprint performance during specific phases of training.

Chapter 8 and chapter 9 draws on the learnings of the cross-sectional, interventional, and case study to provide an evidence-based approach for the practitioner to analyse F-v data, plus categorize and individualize training prescriptions to enhance sprint performance in team and individual sport athletes. Furthermore, both chapters also aim to provide practical training-related recommendations and guidelines to influence programme design and attempt to provide a conceptual framework to guide training prescription and enhance biomechanical and technical characteristics contributing to sprint mechanical characteristics and sprint performance.

Chapter 10 provides a commentary of the overall utility and application of using the SAM method to determine F-v profiles and meaningfully inform training-related practice from a strength and conditioning perspective. This study considers the remaining gaps in the literature, acknowledges the strengths and limitations to the methodology and thesis and delivers additional recommendations to those identified in the narrative review. The evidence gathered provides theoretical and practical guidelines about best practice approaches for utilizing the field method(s) to inform and enhance physical performance in jumping and sprinting actions.

Overall, the current program of research has progressed an important aspect in the field of applied sports biomechanics, offering greater insights into the application of mechanical profiling to enhance physical performance in new sporting populations. The findings provide evidence to suggest (1) F-v characteristics are beneficial to individualize physical preparation strategies in field hockey athletes and demonstrate a level of mechanical transfer, (2) horizontal mechanical characteristics adapt to specific training methodology thereby addressing mechanical strengths and weaknesses, (3) monitoring horizontal mechanical characteristics over longer periods can further direct training strategies such as periodisation models and programme design to enhance sprint performance in track sprinters, and 4) use of specific training programmes and a conceptual framework to provide greater structure for practitioners to address mechanical strengths, weaknesses and imbalances based on biomechanical and technical characteristics of physical performance. This body of research has significant implications for coaches and sports biomechanists who want to improve physical performance by enhancing lower limb mechanical characteristics via training and physical preparation strategies.

**DECLARATION**

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university

2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and

3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed....................................................

Date........................................................ 6-June-23

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Finally, to my beautiful wife Amy and my children Noah, Arlo and Edie. We did it. We really did it. I could not have completed this without your unwavering love, support, and patience throughout this process. This is as much your PhD as it is mine. This thesis has cost us many nights together as I sat there hammering away on my laptop and from all the times when I felt discouraged or wondered why I was doing this, you were always there with positive words of encouragement, so I thank you for this.

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## LIST OF PUBLICATIONS AND PRESENTATIONS

*Publications forming part of this thesis*

Chapter 3

**Hicks D**, Drummond C, and Williams KJ. Measurement Agreement Between Samozino's Method and Force Plate Force-Velocity Profiles During Barbell and Hexbar Countermovement Jumps. *Journal of Strength and Conditioning Research* 36: 3290-3300, 2021.

Chapter 4

**Hicks D**, Drummond C, Williams K, and van den Tillaar R. Force-Velocity Profiling in Club-Based Field Hockey Players: Analyzing the Relationships between Mechanical Characteristics, Sex, and Positional Demands. *Journal of Sports Science and Medicine* 22: 142-155, 2023.

Chapter 5

**Hicks D**, Drummond C, Williams K, and van den Tillaar R. Investigating Vertical and Horizontal Force-Velocity Profiles in Club-Level Field Hockey Athletes: Do Mechanical Characteristics Transfer Between Orientation of Movement? *International Journal of Strength and Conditioning* 3: 1-14, 2023.

Chapter 6

**Hicks D**, Drummond C, Williams KJ, and van den Tillaar R. The effect of a combined sprint training intervention on sprint force-velocity characteristics in junior Australian football players. *PeerJ*: 2-22, 2023.

Chapter 7

**Hicks D**, Drummond C, Williams K, and van den Tillaar R. Exploratory Analysis of Sprint Force-Velocity Characteristics, Kinematics and Performance across a Periodised Training Year: A Case Study of Two National Level Sprint Athletes. *International Journal of Environmental Research and Public Health* 19: 1-16, 2022.

Chapter 8

**Hicks, D**, Drummond, C. Williams, K. Pickering, C. van den Tillaar, R. Individualization of training based on sprint force-velocity characteristics: A conceptual framework for biomechanical and technical training recommendations. *Strength and Conditioning Journal (published).*

Chapter 9

**Hicks D**, Schuster J, Samozino P, and Morin JB. Improving Mechanical Effectiveness During Sprint Acceleration: Practical Recommendations and Guidelines. *Strength and Conditioning Journal* 42: 45-62, 2019.

*Publications not forming part of this thesis*

Pickering C, **Hicks D**, and Kiely J. Why Are Masters Sprinters Slower Than Their Younger Counterparts? Physiological, Biomechanical, and Motor Control Related Implications for Training Program Design. *Journal of Aging and Physical Activity* 15: 708-719, 2021.

*Presentations*

**Hicks D**. (2021). Optimizing sprint performance using a quadrant-based approach to force-velocity profiling. Young Hour of Power (YHOP) Presentation at the 2021 ASCA International Conference on Applied Strength and Conditioning, Gold Coast, Australia.

# CHAPTER 1: GENERAL INTRODUCTION

## Chapter Overview

This introductory chapter provides a brief background to the force-velocity (F-v) relationship and the key determinants of performance in jumping and sprinting actions via field-based mechanical profiling using *Samozino's method*, hereinafter known as the SAM method (283, 286). Next, the reliability and validity of this methodological approach is explored in reference to jumping and sprinting actions. Following this, the application of using individualized and optimized mechanical characteristics to enhance physical performance and reduce risk of injury are investigated. Then, understanding the links between mechanical characteristics and the specific training programmes required to enhance jump and sprint performance is discussed. Finally, a summary of the main aims of the thesis and content for subsequent chapters is provided.

## Background

Movement tasks such as maximal jumping and sprinting actions are underpinned by the mechanical characteristics of the human body, specifically, force, velocity, and power (66, 67, 235, 332). In sports biomechanics, quantifying the mechanical variables that govern human movement tasks provides vital information on the current state of the neuromuscular system. Furthermore, understanding how mechanical variables interact with each other to optimize physical performance is of interest to sport performance coaches as it can provide a roadmap to improve neuromuscular output in both training and competition, thereby improving physical performance. One method to quantify the relationship between force and velocity in multi-joint actions is the concept of F-v profiling.

Compared to other strength diagnostic assessments such as 1-repetition maximum (1RM) testing or standardized fitness test batteries, which are typically a *'one-size-fits-*

*all'* approach, F-v profiling has greater potential benefits to practitioners and athletes, one of which is the ability to individualize training interventions based on mechanical characteristics (242, 283, 286). Existing literature using the SAM methodology suggests the mechanical variables obtained using the 'simple' field method approach is valid and reliable (283, 286). However, at the time of beginning this thesis (Jan 2018), research studies were limited to theoretical and conceptual literature and few cross-sectional and interventional studies (173, 235, 237, 284, 287, 288) performed by a small group of researchers and therefore greater exploration of methodology was warranted.

## Macroscopic Approach to Force-velocity profiling

Evaluating mechanical variables in functional tasks is often limited to laboratory settings utilizing expensive technology such as in-ground force plates (173, 252, 254), three-dimensional motion capture (232, 307) and other ergometers, however access to this technology can be restrictive to the practitioner. Therefore, simple 'field methods' using a macroscopic biomechanical model and inverse dynamics approach has been proposed by Samozino et al. (283, 286), i.e., the 'SAM method'. Essentially, the SAM method *brings the laboratory to the field*, thereby allowing practitioners including strength and conditioning coaches and sport scientists to quantify the mechanical characteristics of jumping and sprinting performance using only basic body measures including body mass, standing stature, lower-limb length, jump height and velocity-time (or position-time data). This type of macroscopic approach is possible using inverse dynamics, which describes the process of the mechanical output, i.e., the performance, being used in biomechanical modelling to indirectly estimate the underlying mechanical properties (i.e., forces) which produced the performance (51). Jumping and sprinting assessments, which are included in typical test batteries in team sports (333), include testing jump height and sprint time as the performance outcomes. However, the outcome only provides information about 'what' happened in the test, whereas the vertical (jump) and horizontal (sprint) F-v profile potentially provides more insightful information about 'how' the performance was produced, thereby identifying the mechanical characteristics, often referred to in the literature as 'determinants' of performance (150). Therefore, compared with traditional fitness tests or resistance training methods where strength is typically the dominant factor considered to improving performance (319), the use of F-v profiles to provide data-driven decisions which inform interventions to optimize (304) and individualize (195) training to enhance performance on the field, court or track is of interest to sport practitioners.

## Validity and Reliability

Determining the test-retest reliability and agreement between novel quantitative assessment techniques is essential to ensure mechanical variables are reproducible and valid against technology rated as the 'gold standard' (152). This is of greater importance in an elite sporting environment where error in data collection may mask a positive change in performance, when in fact the change is less than the smallest worthwhile change or minimal detectable change (116, 153). Due to the macroscopic approach of field-based F-v profiling methodology (283, 286), most F-v variables are *indirect* measures of mechanical output and require differentiation from existing variables. For example, the vertical F-v profile uses an indirect measure of jump height (i.e., arial time) and center of mass displacement values to estimate vertical ground reaction force (GRF), whereas during the sprint action, the horizontal component of the total ground reaction force is derived from position-time or velocity-time data and anthropometric and environmental variables. Two previous validation studies (129, 176) focussed on jumping using the SAM method, identified acceptable levels of mean bias for force, velocity and power (<3.0%) and strong associations ($r > 0.96$) between methods, with similar levels of validity (mean bias < 5.0%) and reliability (CV < 4.0%, SEM = -3.9-4.0%), reported for studies using SAM methodology to determine sprint mechanical characteristics (246, 266). It was noted during these studies that linear position transducers and accelerometer provide greater understanding of overall kinetic-patterns, yet the SAM method provides strong reliability and greater ease of processing time. Despite these findings, research studies challenging the utility, validity and reliability of F-v profiling and key variables have also been identified (29, 199, 200, 336). Several of the opponents to the SAM methodology identified measurement method of the F-v profile altered the characteristics of the F-v slope. Therefore, the subsequent training prescription may differ for the same athlete depending on how the data was collected. Furthermore, this highlights the need for pilot studies (268) and validation studies (129, 176, 246, 266) against laboratory grade technology before attempting to use new field-based equipment for mechanical profiling.

## Mechanical Characteristics

Quantifying the biomechanical determinants of jump and sprint performance of athletes within a specific sport can provide insight to coaches about the mechanical characteristics required on the court, field or track. In many field-based sports, global positioning systems provide time-motion analysis (79, 118, 209) about the physical actions which occur throughout the game (i.e., jog, sprint, walk, change direction), however the biomechanical characteristics contributing to movement patterns across the field (or court) are often not assessed and therefore the mechanical determinants of physical performance remain unknown. Previous cross-sectional studies using the SAM method to quantify mechanical characteristics in team and individual sports such as rugby league, soccer, ballet, and sprinting (74, 105, 170, 315) have highlighted the utility of improving our understanding of performance outcomes through analysis of the kinetics and kinematics of performance. Specifically, by analyzing how athletes produce force and power across a range of movement velocities during jumping and sprinting actions, coaches can begin to develop a set of benchmarks or priori values which athletes of different ability levels should be a targeting to improve overall performance.

Furthermore, cross-sectional analysis of mechanical characteristics has enhanced understanding of an individual's potential neuromuscular function and limits by identifying mechanical strengths, weaknesses and imbalances (242). In a sporting context, this information may be useful for strength and conditioning coaches when developing individualized training interventions or physical preparation strategies, plus providing baseline data of athletes at different performance levels within the same sport.

## Individualization of Training

It is largely accepted within sport science and physical preparation, athletes of different ages, ability, sporting background and performance, should undertake different forms of training. This adheres to the training principle of individualization (32), which describes how coaches must make considerations for an athlete's individual characteristics (i.e., skill, physiology, biomechanics), when planning training sessions. A failure of many training programmes is to use the session design from higher performance levels (i.e., elite) with novice or youth athletes, potentially placing them at risk of injury. Existing literature suggests mechanical differences exist in jumping and sprinting actions when comparing sports and performances levels (174), with players from professional or elite levels within the sport displaying superior F-v characteristics and associated mechanical variables. Similar observations have been made when comparing mechanical characteristics between youth academy athletes (99, 104), along with athletes at different stages of maturation such as pre or post peak height velocity (112), however this population group appears under researched. Additionally, when comparing similar mechanical characteristics between vertical and horizontal F-v profiles, it has been suggested that the transfer of characteristics between actions, i.e., jump characteristics associated with sprint characteristics, is higher for athletes of lower ability levels (174). Despite these findings, conjecture remains regarding the nuances of training in response to F-v data, however mechanical profiling appears to provide greater opportunities to individualize and differentiate training based on current neuromuscular output.

### Targeted Training and Performance

Research examining mechanical characteristics within the sporting context suggests mechanical profiling is potentially a more insightful neuromuscular assessment than other outcome based approaches (i.e., team sport fitness batteries)(249) and one which can inform short and long-term training interventions. Once mechanical strengths, weaknesses and imbalances have been quantified, individualized training programmes based on the F-v (and load-velocity) relationship can be developed which target specific aspects of the F-v continuum, rather than using a 'one-size fits all' approach. This type of approach to training has often attempted to reduce the F-v imbalance and direct mechanical characteristics to the 'optimal' F-v profile (175). Despite previous research (66, 164, 218, 301) focussing on the power-load relationship to design training programmes, the SAM method has focussed on making inter-athlete comparisons, independently of maximal power capabilities, thereby identifying whether the athlete's F-v profile is more *force oriented* (i.e., strength) or *velocity oriented* (i.e., speed) compared to their peers or baseline values specific to the sport (or position within the sport)(242). If an athlete has a force-oriented F-v profile it suggests the slope of the profile is steep where force is the dominant variable contributing to external maximal power expression yet may also highlight velocity is a weakness. And vice versa, an athlete with a velocity-oriented F-v profile displays a 'flatter' F-v profile where velocity is the dominant variable contributing to external maximal power expression, potentially highlighting the force component as a weakness. The slope of the F-v profile has been suggested to act as a 'roadmap' of which exercises, and training interventions should be included in an athlete's training programme (150). Given the importance of physical preparation in team and individual sports, greater interventional research studies using mechanical characteristics to direct training strategies would therefore be useful to practitioners to understand the sensitivity of the F-v profile to training stimuli.

## Monitoring Performance

Training load monitoring within a sporting context is typically used to assess the physical work the athlete completes during a training session or game (i.e., external load) and the athlete's within-training response to the specific training or game (i.e., internal load) (71, 158). From a biomechanical perspective, monitoring of performance largely focusses on assessing mechanical characteristics, for example jumping and sprinting actions, to better understand the response to specific forms of training. Although quite limited in its application within a mechanical profiling context, monitoring mechanical characteristics such as force, velocity and power has been used to assess how athletes' respond to a particular training stimulus (i.e., resisted or assisted sprint training)(195). Furthermore, other literature within the field has also explored monitoring mechanical characteristics with reference to detecting levels of fatigue, injury risks and return to play protocols post injury. These studies have highlighted acute changes to mechanical characteristics (i.e., reduced horizontal force production) via repeated sprint training could potentially be used as a 'red flag' for higher risk of injury occurring (98, 169). Once sustaining an injury, research has suggested pre-injury mechanical characteristics could be used as baseline variables to monitor when the athlete has progressed to full performance and overcome the injury, at least from a mechanical perspective (223). Further exploring a monitoring approach to mechanical characteristics using data-driven short and long-term training interventions should therefore be considered useful. This would allow practitioners to examine the effectiveness of training, the impact of competition across different phases of the season and to establish relationships between characteristics and performance outcomes at key periods.

## Training Recommendations and Guidelines

Training programmes within a sporting context are generally based on traditional training principles including progressive overload, specificity, volume and intensity (32). Furthermore, strength and conditioning coaches often use periodisation models to prescribe specific types of training at different time points of the competitive sport season (31). Despite these approaches, F-v profiling using either an individualized or optimized approach to mechanical characteristics requires a different approach to training due to the necessity to prescribe training based on individual F-v requirements. Many of the cross-sectional and short-term interventional F-v studies often highlight training methods or specific exercises which could be used enhance specific mechanical characteristics evident in vertical or horizontal F-v profile yet there are limited applied journal articles explaining in detail how to address this. Previous research have attempted to prescribe training (10-weeks) based on the F-v profile and found limited group differences despite targeted training towards or away from their theoretical F-v slope (200), yet conjecture has also been raised about the overall strength and conditioning programme used in this study (290), compared with similar research studies who found positive changes using this methodology (304).

Therefore, it is essential practitioners understand the links between *the data* and *applied practice* through specific training recommendations, guidelines, and programmes to make actionable decisions from F-v profiling assessments.

From a strength and conditioning perspective, F-v profiling therefore quantifies the F-v conditions under which maximal power expression occurs, which when maximized, enhances mechanical F-v characteristics and neuromuscular output, thereby improving jump and sprint performance, a key performance indicator in many team and individual sports (73). It is therefore essential to determine the utility of the SAM method across various sports and population groups to understand the effectiveness of using individualized training interventions to enhance jump and sprint mechanical characteristics. Furthermore, once quantified, determining the most appropriate approach to enhance mechanical characteristics via physical preparation strategies is also a current limitation of the methodology.

## Aims

This thesis is based on a series of studies that were conducted with the aim of improving the practitioners understanding of the application and utility of mechanical profiling to improve physical performance in jumping and sprinting actions across a range of different cohorts.

Specifically, the objectives of the thesis were to examine the reliability and validity of using field method(s) to determine F-v profiles. Furthermore, cross-sectional analysis explored the application of using profiling methods to differentiate between sex and positional demands in team sport, while also analysing whether mechanical characteristics transfer between force-vectors. Additionally, an interventional study investigated adaptations to F-v characteristics in response to a combined sprint training intervention, whereas a longitudinal case study explored and monitored changes to sprint mechanical characteristics in response to training and competition across a track and field season. Finally, two applied practice chapters concluded the thesis to draw the information together and provide training direction, recommendations and guidelines to effectively use mechanical profiling to inform training design and programming. The specific aims of the thesis were to:

1. Review existing literature related to the F-v relationship and F-v profiles established using field methods in jumping and sprinting actions.
2. Determine the reliability and validity of using field methods to determine F-v profiles and characteristics.

3. Cross-sectionally explore differences in the mechanical characteristics from F-v profiles between different sporting populations.
4. Investigate the influence of short-term and long-term training interventions on the F-v profile.
5. Determine strategies to categorize and individualize training interventions to optimize F-v characteristics and improve physical performance.

## Outline of the Thesis

The overarching aims of this research were achieved by conducting a series of quantitative studies and reviews which are described in each of the subsequent chapters (Figure 1.1). It is worth noting that the timing of this research was sometimes affected by the COVID-19 global pandemic which impacted various studies due to availability of participants due to government imposed lockdowns, however reasonable outcomes were still observed.

In Chapter 2, a narrative literature review was conducted to critically appraise the literature concerning field methods to determine F-v profiles in jumping and sprinting actions using a macroscopic inverse dynamics approach. Chapter 3 presents Study 1, a validation study focussed on Samozino's method to determine vertical F-v profiles via countermovement jumps at various loading conditions and its agreement with force plate technology. Chapter 4 presents Study 2, which used an observational cross-sectional analysis to determine the positional and sex-specific associations between the vertical F-v profile in club-level field hockey players. Chapter 5 presents Study 3, a further observational cross-sectional analysis exploring the mechanical relationships between vertical and horizontal F-v profiles in field hockey athletes. Participants in both Chapter 4 and Chapter 5 were originally recruited for a 16-week interventional study, however due to the onset of COVID-19 (March 2020), these studies were concluded at approximately the halfway point of the study due to South Australian government lockdowns. Therefore, only cross-sectional data could be utilized.

Study 4 (Chapter 6) investigated the influence of a 7-week combined sprint training intervention (i.e., assisted and maximal sprint training) on the sprint F-v profile in junior Australian football players. Study 5 (Chapter 7) is a case-study which longitudinally analysed changes to the sprint F-v profile and performance across a training year in two national level sprint athletes. Chapter 8 and Chapter 9 provide practical training-related recommendations and guidelines to further analyse F-v data using a categorization system to individualize training prescription, plus provide suggested training interventions and programmes to improve sprint performance in team and individual sport athletes. The final chapter (Chapter 10) provides a summary of the program of research, including theoretical and practical implications and explores new avenues for future research.

All chapters in this thesis are formatted as manuscripts for publication. Chapters which have been published are listed below.

- Chapter 3: *Journal of Strength and Conditioning Research*
- Chapter 4: *Journal of Sport Science and Medicine*
- Chapter 5: *International Journal of Strength and Conditioning*
- Chapter 6: *PeerJ*
- Chapter 7: *International Journal of Environmental Research and Public Health*
- Chapter 8: *Strength and Conditioning Journal*
- Chapter 9: *Strength and Conditioning Journal*

Due to similar methodology used across studies, there is some repetition of information in various sections of each chapter as they have been written specifically for publication.

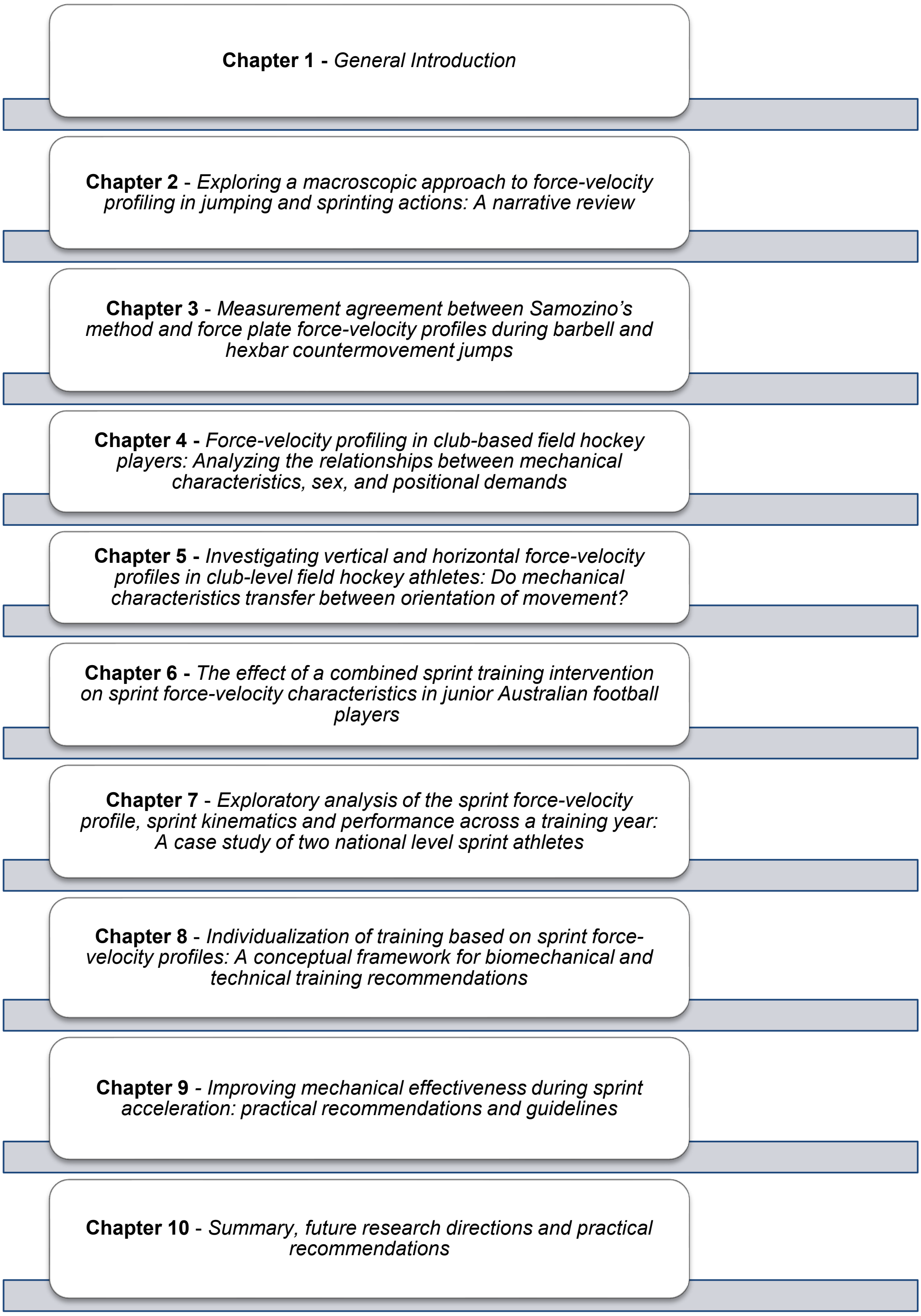


**Figure 1.1.** Thesis flowchart

# PRELUDE

Sports practitioners have recently shown greater interest in using 'field' methods to obtain mechanical F-v characteristics in jump and sprint actions. Previously, mechanical characteristics which could be used to inform training and physical preparation strategies were only available in a laboratory setting using expensive technology, however a macroscopic approach using inverse dynamics has made it possible to 'bring the laboratory to the field' and provide insight to neuromuscular performance and mechanical output. The purpose of the following narrative review was to critically appraise the utility of using mechanical profiling to guide training interventions to improve performance. This review identifies gaps and limitations in the current literature, which in turn sets the foundation and guides the research within this thesis.

# CHAPTER 2

## Exploring a macroscopic approach to force-velocity profiling in jumping and sprinting actions: A narrative review

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**Statement of co-authorship**: All authors were involved in formulating the concept and design of the study. Dylan Hicks conducted the analysis and completed the initial draft of the manuscript. All authors edited multiple revisions of the chapter.

**Abstract**

Assessing, evaluating and improving neuromuscular output in functional human movement tasks such as jumping, and sprinting is typically considered beneficial to sport performance. To achieve this, an assessment known as Force-velocity (F-v) profiling assists practitioners to explain the underpinning neuromuscular and biomechanical mechanisms of the performance. The aim of this review was to critically appraise the literature concerning Samozino's simple field methods, hereinafter referred as the 'SAM method', to determine F-v profiles in jumping and sprinting actions using a macroscopic field based approach. In addition, we aim to (a) explore the biomechanical models for determining jumping and sprinting F-v profiles using inverse dynamics, (b) analyse the reliability and validity of jump and sprint F-v profiling methodology, (c) explore the concept of optimizing and individualizing the F-v profile, and (d) the utility of using profiling to inform training interventions to enhance sport performance. When profiling athletes in jumping or sprinting actions, we recommend practitioners use strict, validated methods to ensure correct data is being used in the SAM methods. Reliability concerns with the SAM method(s) should be addressed by practitioners performing their own pilot studies, along with ensuring sufficient familiarization time for participants prior to the F-v assessment. Individualizing and optimizing the F-v profiling in jumping and sprinting has identified the sensitivity of the F-v profile to respond to specific training interventions while also identifying training improvements greater than control groups. Furthermore, across many individual and team sports, the effectiveness of F-v profiling is highlighted by the ability to distinguish between age, ability level, field position and performance, along with identifying potential risk of injury and monitoring return to performance. Finally, we provide some recommendations about effectively implementing the SAM method of F-v profiling in the team and individual sport environment.

## Introduction

Force, velocity, and power are the underpinning neuromuscular qualities which influence how high someone can jump and how fast someone can run (66, 67, 235, 332). During individual and team sports such as track and field, rugby, basketball and volleyball, the ability to rapidly accelerate one's bodymass in either the vertical or horizontal direction is often a determining factor in performance (242). From a biomechanical standpoint, to improve an athlete's performance in functional tasks, first the mechanical qualities contributing to performance must be quantified. Once the contributing mechanical qualities are evaluated, it is possible to then determine any potential strengths or weaknesses, plus analyse the interaction between mechanical qualities in reference to the performance outcome. One approach to determine the linear relationship between force and velocity qualities is the concept of F-v profiling. F-v profiling is a neuromuscular assessment tool aimed at quantifying mechanical variables in maximal effort movement tasks. For practitioners working with athletes, this information can potentially allow for greater insight into the mechanical imbalances or deficiencies evident in movement tasks, thereby providing a window of opportunity to individualize training interventions and improve physical performance.

Evaluating mechanical variables in functional tasks is often limited to laboratory settings utilizing expensive technology such as in-ground force plates (173, 252, 254), three-dimensional motion capture (232, 307) and other ergometers, however access to this technology can be restrictive to the practitioner. Therefore, simple 'field methods' using a macroscopic biomechanical model and inverse dynamics approach has been proposed by Samozino et al. (283, 286), hereinafter referred as the 'SAM method'. Inverse dynamics describes the process of the mechanical output, i.e., the performance, being used in biomechanical modelling to indirectly estimate the underlying mechanical properties (i.e., forces) which produced the performance (51). In jumping and sprinting assessments, which are included in typical test batteries in team sports (333), jump height and sprint time are the performance outcomes. However, the outcome only provides information about 'what' happened in the test, whereas the F-v profile provides information about 'how' the performance was produced, thereby identifying the mechanical characteristics of performance (150). Therefore, compared with traditional fitness tests or resistance training methods where strength is generally the dominant factor considered to be driving performance (319), the use of the SAM method to determine F-v profiles, can provide data about how training interventions can be optimized (304) and individualized (195) to enhance performance on the pitch, court or track, which is of interest to sport practitioners, specifically those working in the 'field'.

Therefore, the primary aim of this review is to investigate the application of using the SAM method(s) of F-v profiling to determine mechanical characteristics and improve physical performance in jumping and sprinting actions. Secondary aims include: (a) exploring the F-v relationship and biomechanical models used in the SAM method(s) for determining vertical and horizontal F-v profiles, (b) analyse the reliability and validity of vertical and horizontal profiling F-v methodology, (c) explore the concept of optimizing and individualizing the F-v profile, and (d) the utility of using profiling to inform training interventions to enhance sport performance.

## Background

The mechanical determinants governing muscle function provide vital information about the neuromuscular limits of the human body. Seminal studies pioneered by Hill (151), focused on the *in vitro* studies of muscle function in amphibians (151) which determined the classical hyperbolic F-v relationship. Studies on skeletal muscle formed the theory that an increase in velocity resulted in a decrease in the magnitude of work performed and force produced (111, 117). This theory was recognised in the classical graphical representation of the F-v relationship (Figure 2.1). The ability to understand the relationship between contractile velocity, work, energy and magnitude of force, provided future thought and insight into the muscle's organisation and structure, and therefore potential capabilities (117).

However, as research progressed to *in vivo* studies on single joint actions (327, 328) and then multi-joint actions such as jumping and sprinting, the F-v relationship of these multi-joint actions was shown to be linear or quasi-linear (30, 162). Researchers concluded the F-v relationship differed when *in vivo* due to various joints integrating and combining to produce force, and muscle coordination being underpinned by neural mechanisms and segmental dynamics of the limbs (30).

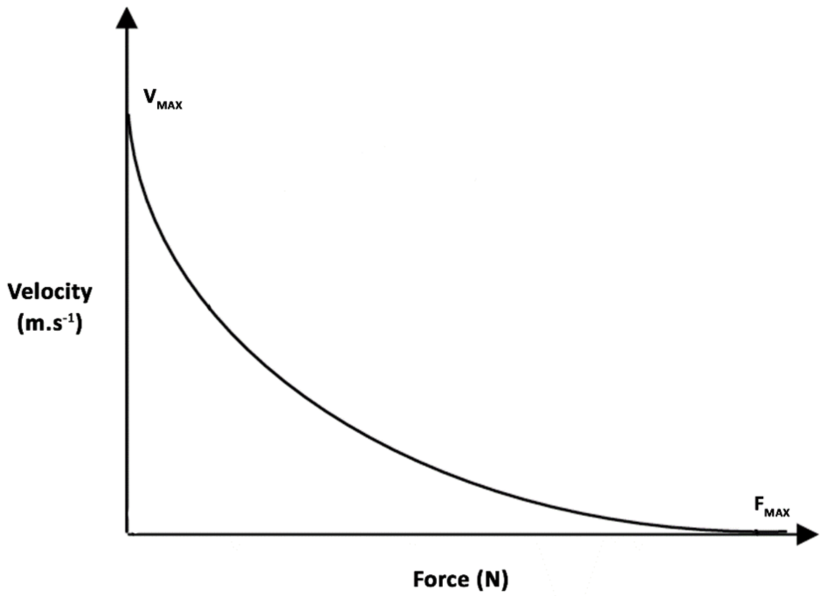


**Figure 2.1**. Classic hyperbolic force-velocity relationship as proposed by A. V. Hill. ($V_{MAX}$ = maximal velocity, $F_{MAX}$ = maximal force)(151).

F-v profiling methodology has been used to assess maximal muscle functions in various functional tasks such as cycling, bench press and leg extensions (78, 94, 95, 110, 162, 235, 266, 267, 286, 358, 366), which offers insight to the current state and capacity of the neuromuscular system. However, this review will primarily focus only on the application of F-v profiling using the SAM method in vertical jump (283) and sprinting actions (286). The key mechanical variables obtained from vertical (i.e., jumping) and horizontal (i.e., sprinting) F-v profiles include theoretical maximal force ($F_0$), theoretical maximal velocity ($v_0$) and theoretical maximal power ($P_{MAX}$). Theoretical maximal force ($F_0$) and theoretical maximal velocity ($v_0$) are the intercepts of the inverse linear F-v relationship, while theoretical maximal power ($P_{MAX}$) represents the apex of the parabolic relationship between power and velocity (Figure 2.2). Despite theoretical maximal power representing the product of theoretical maximal force and theoretical maximal velocity, force and velocity qualities have been suggested to be independent of each other, thereby requiring different training interventions to improve each mechanical quality (359). Furthermore, independent mechanical qualities remain a quasi-reflection of the intrinsic properties of the neuromuscular, osteo-articular systems of the body (360) and the segmental dynamics of the upper and lower limbs (30, 232).

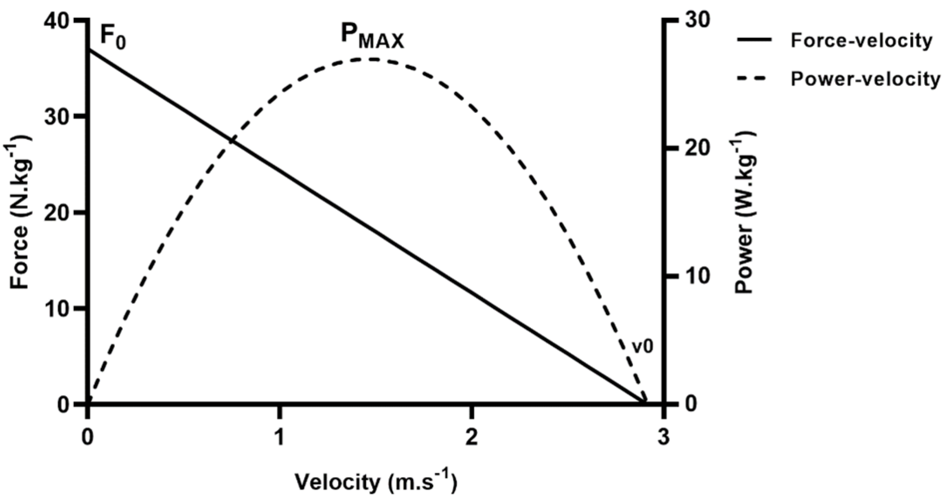


**Figure 2.2**. An example of the linear force-velocity relationship and parabolic power-velocity relationship derived from a series of countermovement jumps against incremental external loads. ($F_0$ = theoretical maximal force, $P_{MAX}$ = theoretical maximal external power, $v_0$ = theoretical maximal velocity).

To determine mechanical characteristics, the SAM method uses simple inputs in the biomechanical model such as anthropometric data, centre of mass displacement, jump height and position-time or velocity-time data. These inputs can be collected by the coach with limited technology, such as a smartphone (12, 274), to determine the key mechanical data necessary to analyse the performance. Therefore, essentially bringing the laboratory into the real-world sport setting such as the track, court or field. In jumping tasks, the vertical F-v profile is determined by performing squat jumps or countermovement jumps in a smith machine (176) or free-weight equivalent (i.e., barbell, hexbar)(149) against a series of external loads (i.e., 2-9 loads)(113, 121, 261) which span the F-v continuum (1) and assessing the jump height against each load. Whereas, the horizontal F-v profile is determined by performing a maximal 20-40m sprint effort, with position-time data collected with timing gates (145, 338) or global positioning systems (192, 239), or velocity-time data collected via radar (248), optical laser (125) or a motorized pulley device (339). This information can then be processed in custom-made Microsoft Excel spreadsheets (243, 244) which derive all F-v variables for further analysis and establishes the linear F-v relationship.

Despite being regarded as ‘simple’ methods in reference to gold standard technology such as in-ground force plate systems (176, 252), the SAM method has been reported to be valid and reliable, however some research has questioned the intra and inter-session reliability of the F-v measures. Samozino et al. (283) and Jimenez et al. (176) both reported high reliability (ICC>0.98, CV <1.0%) and low mean bias (<2.88%) in squat jumps and countermovement jumps respectively, when compared to force plate technology. Furthermore, research on the agreement between force plate technology in sprinting compared to the SAM method has shown strong agreement of inter-trial reliability (SEM = 2.36%) and low absolute mean bias (4.08%) via two methods of over-ground sprinting on in-ground force plates over 40-60m (246, 266). To ensure accuracy of mechanical characteristics from simple inputs, further exploration of the biomechanical models used in the SAM method(s) to determine vertical and horizontal profiles is warranted.

## Force-velocity profile – Biomechanical models

### *Vertical force-velocity profile (Jump F-v profile)*

The macroscopic biomechanical model used in the SAM method to determine vertical F-v profiles explores the relationship between the power output produced by the lower limbs in vertical jump actions and the mechanical characteristics which influence the outcome, i.e., force and velocity (283). The biomechanics of ballistic actions such as jumping have been the focus of sport scientists for almost 50 years, where the aim was to determine how the neuromuscular characteristics such as power influence jump performance (81, 82). Vertical jump assessment is arguably the most used action to evaluable the mechanical characteristics of the lower limbs due to the simplicity of the test plus the strong relationship which is evident with external maximal power (137). However, measuring force and velocity often requires expensive instruments in a laboratory setting (82) and therefore a need to determine mechanical characteristics 'for the field' is desirable for sport practitioners. Various field tests which indirectly quantify power in the lower limbs have been explored by Sargeant et al. (294) and Margaria et al. (213) and Bosco (83). Bosco highlighted a strong relationship ($r = 0.95$) and high reliability for evaluating mean mechanical power during explosive stretch-shortening exercises using contact time and flight time (34), however the characteristics could not describe actions such as the squat jump or countermovement jump which are commonly used in sport science, nor describe neuromuscular characteristics of the entire F-v continuum (1).

Based on experimental equations which showed maximal power output was highly dependent on the height achieved in the vertical jump and bodymass (137, 197, 198), Samozino's et al. (283) model uses the three simple parameters, i.e., bodymass, jump height and push-off distance, to determine mechanical variables using a macroscopic model based on the fundamental principles of dynamics applied to the body center of mass. Jump height is be determined from flight time (i.e., time in the air between take-off and landing), using Newton's Laws of motion, a method initially proposed by Asmussen and Bonde-Petersen (6). Furthermore, by analyzing the potential and kinetic energy at different time points of the movement, plus the flight time of the jump, it is possible to determine mean values for force, velocity and power produced by the lower limbs during the vertical jump action. Definitions and practical description of vertical F-v variables are listed in Table 2.1. A detailed explanation of the biomechanical model underpinning the SAM method is highlighted in Equations 1-8.

For all maximal effort vertical jump actions, whether against bodymass and gravity or an external load, and assuming the take-off and landing position during the jump action is the same, i.e., plantar flexed toes, jump height can be determined from arial time ($T_A$) as outlined in Equation 1 (6):

$$h = \frac{1}{8} g T_A^2 \qquad \text{[Eq 1]}$$

* g = gravitational acceleration

Then, from Equation 1, vertical take-off velocity can be expressed as a function of jump height:

$$v_{TO} = \sqrt{2gh} \qquad \text{[Eq 2]}$$

**Table 2.1.** Definitions and practical description of vertical force-velocity variables

| Variable | Abbreviation | Practical Interpretation |
|---|---|---|
| **Theoretical maximal vertical force (intercept) production extrapolated from the linear loaded countermovement jumps F-v relationship** | Absolute $F_0$ (N)<br>Relative $F_0$ (N.kg$^{-1}$) | Maximal concentric force output in the vertical direction per unit of body mass. Describes the athlete's force capability to project the centre of mass in the vertical direction. |
| **Theoretical maximal movement velocity (intercept) extrapolated from the linear loaded countermovement jumps F-v relationship** | $v_0$ (m.s$^{-1}$) | Maximal movement velocity in the vertical direction during the countermovement jump. Describes the athlete's ability to produce force at high velocities in the vertical direction. |
| **Maximal mechanical external power output in the vertical direction ($P_{MAX}$ = $F_0$ x $v_0$/4)** | Absolute $P_{MAX}$ (W)<br>Relative $P_{MAX}$ (W.kg$^{-1}$) | Maximal external power-output capability during the concentric action of the countermovement jump per unit of body mass. |
| **Slope of the force-velocity relationship** | Absolute $S_{FV}$ (N.s.m$^{-1}$)<br>Relative $S_{FV}$ (N.s.m$^{-1}$.kg$^{-1}$) | Index of an athlete's individual balance between force and velocity capabilities. The more negative the value, and steeper the F-v slope, the more force-dominant the athlete is. |
| **Jump height** | JH (m) | The maximal centre of mass displacement achieved during the flight phase of the countermovement jump. |
| **Flight time** | FT (sec) | ArialArialtime of the athlete between 'take-off' until 'landing' in the countermovement jump |

With the final expression of mean velocity across the propulsive phase described as:

$$v = \sqrt{\frac{gh}{2}} \qquad [Eq\ 3]$$

* g = gravitational acceleration ($-9.81 m.s^{-2}$), h = jump height

During a maximal countermovement jump when the center of mass is at its lowest point prior to beginning the upward propulsive phase (in a squat jump, this is the starting point), the lower limbs perform mechanical work to elevate the body center of mass from its lowest position to the maximal vertical height attainable. At the transfer point from negative (i.e., body moving downwards) to positive acceleration (i.e., body moving upwards), when velocity is zero, the total work performed ($W_T$) equals the potential-energy change between the two positions.

$$W_T = mg(h_{PO} + h + h_s) - mgh_s \qquad [Eq\ 4]$$

$$W_T = mg(h_{PO} + h) \qquad [Eq\ 5]$$

*$h_{PO}$ = height of push-off, $h_s$ = starting height, h = jump height, m = bodymass, g = gravitational acceleration ($-9.81 m.s^{-2}$)

From Equation 5, the work performed during lower limb extension is equal to the product of $h_{po}$ and mean vertical force, therefore this can be described by the following equation:

$$F = \frac{W_T}{h_{PO}} \qquad [Eq\ 6]$$

* $W_T$ = total work performed, $h_{po}$ = height of push-off

Equations 5 and 6 can then be used to create Equation 7 and determine mean force in the propulsive phase:

$$F = \mathrm{mg}\left(\frac{h}{\mathrm{h}_{po}} + 1\right) \qquad \textit{[Eq 7]}$$

* m = bodymass, g = gravitational acceleration (-9.81m.s$^{-2}$), h = jump height, $h_{po}$ = height of push-off

Mean power produced during the propulsive phase of the vertical jump can then be expressed as the product of force (Equation 7) and velocity (Equation 3):

$$P = \mathrm{mg}\left(\frac{h}{\mathrm{h}_{po}} + 1\right)\sqrt{\frac{gh}{2}} \qquad \textit{[Eq 8]}$$

* m = bodymass, g = gravitational acceleration (-9.81m.s$^{-2}$), h = jump height, $h_{po}$ = height of push-off

Since the height of push-off ($h_{po}$) is key to determining mean force and power it is critical to ensure accuracy of this measurement. To limit variability in eccentric displacement when performing a maximal countermovement jump, recent literature has recommended using an external constraint such as a band or box to control for squat depth (i.e., $h_{po}$), and ensure the height of push-off is reliable between all external loads (149, 160, 161). Failure to establish a consistent push-off distance will likely result in significant errors in the biomechanical model. The squat jump has a fixed starting point due to solely focussing on the concentric phase of the jump action. Further details on equations 1-8 are explained in recent literature (281, 283).

*Horizontal force-velocity profile (sprint F-v profile)*

The macroscopic biomechanical model to determine horizontal F-v profiles is based on quantifying the F-v and power-velocity (P-v) relationships contributing to maximal effort sprint accelerations (286). The F-v and P-v relationship describe the change in an individual's horizontal force and power production as running velocity increases. Seminal research on the mechanical variables in running and cycling, specifically force, velocity and power, were explored by Furusawa et al. (117), Cavagna et al. (39) and Best and Partridge (20), which showed that applying an external resistance to a muscular movement results in proportionally reduced movement velocity. As research progressed, it was possible to quantify mechanical sprint variables via instrumented treadmills (127, 128, 235, 236, 245), (i.e., dynamometers and direct measure of ground reaction forces), where a key finding showed that orientation of the total force applied to the ground during sprint acceleration was of greater importance to sprint performance than the magnitude of total force (236). However, the obvious limitations to this approach were the analyses occurred in the laboratory with expensive equipment and did not replicate the true terrestrial demands of sport. Therefore, sprint profiling focussed on over-ground sprinting using a macroscopic biomechanical model was developed, described as a 'simple' method, to determine sprint mechanical characteristics. This model first appears in the literature from Cavagna et al. (39), Rabita et al. (266) and Samozino et al, (286) based on initial studies and proposal by di Prampero (88), Arsac and Locatelli (5) and Ingen Schenau et al (341). Using an inverse dynamics approach and recording an individual's horizontal center of mass velocity over time during a sprint acceleration (i.e., using radar, optical laser), the model can determine the step-averaged force and power production in the anterior-posterior direction, see equations (1-8) below. Definitions and practical description of horizontal F-v variables are listed in Table 2.2.

**Table 2.2.** Definitions and practical description of horizontal force-velocity variables

| Variable | Abbreviation | Practical Interpretation |
|---|---|---|
| **Theoretical maximal horizontal force production, extrapolated from the linear sprint F-v relationship.** | Absolute $F_0$ (N)<br>Relative $F_0$ ($N.kg^{-1}$) | Maximal force output (per unit body mass) in the horizontal direction. Initial "push" of the athlete into the ground during sprint acceleration. |
| **Theoretical maximal running velocity, extrapolated from the linear sprint F-V relationship.** | $v_0$ ($m.s^{-1}$) | Maximal sprint velocity in the horizontal direction, should mechanical resistances be null. Describes the athlete's ability to produce force at high velocities in the horizontal direction. |
| **Maximal mechanical power output in the horizontal direction ($P_{MAX} = F_0 \times v_0/4$)** | Absolute $P_{MAX}$ (W)<br>Relative $P_{MAX}$ ($W.kg^{-1}$) | Maximal power-output capability of the athlete in the horizontal direction (per unit body mass) during sprint acceleration. |
| **Slope of the force-velocity relationship** | Absolute $S_{FV}$ ($N.s.m^{-1}$)<br>Relative $S_{FV}$ ($N.s.m^{-1}.kg^{-1}$) | Index of an athlete's individual balance between force and velocity capabilities. The more negative the value, and steeper the F-v slope, the more force-dominant the athlete is. |
| **Maximal ratio of force (RF), computed as ratio of step-averaged horizontal component of the ground reaction force to the corresponding resultant force (for sprint times >0.3 sec).** | $RF_{MAX}$ (%) | Theoretical maximal effectiveness of force application. Proportion of total force production that is directed in the forward direction of motion at start of sprint. |
| **Rate of decrease in RF with increasing speed during sprint acceleration, computed as the slope of the linear RF-V relationship.** | $D_{RF}$ (% per $m.s^{-1}$) | Describes the athlete's capability to limit the inevitable decrease in mechanical effectiveness with increasing speed. |

When performing a maximal effort sprint acceleration, horizontal velocity increases systematically and follows a mono-exponential function (89). Equations 1 and 2 identify how $v_{Hmax}$ and $\tau$ can be determined from velocity-time or position-time data respectively using least square regression analysis (280).

$$v_H(t) = v_H max \, . \left(1 - e^{-t/\tau}\right) \qquad [Eq\ 1]$$

$$x(t) = v_H max \, . \left(t + \tau . e^{-t/\tau}\right) - v_H max \qquad [Eq\ 2]$$

*$v_H$= horizontal velocity, $v_H max$ = maximum horizontal velocity, t = time, $\tau$ = acceleration time constant

Maximal horizontal velocity ($v_H max$) is achieved at the end of the sprint acceleration, where $\tau$ is the acceleration time constant. Upon integration and derivation of $v_H(t)$ over time, the body's center of mass position and acceleration as function of time during the sprint acceleration can be expressed as follows:

$$A_H(t) = \left(\frac{vHmax}{\tau}\right) . \, e^{-t/\tau} \qquad [Eq\ 3]$$

*$a_H$= horizontal acceleration, t = time, $\tau$ = acceleration time constant

Then, step-averaged horizontal ground reaction force (GRF) can be calculated across the sprint effort from the horizontal acceleration of the individual's center of mas, along with their known bodymass.

$$F_H\,(t) = m \, . \, a_H\,(t) + F_{aero}\,(t) \qquad [Eq\ 4]$$

*$F_H$= horizontal force, m = bodymass, $a_H$= horizontal acceleration, Faero= aerodynamic friction force, t = time

The aerodynamic drag to overcome during sprinting is proportional to the square of the velocity of air relative to the athlete, along with environmental factors including temperature, barometric pressure, and wind velocity:

$$F_{aero}(t) = k \cdot (v_H(t) - v_w)^2 \qquad [Eq\ 5]$$

$$K = 0.5 \cdot \rho \cdot Af \cdot Cd \qquad [Eq\ 6]$$

$$\rho = \rho_0 \cdot \frac{Pb}{760} \cdot \frac{273}{273+T°} \qquad [Eq\ 7]$$

$$Af = (0.2025 \cdot h^{0.725} \cdot m^{0.425}) \cdot 0.266 \qquad [Eq\ 8]$$

* $F_{aero}$= aerodynamic friction force, $v_w$= wind velocity (if any), k = aerodynamic friction coefficient (5), $v_H$= horizontal velocity, $\rho$ = air density, $Af$ = frontal area of athlete, $Cd$ = drag coefficient (0.9), $Pb$ = barometric pressure, $T°$ = tempature (°C) , $h$ = height, m = mass.

Moreover, power output in the antero-posterior direction ($P_H$) can then be calculated as the product of horizontal force ($F_H$) and horizontal velocity ($v_H$), modeled at each time interval (i.e., 0.1 sec). By modeling the linear relationship between $F_H$ and $v_H$, we can extrapolate the data to obtain the maximal intercept values of force, $F_H0$, and velocity, $v_H0$, at the corresponding axis. Furthermore, the power-velocity relationship can be determined using a 2nd order polynomial regression to the $P_H$-$v_H$ relationship (266, 286), where maximum power ($P_H$max) is visualized as the apex of the parabolic curve between $F_H0$ and $v_H0$ and calculated as:

$$\frac{FH0 . vH0}{4} \qquad [Eq\ 9]$$

In this instance, power does not refer to the work performed in a time interval at a single joint, rather maximal external horizontal power ($P_H$max) refers to mechanical work associated with the step-averaged component of horizontal force, explained by the change in mechanical kinetic energy of the body centre of mass in the horizontal direction between steps. Work performed also accounts for environmental factors such as air resistance. With considerations in the model including standing stature, body mass and an individual's aerodynamic friction coefficient (5, 280), this approach to F-v profiling has applications to the body center of mass through the fundamental laws of dynamics only and does not represent nor quantify other mechanisms contributing to performance such as running kinematics (i.e., stride length, stride frequency) or muscle function at the microscopic level (i.e., fascicle length, motor unit recruitment).

The linear slope of the horizontal F-v relationship, $S_{FV}$, can then be determined from the intercepts of the F-v curve using the following formula:

$$\frac{-FH0}{vH0} \quad \textit{[Eq 10]}$$

By then applying the fundamental laws of dynamics in the vertical direction, it is possible to calculate associated F-v variables. The mean net vertical component of GRF (F$v$) applied to the body COM over each step can then be modeled over time as equal to the individual's body weight (89).

$$Fv\ (t) = m\ .\ g \quad \textit{[Eq 12]}$$

* Fv = net vertical component of GRF, t = time, *m* = bodymass, *g* = gravitational acceleration (-9.81m.s$^{-2}$)

As highlighted in Table 2.2, the ratio of force (*RF* in %) can be calculated at each time interval using the following equation:

$$RF = \frac{FH}{\sqrt{F^2_{H+}\ F^2_v}}\ .\ 100 \quad \textit{[Eq 13]}$$

Following this, we can then plot *RF* against $v_H$ with a linear regression, where the slope of the relationship between variables corresponds to the decrement in ratio of forces across the sprint effort as velocity increases, calculated from approximately 0.3 seconds

(307) after overcoming inertia due to the initial aerial time for the foot to make contact with the ground again and force application begins.

The current literature on horizontal F-v profiling suggests there are a variety of methodologies to model the body centre of mass in the horizontal direction. Specifically, the practitioner must collect velocity-time or position-time data to model the F-v characteristics which has typically been performed using radar (84, 100, 235), optical laser (98, 337, 339), portable robotic device (i.e., 1080Sprint$^{TM}$)(195), global positioning systems (239), photocells and electronic timing gates (338), and smart phone applications (125, 274) which utilize high-speed camera (i.e., 120-240fps). Further details on the biomechanical model for horizontal F-v profiling are addressed by Samozino (280). A summary of the methodological approaches to determine field-based F-v profiles using the SAM method are highlighted in Table 2.3.

**Validity and Reliability**

Determining the test-retest reliability and agreement between F-v profiling methodology (vertical and horizontal) is essential to ensure mechanical variables are reproducible and valid against technology rated as the 'gold standard'. This is of greater importance in an elite sporting environment where error in data collection may mask a positive change in performance, when in fact the change is less than the smallest worthwhile change or minimal detectable change (116, 153). Due to the macroscopic approach of F-v profiling methodology, most F-v variables are indirect measures of mechanical output and require differentiation from existing variables (see sections above on biomechanical models). For example, the vertical F-v profile uses an indirect measure of jump height (i.e., arial time) and center of mass displacement values to determine vertical force, while horizontal force is derived from position-time or velocity-time data and anthropometric and environmental variables.

**Table 2.3.** Methodological details for determining field-based force-velocity variables.

| **Vertical force-velocity profile** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Anthropometric details required** | **Kinematic details required** | **Jump Types** | **Loading Equipment** | **Loading approach** | **Typical loading parameters (multiple load/randomized order)** | **Force-velocity variables obtained** | **Methods to calculate force-velocity profile** |
| - Mass (kg)<br>- Height (m)<br>- $h_{po}$ (height of push-off; m)<br>- $h_s$ (height of CM in starting position; m)<br><br>**Environmental details required**<br>Nil | Flight time (determine jump height)<br>• OptoJump<br>• Smartphone application with high-speed camera [240fps] (i.e., MyJump App) | - Squat Jump<br>- Countermovement Jump | Constrained<br>• Smith machine<br>Unconstrained<br>• Barbell<br>• Hexbar<br>• Weight-vest | - 2-point method (distal points)<br>- Multiple-point method (3-9 loads across the force-velocity continuum, using the mean of 3 trials at each load) | - Bodymass (BM)<br>BM + 20% externally added mass relative to BM<br>- BM + 40% externally added mass relative to BM<br>- BM + 60% externally added mass relative to BM<br>- BM + 80% externally added mass relative to BM | - $F_0$ ($N.kg^{-1}$)<br>- $v_0$ ($m.s^{-1}$)<br>- $P_{MAX}$ ($W.kg^{-1}$)<br>- $S_{FV}$ ($N.s.m^{-1}$)<br>- $SFV_{OPT}$<br>- $FV_{IMB}$ (%) | Customized Microsoft Excel spreadsheet<br>- *vjsim* R Package |
| **Horizontal force-velocity profile** | | | | | | | |
| **Anthropometric details required** | **Kinematic details and equipment required** | **Sprint Types** | **Loading Surface** | **Loading approach** | **Typical loading parameters** | **Force-velocity variables obtained** | **Methods to calculate force-velocity profile** |
| - Mass (kg)<br>- Height (m)<br><br>**Environmental details required**<br>- Temperature (°C)<br>- Barometric pressure (Hg) | Position-time data<br>• Timing gates (5m, 10m, 15m, 20m, 25m, 30m)<br>• Global positioning system unit (10Hz)<br>• Smartphone application with high-speed camera [240fps] (i.e., MySprint)<br><br>Velocity-time data<br>• Radar gun (36-47Hz)<br>• Optical Laser (2.56Hz)<br>• Portable robotic device (i.e., 1080Sprint™, DynaSpeed) | Maximal effort sprinting over 20-40 metres | - Indoor court<br>- Artificial turf<br>- Athletics track | Use the mean of multiple sprint efforts over the selected distance to improve reliability | Timing gates, GPS, smartphone application, radar and laser<br>• Bodymass<br>Portable robotic device<br>• 0.5kg | - $F_0$ ($N.kg^{-1}$)<br>- $v_0$ ($m.s^{-1}$)<br>- $P_{MAX}$ ($W.kg^{-1}$)<br>- $S_{FV}$ ($N.s.m^{-1}$)<br>- RF (%)<br>- $RF_{MAX}$ (%)<br>- $D_{RF}$ (%)<br>- Tau<br>- $V_{MAX}$ ($m.s^{-1}$) | - Customized Microsoft Excel spreadsheet<br>- *Shorts* R Package |

*kg: kilogram, m: metre, C: Celsius, Hg: mercury, fps: frame per second, Hz: hertz, $F_0$: theoretical maximal force; $v_0$: theoretical maximal velocity; $P_{MAX}$: theoretical maximal power; $S_{FV}$: force-velocity slope; $S_{FVOPT}$: optimal force-velocity slope; $FV_{IMB}$: force-velocity imbalance; $RF_{MAX}$: maximum ratio of forces; $D_{RF}$: decrement in ratio of forces; Tau: relative acceleration; $V_{MAX}$: maximal horizontal velocity).

In the seminal study regarding vertical F-v profiles, Samozino et al. (283) explored the validity and reliability of the SAM method using force-plate technology. With participants (n=11, physically active men) performing squat jumps in a smith machine, acceptable levels of mean bias for force, velocity and power were observed (1.74-2.88%) and almost perfect Pearson correlation coefficients (r > 0.96) were evident between methods. Using similar methodology, Jimenez-Reyes et al. (176) (n=16, male sprinters and jumpers) and Giroux et al. (129) (n=17, 11 sedentary participants / 6 elite athletes) also reported acceptable mean bias values (-9.3-5.0%) for all mechanical variables, along with high relative (ICC > 0.97) and absolute reliability (CV < 8.6%) values when comparing the SAM method with force plates. A further study by Janicijevic et al. (161) (n=13, sport science students) confirmed the results of previous studies showing comparable and higher reliability than force plate values when performing squat jumps from a 90° fixed angle and a preferred jumping angle, however for greater reliability, the authors noted recommended a fixed start point for the squat jump (160). One study by Hicks et al. (149) (Chapter 3) (n=21, active males) showed similar levels of absolute and relative reliability between the SAM method and force plate technology when performing countermovement jumps with free-weights (i.e., barbell, hexbar) however it was reported the SAM method overestimated mean force (0.5-4.5%) and underestimated mean velocity (11.8-16.8%) and power (2.3-7.8%) plus demonstrated fixed and proportional bias. Differences between constrained (i.e., smith machine) and unconstrained (i.e., free-weight) loaded jumps when using the SAM method were supported by Valenzuela et al. (336) (n=23, trained participants) and Sarabon et al. (292) (n=30, youth high level sprinters) who both reported high variability for key variables and poor between-day reliability. Variability in the height of push-off has been raised as a concern in various studies (149, 160, 336) suggesting squat jumps in a smith machine, where the vertical path of the bar is fixed, is likely the more appropriate methodology when using the SAM method in the vertical orientation, along with ensuring distal loads close to the F-v intercepts are selected. Despite the aforementioned studies highlighting mostly strong agreement between methodology and acceptable levels of reliability it is also relevant to consider the sample size and cohorts used within each study. Several key studies have low sample sizes (n < 25), while testing participants largely consisted of recreational participants, suggesting the results and F-v characteristics would likely differ if studies were conducted with athletic populations. Statistical power may also not have been achieved with small sample sizes.

Concerning horizontal F-v profiling, the SAM method derives mechanical variables using position-time or velocity-time data collected during the sprint effort, however initial studies using the macroscopic method were validated against in-ground force-plate technology. Based on the initial work of Cavagna et al. (39) and proposed by Rabita et al. (266), using elite sprint athletes (range: 9.95–10.63 sec), Samozino et al. (286) validated the SAM method by reconstructing the characteristics of a single virtual 40-meter sprint using six force platforms laid in series, embedded in running track. By performing maximal sprint efforts from 10-40 meters, and rearranging the start point of the sprint effort in reference to the force plates, researchers collected 18-foot contacts and the corresponding antero-posterior and vertical ground reaction force components plus F-v, power-velocity and associated variables from direct force-plate measurements and indirect measurements from the SAM method. A concurrent study using radar technology (46Hz) was used to determine inter-trial reliability of the SAM method. Across mean force, velocity and power in the horizontal direction, the mean bias between the SAM method and force plates varied between 1.9-8.0%, with acceptable levels of reliability (CV < 4.0%) and low standard error of measurement (SEM = 4.94%) when using radar technology to collect velocity-time data to compute F-v variables using the SAM method. One suggested limitation which should be highlighted regarding this study is use of different participants to determine agreement between methods (n=9, sprinters) and inter-trial reliability (n=6, sprinters) between trials.

No data was provided regarding the level of athlete between experimental protocols. The findings in this study were supported by a further validation study (246) using a newly developed sprint track with 50-meters of force plates laid in series to collect direct ground reaction force data across a single sprint effort, with velocity measured via a 100Hz laser. The SAM method and embedded force plates showed strong agreement (mean bias 4.71%) and high inter-trial reliability (CV = 0.4-3.6%, SEM = -3.9-4.0%), further identifying, when implemented correctly, the utility of the method to determine mechanical sprint variables. The methodological approach is therefore a key aspect of F-v profiling to ensure reliable and valid data is attainable before using the information to inform coaching practices such as designing training programmes.

To enhance the reliability of measurement using the SAM method along with the validity when compared to gold standard technology, several suggestions have been made to improve the understanding and application of F-v variables (290). Regarding the overall approach to F-v profiling, all participants should be exposed to a rigorous familiarization process (1-3 sessions) across a range of external loads and velocities (vertical) which will be used within the testing session(s). Limting physical activity within 24-hours of the testing session is also recommended to reduce the effects of residual physical fatigue prior to testing. Furthermore, participants must be familiar with applying maximal intent to both jumping and sprinting actions, along with having an understanding of the key technical requirements of each test (i.e., height of push-off distance). Live feedback during the testing session (i.e., jump height or sprint time) may also improve maximal intent during testing. Specific to intervention studies, strength and conditioning programmes must be designed explicitly to enhance one aspect of the F-v continuum which relies on the practitioner using accurate sets, repetitions, and training intensities. Factors which may reduce reliability or validity include number of familiarization sessions, training age, choronological age, fatigue and injury history. If these are not accounted for it will be difficult to detect a 'true change' between-group and within-group when performing interventional studies. Concerns regarding the reliability and validity of field-based F-v profiling have largely focussed on several key areas: measurement methodology (199), (29, 336), the utility of variables to enhance mechanical characteristics via training (200), representation of force-velocity characteristics (29) and inter and intra-day reliability of F-v variables (336). The aforementioned studies highlight agreement between F-v variables was limited when using different different measurement methods (CV: 14-30%), low-between day reliability was evident (CV > 10%, ICC <0.70 for F-v variables) specifically in unconstrained testing conditions (i.e., free weight exercises), plus non-siginificant performance changes were identified when using mechanical profiling to target an athlete's optimal $S_{FV}$. Furthermore, Bobbert et al. (29) have challenged what the F-v profile represents due to several mechanical assumptions within the biomechanical models.

### Quantifying the force-velocity profile

Exploring the F-v profile to enhance mechanical characteristics in jumping and sprinting actions requires knowledge of the mechanical strengths and weaknesses of the athlete, also referred to in the literature as mechanical imbalances or deficiencies (242). It has been highlighted in the F-v literature athletes may exhibit a force or velocity deficit (242), which suggests a greater focus should be placed on either force or velocity qualities to address the imbalance, yet also highlights their reliance on one end of the F-v continuum to express maximal external power. This information is therefore useful for the coach to provide an individualized approach to training strategies based on mechanical information, rather than a 'one-size fits all' approach.

Many of the initial studies using the SAM method to determine both vertical and horizontal F-v characteristics were cross-sectional or observational studies, thereby only identifying or quantifying the biomechanical determinants of performance. Despite only exploring a limited number of sports, mechanical profiling has been shown to differentiate between playing position and level of the athlete within studies focussed on the National Football League (NFL) (85), recreational, sub-elite, elite level sprinters and hurdlers (148, 314-316), plus elite and amateur field and court sport athletes (102, 103, 170, 298, 351).

Regarding NFL athletes, post-hoc analysis of 40-yard dash times from the annual NFL draft combine identified specific mechanical characteristics at three key positions (i.e., Skill player, Big Skill player, Linemen). Of those athletes selected early compared to late in the NFL draft, $P_{MAX}$ in the horizontal direction appeared to be the differentiating factor in performance (i.e., Linemen :18.3-23.7W.kg$^{-1}$; Big Skill: 22.8-24.6W.kg$^{-1}$; Skill: 26.1-27.3W.kg$^{-1}$); Therefore, sprint mechanical characteristics of higher performing players may also provide a pseudo-predictive function for coaching staff to select players. Similarly, Jimenez-Reyes et al. (170) used sprint mechanical profiling to compare mechanical characteristics and positional demands in amateur and elite Futsal and soccer players. Interestingly, the study highlighted the F-v profile was sensitive enough to differentiate between the indoor and outdoor format of the 'soccer' game, highlighting higher levels of $F_0$ (ES: 0.61) and lower $v_0$ (ES: -0.48) values for 1$^{st}$ division Futsal players ($F_0$: 7.70N.kg$^{-1}$, $v_0$: 9.01m.s$^{-1}$) when compared to the 1$^{st}$ division soccer players ($F_0$: 7.35N.kg$^{-1}$, $v_0$: 9.25m.s$^{-1}$), thought to be caused by the larger number of accelerations over shorter distances during this court-based game. Furthermore, a study by Cross et al. (74) identified sprint mechanical and performance characteristics over 20-30m could differentiate between rugby codes and the mechanical demands at each position in the sport. Using a population of 30 elite rugby players (15 rugby union, 15 rugby league), it was reported rugby union backs produced faster split times during early acceleration and greater relative $F_0$ and $P_{MAX}$ values compared to rugby league backs. However, higher absolute $F_0$ values (8.48N.kg$^{-1}$) reported for rugby union forwards was thought to be attributed to greater body mass, therefore potentially providing greater sprint momentum.

Extending on these findings within a rugby context, Watkins et al. (351) explored sprint mechanical differences between rugby players at amateur clubs, professional and international competitions and found those who played at the elite level possessed superior F-v characteristics (i.e., more force-dominant F-v profile) and faster sprint times across 30-meters. Also, mechanical characteristics highlighted the unique positional demands and physical attributes observed during rugby union and may provide a benchmark for players attempting to play at a higher level of the sport. Similar approaches to understanding mechanical characteristics of court sport athletes have also been investigated using team handball and basketball players (140). When comparing court sports, handball players displayed superior sprint performance over 40-metres, greater $v_0$ values and a more velocity-oriented F-v profile, seemingly identifying the need for greater sprint ability compared to basketball players.

Overall, cross-sectional studies across a range of largely field-based sports identify jump and sprint F-v profiling is sensitive enough to differentiate between the mechanical demands across positions and performance level (i.e., novice, club, professional, international) within the same sport. Furthermore, it has been suggested using mechanical profiling in this manner can provide coaching staff with specific benchmarks for performance for different levels of competition and positional groups. Over periods of time (short or long-term interventions) or different phases of the season, this data could then be used to direct primary, secondary, and tertiary training strategies to prepare players to move to a higher level of competition (i.e., professional to international).

**Individualizing the force-velocity profile**

Individualized training based on initial F-v characteristics has also been explored across athletic populations to understand the sensitivity of the profile to adapt to training stimuli. Compared to optimized F-v focussed studies which attempt to reduce mechanical imbalances, individualized interventional training studies appear to determine changes to initial F-v characteristics in response to a specific training stimulus, rather than targeting optimal F-v conditions for each athlete.

In a study assessing the horizontal F-v profile (195), 16 semi-professional and professional rugby players were divided into two experimental groups (resisted sprint training[n=6] and assisted sprint training[n=10]) depending on their individual $S_{FV}$. Over an 8-week in-season period, players were prescribed individualized sprint training using a velocity-based training approach which corresponded to a specific aspect of the F-v continuum. Despite the results highlighting only small within-group differences for the resisted sprint training group, 20-metre time, and significant between-group performance improvements, $F_0$, both groups did show changes to the $S_{FV}$ in the desired direction based on the training undertaken. In a similar study using the initial sprint F-v characteristics from a group of professional soccer players, Lahti et al. (194) used a 9-week training protocol, followed by a two-week taper period to assess changes to mechanical characteristics based on a resisted sprint training protocol also using a velocity decrement (50-60%). Across this period, it was noted if the athlete exhibited a force-oriented F-v profile prior to starting the intervention, it reduced their potential to enhance this aspect of their profile, suggesting alternative training methods other than resisted sprint training may be necessary to shift F-v characteristics.

Despite most interventional F-v studies focussing on adult athletic populations, a limited number of studies have explored F-v characteristics in youth populations. Within a group of 26 junior Australian football players, Edwards et al. (101) used a six-week resisted sprint training protocol to determine the magnitude of change to mechanical characteristics. Post-intervention results showed significant improvements to $F_0$ (ES: 0.63), $v_0$ (ES: 0.99), $P_{MAX}$ (ES: 1.04), and $RF_{MAX}$ (ES: 0.99), suggesting this training stimulus is effective in enhancing sprint F-v characteristics and performance. A similar resisted sprint training approach (8-weeks) was used in high school athletes with researchers exploring the effect of pulling sleds (37) compared to pushing sleds (36) on sprint F-v characteristics. From a group of 50 high school athletes, three intervention groups (and a control group) were established based on sled pushing resistance causing a 25, 50 and 75% velocity decrement. Although sprint performance outcomes improved across all split times ($p<0.05$, 0-20m), significant changes were not evident for $F_0$, $v_0$ or $P_{MAX}$ for either resisted group. Within-group comparisons showed the greatest magnitude of change in the heavy resisted group. In the sled pulling intervention, sprint performance improved in all resisted training groups, with no changes evident in the unresisted sprinting group. Interestingly in this study, pre-post mechanical changes were specific to the loading protocol, i.e., $F_0$ increased the most in the moderate to heavy sprint group, whereas $v_0$ increased in the unresisted sprint training group and $P_{MAX}$ increased in all resisted training groups. This highlights the sensitivity of F-v characteristics to adapt to specific exercises across the F-v continuum. Despite individualized F-v training not showing conclusive or expansive findings in youth populations, it thereby highlights a potential gap in the literature, but may also identify the maturation status of the athlete, i.e., pre-post peak height velocity (188, 211) could affect potential F-v adaptations.

### Optimizing the force-velocity profile

Within the last decade, researchers have postulated the concept of an optimal F-v profile based on the current F-v characteristics of the athlete (242, 282, 288). Regarding the vertical F-v profile and relative to bodymass, performance during lower limb ballistic actions was shown to depend on lower limb maximal power ($P_{MAX}$) output, height of push-off ($h_{po}$), individual characteristics of the F-v profile, i.e., the slope ($S_{FV}$) and the afterload opposing the motion (i.e., inertia, inclination)(288). Conceptually, the optimal vertical F-v profile ($S_{FV}OPT$) corresponds to the ideal balance between force and velocity capabilities for a given maximal power output expressed vertically, where jumping performance (i.e., height achieved) is optimized when maximal power increases and the difference (referred as the F-v imbalance) between the actual and optimal profile is reduced. During initial studies using a theoretical approach (288) and then later experimentally (282), a F-v imbalance, i.e., unfavourable characteristics in force and velocity, may be related to differences up to 30% in jump performance between two individuals with similar maximal power output. Furthermore, an F-v imbalance, identifies whether a force or velocity deficit exists which could then be addressed with a training intervention which focuses on specific aspects of the F-v continuum. Therefore, designing training programmes to optimize mechanical performance may be a useful methodology to improve neuromuscular performance.

Using an 'optimized' approach to training based on initial vertical F-v profile characteristics, Jiménez-Reyes et al. (172, 175) reported significant effects leading to a reduction in the F-v imbalance and improved vertical jump performance, despite minimal changes to maximal power. In an initial 9-week interventional resistance training study, 84 trained athletes were divided into an optimized group with sub-groups (i.e., force deficit, velocity deficit, well-balanced), non-optimized group and a control group, aimed at reducing their F-v imbalance and improving jump performance. Post intervention effects highlighted jump performance and a reduction in the F-v imbalance in the optimized group ($-0.11 \leq d \geq 1.60$) exceeded the non-optimized ($-0.17 \leq d \geq 0.14$) and control group ($-0.09 \leq d \geq 0.01$). Greater change in jump height was also associated with a greater reduction in F-v imbalance. In a similar 9-week study with sub-groups (i.e., high and low force-deficit, high and low velocity-deficit), participants performed specific training focussed on sections of the F-v continuum. Across all mechanical variables and the performance outcome, small to extremely large effects were noted for force-deficit ($-1.22 \leq d \geq 1.45$) and velocity-deficit ($-2.36 \leq d \geq 2.72$) groups. Interestingly, the study highlighted that larger initial F-v imbalances required a longer duration of training ($r = 0.82$, $p < 0.01$) to reach the optimal F-v profile and a detraining period of 3-weeks did not reduce mechanical output.

Similar interventional resistance training studies aimed at reducing the F-v imbalance have also demonstrated significant differences in jump height compared to control groups in ballet dancers and professional rugby league players (105, 304, 363). Briefly, over a 9-week period, 46 ballet dancers were divided into a control group (n=10) and an experimental group (n=36, high or low force deficit) based on initial vertical F-v characteristics. Post-testing identified significant changes ($p<0.05$) for most mechanical variables (i.e., $F_0$, $v_0$, jump height, $FV_{IMB}$) in the experimental group, with changes evident for $P_{MAX}$ only in the control group. Over a similar intervention period (8-weeks), elite rugby players showed targeted physical preparation training based on vertical F-v characteristics significantly reduced their $FV_{IMB,}$ largely due to changes to $F_0$, whereas limited changes were noted in the general strength-power group. These studies, across a range of sports, identified that optimized and individualized training intervention aimed at addressing the individual F-v imbalance appear to be show greater utility to improving jump performance compared with a traditional, generic resistance training programme which did not consider the level of F-v imbalance.

More recently, Samozino et al. (285) have presented the concept of an optimal horizontal F-v profile for sprinting based on their similar validated approaches in jumping actions. The study identified that sprint acceleration performance depends on step averaged horizontally directed power across the entire acceleration distance and the slope of the F-v profile, which in sprinting is the ratio between the production of horizontally directed force ($F_0$) at low (i.e., overcoming inertia off the start line) and high (i.e., maximal velocity) velocities ($v_0$). Based on model simulations, an individual's aerodynamic friction coefficient (5) (i.e., stature), maximal power output in the horizontal direction and sprint distance, an optimal sprint F-v profile could be determined to maximize acceleration performance. Therefore, the optimal F-v profile will facilitate reduction in sprint times across the acceleration distance by allowing the individual to remain as close as possible to their optimal velocity across the acceleration phase. It was further reported that differences between an individual's actual and optimal F-v sprint profile depended more on the sprint distance rather than the individual F-v characteristics. Aside from being influenced by maximal horizontally directed power values, as sprint distance was reduced (< 15-meters) the $S_{FV}OPT$ would become oriented towards horizontal force capabilities (i.e., force dominant), whereas as sprint distance increased (>15-meters) velocity capabilities would be of greater importance to sprint performance and the $S_{FV}OPT$ would orient towards being velocity dominant. Although previous studies have quantified the F-v profile during sprinting and identified differences in the slope of the individual F-v profile, where profiles have been characterized with a force-deficit, velocity-deficit or balanced profile, this is the only study exploring the concept of an optimal F-v sprint profile using model simulations fit to an existing data set of 231 male and female athletes.

Despite highlighted studies demonstrating positive changes from reducing the F-v imbalance through optimizing the training programme, Lindberg et al. (200) challenged this view in a study including 40 highly trained team sport athletes. The results demonstrated no difference in jump performance (i.e., squat jump, countermovement jump, 10m or 30m sprint time) when training towards their optimal profile compared to groups training away from the optimal profile, with effect sizes ranging from 0.30-0.50. The authors concluded that irrespective of the initial F-v profile, individualized training to reduce the F-v imbalance was not supported by the findings. However, when compared to previous studies (105, 172, 175), upon closer look at the individualized resistance training intervention, inconsistencies in agreement between studies may be due to the training cohort or more likely, the training content of the three training groups (i.e., force program, balanced program, velocity program), with rep and load schemes which do not appear to support the targeted training focus.

Further research has provided contradictory evidence to suggest individualized sprint training may be no more effective than generalized training. Based on initial sprint F-v characteristics, 17 professional and semi-professional handball players were divided into an intervention group (resisted or assisted sprinting, or a mix of both training methods) or a control group (general sprint training) and performed an 8-week (16 sessions) targeted sprint training intervention (268). Concluding the intervention, both groups improved 30-m sprint performance (Δ 0.05-0.06sec), however between-group mechanical differences were trivial or unclear.

Despite various research studies suggesting targeting mechanical imbalances via an optimized training approach is best practice, conjecture remains whether significant relationships exist between the mechanical variables demonstrated in the vertical and horizontal profile. It therefore remains unclear whether addressing mechanical characteristics in both force vectors with targeted training reduces mechanical imbalances or if specificity of movement dictates mechanical transfer.

### Transfer of mechanical characteristics

Research identified in this review has previously highlighted the F-v profile will adapt to specific training interventions however it remains unclear whether mechanical imbalances which exist in one orientation, for example, whether a force-deficit in a vertical profile will also be evident in the horizontal profile? With a large cohort of 553 participants from a range of sports (n=14) and ability levels, Jiménez-Reyes et al. (174) performed maximal squat jumps (vertical) against a series of external loads and 30-40m sprint efforts (horizontal) to determine mechanical relationships in both force orientations. Overall, the authors reported Pearson correlation coefficients of -0.12 to 0.58 for $F_0$, -0.31 to 0.71 for

$v_0$, -0.10 to 0.67 for $P_{MAX}$, and -0.92 to -0.23 for the performance outcomes (i.e., jump height and sprint time), highlighting varying levels of mechanical association between force-vectors. Across the majority of sports analysed, $P_{MAX}$ explained the greatest variability in sprint performance (305), plus demonstrated the strongest relationship between jumping and sprinting actions and this has been supported in similar studies involving amateur netball players, high-level sprint athletes and professional male and female football players, ($0.40 \leq r \geq 0.75$, $p \leq 0.04$) (107, 180, 212, 317). Force and velocity qualities reported much lower mechanical transfer between jumping and sprinting actions, yet achieved statistical significance in some studies, highlighting the independent characteristics of these variables. It has been suggested the transfer of mechanical qualities is greatest for athletes of lower ability levels potentially highlighting training absolute force qualities, irrespective of orientation, would positively impact vertical and horizontal neuromuscular output (174). Moreover, it was further suggested as the ability level of the athlete increased, mechanical qualities became more task-specific and mechanical transfer diminished (174). Further studies highlighted the magnitude of transfer may also be dependent on the task and background of the athlete (113, 174, 180). At the elite level, these findings highlight neuromuscular output in jumping actions should not be used to infer performance changes or outcomes in sprinting actions. The literature suggests practitioners should perform F-v profiles in both the vertical and horizontal orientation to determine the magnitude and effectiveness of force application and to provide a more comprehensive assessment of neuromuscular qualities.

### Monitoring, injury risk factors and return to play

Many of the F-v profiling applications to date have been diagnostic in nature yet several studies have also identified more novel applications. It has been suggested that F-v profiling and mechanical characteristics could be used as a monitoring tool in athletic populations and potentially highlight injury risk factors. In a small population of elite rugby league athletes (n=7), De Lacey et al. (83) utilized a 5-point ascending load vertical F-v profile (0, 25, 50, 75, 100% bodymass) to assess and monitor mechanical characteristics both before and after a 21-day taper period leading into the competition season. A taper is a reduction in training load over a period which may allow an athlete to recover from training stress to optimize physical preparedness for competition (32). The findings identified changes to $F_0$ and $P_{MAX}$ and a more force-oriented F-v profile post taper, therefore highlighting the utility of F-v profiling to identify acute changes in mechanical performance. A similar approach to monitoring mechanical characteristics has also been used with elite male soccer players (171), where the horizontal F-v profile was assessed across two seasons. The results demonstrated the magnitude of $F_0$, $P_{MAX}$ and $RF_{MAX}$ was higher during the middle of the season compared to season's end, therefore suggesting mechanical characteristics, particularly acceleration ability, may diminish during the competition season if not maintained with specific training. Similar approaches to monitoring using the SAM method for sprint mechanical characteristics have also been explored in elite Australian football players (248). Further research on monitoring mechanical variables from F-v profiles is evident in other athletic populations such as weightlifting (291) and with skeleton (55) athletes despite using alternative F-v methodology than the SAM method.

Regarding F-v profiling and injury risk factors, a previous case study with a field sport athlete highlighted the sensitivity of the F-v profile to indicate specific changes to mechanical characteristics both preceding injury and during return to play protocols (223). For the athlete returning from hamstring injury, significant changes (-20.5%) in horizontally directed force output (pre=8.3N.kg$^{-1}$, post 6.6N.kg$^{-1}$), yet with similar $v_0$ values, highlighting reduction in mechanical power is more related to producing force at low velocities when accelerating, and therefore a limiting factor post-injury. Furthermore, monitoring of mechanical variables has also been investigated to analyse fatigue-induced changes to repeated-sprint efforts. In a study with elite rugby sevens athletes (169), sprint F-v characteristics were measured across ten 40-metre sprint efforts with a 30-second recovery period between sprints. The findings highlighted decreases to both $v_0$ and $F_0$, plus $RF_{MAX}$ was much lower in the latter sprints, largely due to technical factors related to horizontally directed force, particularly at higher running velocities. A further case study (rugby athlete) focussed on repeated-sprint ability also identified the suspected compensation of reducing $v_0$ capabilities by placing a greater emphasis on maximal force output, $F_0$, in the initial stages of a repeated series of sprints (223). Thus, given the importance of force application during sprint acceleration, changes to sprint mechanical characteristics may provide an opportunity for coaches to alter training sessions to reduce the risk of injury due to fatigue. Furthermore, in a prospective study of 284 football (soccer) players (98), sprint mechanical profiling was assessed at different times across a season and identified force production at lower velocities ($F_0$), i.e., when accelerating from a stationary start, was significantly associated with a higher rate of new hamstring injury in the weeks following the mechanical assessment. It was reported for every $1N.kg^{-1}$ decrease in horizontally-directed force production, there was an association with 2.67 times higher risk factor of sustaining a new hamstring injury. Finally, recent research by Morin et al. (239) has investigated the concept of performing on-field *in-situ* F-v profiling during training session activities (i.e., drills and small-sided game), thereby 'testing players without testing them'. This is a new approach when compared to initial studies. Instead of performing typical isolated sprint testing, acceleration-speed data was collected via GPS from 16 professional football players across a 2-week training period. From approximately 50 data points per player, acceleration-speed profiles were created ($R^2 > 0.984$) with acceptable standard error or measurement across variables (3.31-7.64%), suggesting passive data collection during training sessions or gameplay is reliable and may lead to a more game-specific assessment and monitoring tool for mechanical variables in sprinting.

This approach to horizontal F-v profiling will likely expand into other field sports as practitioners see the value of on-field testing during typical training sessions.

## Limitations

Despite the benefits of using a macroscopic approach to determine mechanical variables in maximal ballistic action, various limitations to the methodology have been identified in the recent literature. Firstly, commentary on the methodology have been presented both in reference to the biomechanical model (29), along with the potential misconceptions of using specific mechanical terminology. Cleather (50) questions the model and assumptions made in calculating mechanical variables specific to the vertical F-v profile, and suggests Samozino et al. (284) have misrepresented the impulse-momentum relationship with an instantaneous relationship between force and velocity. Further misconceptions have been raised with the use of the mechanical terminology in reference to orientation, specifically *horizontal force,* and *horizontal power* (142, 260, 347). Haugen (142) reports horizontal force is represented as the effective component of the total ground reaction force, therefore potentially suggesting the vertical component of the ground reaction force is ineffective during acceleration, which is unrealistic to maintain an upright position. In regard to horizontal power, power is a scalar quantity and thereby has no direction, only magnitude (347). In recent horizontal F-v profiling literature (100, 248, 351), the term horizontal power is used ubiquitously, to describe the product of force and velocity in the horizontal direction. Rather than identifying 'directional power', suggestions have been made to report the components of net impulse instead, to ensure mechanical transparency (347). Similar concerns have been raised using the term power in vertical F-v profiling (356). Secondly, the concept of producing horizontal force and power have led to a focus on training interventions based on force orientation (150), which attempt to correct F-v imbalances in jumping and sprinting. The logic stemming from the *force-vector theory*, where performance outcomes will improve if greater magnitude of force and power are produced in a specific direction (i.e., horizontally). Fiztpatrick et al. (114) challenged this theory and found non-significant changes ($p = 0.561$, $\eta^2 = 0.035$) in performance when using vertical and horizontal exercises, suggesting practitioners should refer to dynamic correspondence (320) when selecting exercises to improve performance. Thirdly, despite recent literature identifying moderate to large correlations between maximal power in jumping and sprinting actions, thereby highlighting the neuromuscular transfer this quality between actions, lower correlations were reported between maximal force and velocity, specifically in elite level athletes (107, 174, 180, 212, 317). These findings highlight a level of task-specificity for the underlying mechanical determinants of both actions, which has also been reported in other F-v profiling studies (113). Furthermore, to gain deeper insight into neuromuscular function, it has been recommended that both vertical and horizontal F-v profiles be assessed (107). Finally, as identified in earlier in this review, Samozino's field method of F-v profiling provides *indirect measures* of the linear F-v relationship of jumping and sprinting actions based on a macroscopic inverse dynamics approach. The field methods are not to replace gold standard measurement tools such as force plate technology yet have been validated against these measures and provide an avenue to *bring the laboratory to the field*. This appears to be the true utility of the method. Overall, measurement agreement concerns with the SAM method in comparison to laboratory-based technology appear to concern study methodology.

### Gaps in the literature

Therefore, despite the growth in F-v profiling literature over the past decade, this narrative review identified significant gaps in the research plus limited connections between diagnostic F-v assessment and training applications. Some key areas which require greater exploration include:

1. Between studies, it is evident there is limited standardization across F-v profiling protocols regarding methodological practice. Different studies have used a range of methods (i.e., technology, exercises) to assess mechanical characteristics, making it challenging to compare results and determine utility of methodology. Therefore, greater research is needed on the reliability and validity of these methods, and their comparison with gold-standard, laboratory-based methods.
2. There exists limited research on the use of F-v profiling in specific sports. Despite F-v profiling use in sports such as soccer and rugby, there is limited research on its specific application in many other team and individual sport populations.
3. While F-v profiling is widely used in adult sport populations (and aging general population groups)(2, 3), there is limited research on the application of the methodology in young athletes, which may have implications in reference to maturation status such as peak height velocity (188, 211), musculoskeletal development and performance.
4. While initial F-v profiling studies were diagnostic in nature, greater research studies focussed on changes to mechanical characteristics in response to specific training interventions over longer periods, potentially addressing mechanical strengths and weaknesses are necessary.
5. Studies focussed on the use of F-v profiling to monitor changes to mechanical characteristics over the course of a competitive sport season is under researched. Monitoring variation to mechanical characteristics assessed via F-v profiling may potentially identify *windows of opportunity* for practitioners to improve neuromuscular output at specific time points of the season.

6. There is a paucity of conceptual frameworks, training recommendations and guidelines specific to enhancing vertical and horizontal mechanical characteristics and greater links must be made for practitioners by linking the data to programme design.

These gaps in the literature highlight the need for further research to better understand the utility and potential limitations of F-v profiling in different sports and populations.

## Conclusion

The SAM method provides practitioners with greater understanding of the underlying mechanical characteristics displayed by athletes in maximal jumping and sprinting actions using low-cost, simple methods. Embedding a neuromuscular assessment such as F-v profiling within the sport training season provides ongoing insight to the change in mechanical characteristics in response to specific forms of training. This information may assist practitioners to reduce mechanical imbalances by optimizing and individualizing training programmes to further enhance jump and sprint performance. Importantly, future research should explore current methodology concerns of mechanical profiling with new validation studies, plus further understand new applications of mechanical profiling in a greater number of team and individual sport populations groups, which include athletes with diverse training backgrounds, ability level (i.e., novice, state level, national level, elite level etc) and of different ages (i.e., youth, adult etc). Finally, greater links must be developed between quantifying F-v characteristics and subsequent training recommendations and programmes which coaches can utilize within their daily practice.

This narrative review therefore provides an important contribution to the field of sports biomechanics and strength and conditioning by highlighting the current applications of ‘field based’ mechanical profiling in sport to quantify jump and sprint performance.

# PRELUDE

Two of the key findings of the narrative review (Chapter 2) were 1) the importance of conducting reliability studies on models or technology used to determine F-v variables, and 2) the importance of using standardized protocols when conducting F-v assessments to ensure validity of data, thereby detecting changes in F-v variables in response to training interventions. Although previous field-based F-v assessments have been validated using a squat jump and countermovement jump action in a smith machine, a paucity of research exists using field methods on common free weight exercises such as barbell and hexbar countermovement jump actions. Therefore, the primary aim of the study was to determine the validity and reliability of Samozino's field method to calculate mean force, velocity, and power (F-v profile), during the propulsion phase of a countermovement jump using a barbell and a hexbar. Furthermore, this study aims to compare jump mechanical characteristics from the field method when compared with force plate analysis. A secondary aim was to determine the utility of using simple field methods in free weight exercises for future studies. We hypothesized that mechanical outputs assessed via the field method would show acceptable levels of reliability due to the simplicity of inputs into the model, and variability in jump strategy would increase as external loading conditions changed, thereby affecting the height of push-off and validity of field method when compared to force plate data. This chapter provides practitioners with insight to the reliability and validity of jump F-v profiling in recreational athletes when comparing field methods with force plates.

## CHAPTER 3: STUDY 1

# Measurement agreement between Samozino's method and force-plate force-velocity profiles during barbell and hexbar countermovement jumps


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## Abstract

This study aimed to measure agreement between using Samozino's method and force plates to determine mean force, velocity and power during unloaded and loaded barbell and hexbar countermovement jumps. Twenty-one subjects performed countermovement jumps against incremental loads using both loading conditions. Ground reaction force was recorded using a dual-force plate system (1000Hz) and used as the criterion method to compare to Samozino's method. Reliability and validity was determined by intraclass correlation coefficients (ICC), coefficient of variation (CV), limits of agreement plots and least products regression analysis. Samozino's method provided acceptable levels of reliability for mean force, velocity and power (ICC > 0.90, CV% < 5.5) across both loading conditions. Limits of agreement analysis showed the mean bias was 2.7%, 15.4%, 7.2% and 1.8%, 12.4%, 5.0% for mean force, velocity and power during barbell and hexbar countermovement jumps respectively. Based upon these findings, Samozino's method is reliable when measuring mean force, velocity and power during loaded and unloaded barbell and hexbar countermovement jumps, but also identifies limitations regarding concurrent validity compared to the gold standard. Across loading conditions, Samozino's method overestimated mean force (0.5-4.5%) and underestimated mean velocity (11.81-16.78%) and mean power (2.26%-7.85%) compared to the force plates. Due to fixed and proportional bias between criterion and predictor, the results do not support the use of Samozino's method to measure mean force, velocity and power. Therefore, it is not recommended for practitioners to use Samozino's method to estimate mechanical variables during loaded and unloaded countermovement jump actions using a barbell and hexbar.

## Introduction

Force-velocity (F-v) profiling is a methodological approach used to assess the overall mechanical capabilities of the neuromuscular system (288). An F-v profile describes the slope ($S_{FV}$) between the intercepts of both mechanical variables, theoretical maximal force ($F_0$) and theoretical maximal velocity ($v_0$), and represents the individual ratio between force and velocity qualities (281). Understanding these mechanical qualities is of interest to sport scientists in order to identify strengths and weaknesses of the athlete (242), along with directing and monitoring training interventions (172).

Ballistic actions such as the countermovement jump (CMJ) embody many of the neuromuscular and mechanical qualities demonstrated in lower-limb sport specific movements (38, 354), and therefore frequently used by sport scientists to profile the F-v relationship (83, 105, 106, 129, 130, 172, 174, 175, 282, 283). The F-v relationships established within a CMJ profile describes changes to external force and power production at increasing movement velocities (288), while also identifying the underlying neuromuscular and biomechanical factors contributing to jump performance. Jumping actions are largely limited by F-v, power-velocity and length-tension relationships of the lower-limb muscles (30, 66) and provide insight to potential performance changes. Therefore, in sports which frequently expose athletes to vertical jump actions, such as basketball and volleyball, quantifying these capabilities may provide training-related insights to enhance neuromuscular performance.

In many settings, lower-limb F-v profiling typically involves subjects performing unloaded (bodyweight) and loaded CMJ actions against a series of incremental loads using either a traditional barbell or a smith machine. In a laboratory setting, vertical jump kinetics are measured from ground reaction force using in-ground or portable force plates, while centre of mass velocity is derived from ground reaction force-time data through a forward dynamics approach (90). However, methods for measuring force, velocity and power during jumping actions using limited technology and basic anthropometric measures, have recently gained greater prevalence in biomechanics and sport science due to the simple approach to obtaining mechanical data (105, 174, 175, 212, 363).

A simple method to determine vertical F-v profiles, has previously been proposed by Samozino et al. (2008), herein after referred to as 'SAM method' (283). The SAM method has become accessible for practitioners largely due to the simplicity of the approach and negating the need for expensive technology (105). Data generated by the SAM method has previously been used to inform training interventions (172, 175) for performance enhancement and monitoring return to play practice. The SAM method is based on biomechanical modelling where forces are computed from kinematics of the body's centre of mass during vertical jump actions, along with the analysis of the changes in mechanical energy at different points of the movement (281). Using jump height (105) and anthropometric measures including mass (kg), starting height ($h_s$) and height of push-off ($h_{po}$), the SAM method models the following mechanical variables: theoretical maximal force at null-velocity ($F_0$), maximal power output ($P_{MAX}$) and the theoretical maximal velocity at which the lower limbs can jump under zero load ($v_0$) (281). This computation method has previously shown strong reliability and validity using a squat jump (129, 279) and CMJ with a smith machine (176). However, the application of using a smith machine presents various limitations, one of which is the lower ecological validity when performing the jumping action, usually a very natural movement, since the body is fixed to the vertical plane (199). This of course provides increased reliability due to kinematic redundancy (129) but less versatile in an applied training setting. Therefore, if free-weight equipment such as a barbell or hexbar, are used for F-v assessment, will the SAM method continue to show strong levels of agreement when compared to force plate data? To the best of our knowledge, validating the kinetic and kinematic outputs of barbell and hexbar CMJ actions using the SAM method has not been investigated.

The primary aim of the study was to determine the validity and reliability of the SAM method to calculate mean force, velocity and power (F-v-p profile), during the propulsion phase of a CMJ using a barbell and a hexbar. Furthermore, this study aims to compare the ability of the SAM method to determine F-v variables, when compared with force plate analysis. We hypothesized that 1) mechanical outputs assessed via the SAM method would show acceptable levels of reliability due to limited intra-athlete variability when using the anthropometric variables within the model, and 2) variability in jump strategy as loading conditions change (low load/high load, barbell/hexbar) would increase, thereby affecting the height of push-off and validity of SAM method when compared to force plate data.

## Methods

A cross-sectional, counter-balanced experimental design using ordinary least products and limits of agreement statistical analysis was used in this agreement study. Measurement agreement research aims to evaluate the validity of a new method against an established reference technique or gold standard and as a result, only conclusions about interchangeability between the experimental and reference technique can be drawn (234).

All subjects completed anthropometric assessment followed by a warmup, then performed a series of CMJ trials with incrementally increasing loads. Subjects completed CMJ trials with two loading conditions, using a straight barbell and hexagonal barbell (hexbar). A hexagonal barbell is hexagonal in shape and enables users to stand within the constraints of the hexagon frame thereby holding the resistance at arms length, with overall loading much closer to the body centre of mass (325). Subjects 1-10 performed CMJ trials loaded with the barbell first, prior to completing the protocol with the hexbar. Subjects 11-21 performed the jump protocol in the reverse order (e.g., Hexbar then barbell). Counterbalancing loading conditions possibly reduced effects of any form of potentiation (321) from one loading condition to the next. F-v relationships were then determined using the force-time signal from the force plates and the SAM method.

### *Subjects*

Twenty-one recreationally active males (age 26.0 ± 4.1 years, body mass 81.3 ± 6.6 kg, and height 183.7 ± 8.0 cm) provided their written informed consent before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146). Inclusion criteria included: subjects involved in a minimum of 2.5-5 hours per week of moderate to vigorous recreational and/or competitive sport; a background in resistance training of greater than 12 months; and aged 18-35 years. Exclusion criteria maintained that subjects needed to be six-months free of musculoskeletal injuries which may prevent subjects from performing maximal effort jumping actions. In their pre-testing questionnaire, subjects acknowledged their experience with unloaded and loaded CMJ exercises using a barbell and a hexbar.

### *Procedures*

Subjects attended the laboratory for one testing session. Familiarization of the testing protocol was performed by the subject within the 7-days leading into the testing protocol by following pre-recorded annotated videos. Each subject underwent an anthropometric assessment to determine standing stature (metres), mass (kg), plus anthropometric measures identified in the SAM method (283) which included height of take-off, starting height ($h_s$) and height of push-off ($h_{po}$). Height of take-off, measured using a segmometer while lying supine on a bench, corresponded to the distance from the right leg greater trochanter to the most distal aspect of the foot (take-off position); when the foot is fully plantar-flexed, akin to the position observed just prior to leaving the ground. Starting height ($h_s$) was measured using a segmometer as the vertical distance between the ground and the right leg greater trochanter when the subject was in a 90° knee angle crouch position, measured using a goniometer. The difference between $h_s$ to take-off position is referred to as the height of push-off ($h_{po}$) and is used in the computation method as the displacement across the propulsion phase (Figure 3.1).

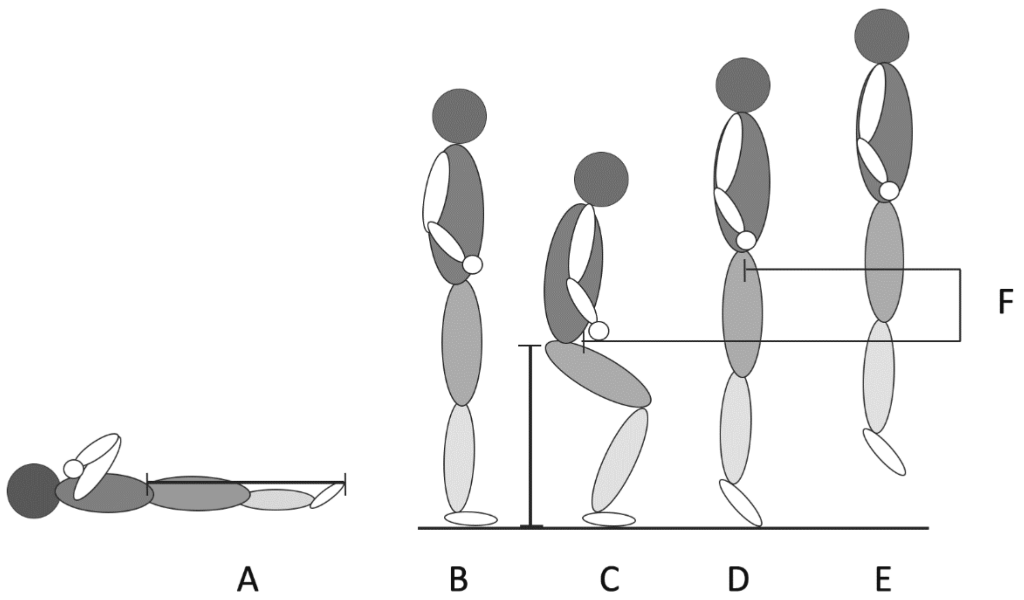


**Figure 3.1.** Anthropometric measurements used in the computation of the field method. A: Height of take-off; B: Initial position and initiation of countermovement jump; C: Starting height (m); D: Take-off position; E: Apex of arial time; F: Height of push-off ($h_{po}$).

Prior to completing the jump protocol, a standardized warm-up consisting of three minutes of step-ups (cadence of 85 on metronome), dynamic movements, and preparatory vertical jumps including a series of maximal unloaded and sub-maximal (15kg) loaded jump trials. Before the maximal jump trials, subjects listened to an audio file which provided a series of external cues, for example, “drive your feet through the floor” and “jump towards the ceiling” (136) to reinforce the intent to jump with maximal intensity.

These cues were also visually displayed in text for subjects to view during the testing session. Before each jump, subjects were instructed to stand up straight and motionless with their left and right foot on the centre of each force plate. If there was subtle movement prior to the initiation of the CMJ, the trial was repeated.

Barbell jump trials were performed with a 15kg free-weight barbell plus weight plates. The barbell (and dowel; bodyweight equivalent) were held across the shoulders between the superior portion of the scapula and the C7 vertebrae. Subjects were encouraged to pull the bar firmly across their upper back to ensure minimal movement of the bar during the movement. Hexbar jump trials were performed with a 15kg free-weight hexbar. Subjects used the high handles of the bar and were standing upright with the bar sitting off the ground prior to descending into the CMJ. The hexbar dowel was a polyvinyl chloride (PVC) hexagon made to the same inner dimensions as the free weight hexbar. For the hexbar trials, subjects were standing upright holding the bar within the hexagonal shape.

For all CMJ trials, subjects were instructed to descend to their starting height ($h_s$) position, and without stopping, ascend as rapidly as possible. The starting height of the propulsive phase was individual for each subject and was not constrained with a box or band, therefore, to encourage individual CMJ strategy. Displacement during propulsion was used in statistical analysis and validated against anthropometric measures, $h_{po}$, during post-processing analysis. Each subject performed CMJ trials against four incremental loads and order: bodymass (BM), BM + 15kg, BM + 30kg and BM + 45kg. A multiple load approach was selected to identify muscle mechanical capacities for each subject across the F-v continuum (163, 168), as used in previous studies (120, 172). Three trials were performed at each load for each jump type, assuming a successful jump. Upon landing for all loading conditions, subjects were asked to touch down with the same leg position as when they took off, (i.e. with an extended leg and maximal foot plantar flexion). If all requirements were not met, the trial was repeated. Each jump trial was followed by a one-minute rest period. Each loading condition was followed by a three-minute rest period. Between loading conditions (barbell to hexbar, or reverse), there was a five-minute change-over and rest period. Rest period guidelines were based on previous validation studies (176) and to ensure the subjects were not pre-fatigued prior to the next trial, loading condition or jump type.

***Equipment and data acquisition for the force-plate method***

All jump trials were conducted with the subject standing with each foot on a separate in-ground AMTI force plate system (450mm x 510mm, AMTI OR6-7-1K-SYS Force Platforms 1000Hz, Watertown, MA) connected to an amplifier system, which measured left and right foot ground reaction forces (GRF). The vertical GRF was continuously sampled at 1000 Hz for each trial and collected via commercial motion capture software (Vicon Nexus 2.10.10, Vicon Motion Systems Ltd. UK) before being stored within a local computer. The data was subsequently exported to a csv file for post-processing analysis. Force-time characteristics were coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA), using CMJ phase descriptions detailed in recent literature (222). Minor changes were made to the determination of the flight phase due to the original SAM method calculations (283) which details the flight phase begins when propulsive force equals zero newtons (the plate is completely unloaded).

The propulsion phase, also known as the concentric or push-off phase, was defined as the point at which centre of mass velocity becomes positive and is physically characterized when the athlete begins moving vertically from their starting height (90° at the knee) until the point of take-off, or the start of the flight phase (222). Mean vertical GRF was determined by averaging force from the dual force plate system across the time points established for the propulsion phase of the jump. The instantaneous vertical velocity across the propulsion phase of each jump type was determined via integration of the centre of mass (COM) vertical acceleration signal over time via force plate data and then averaged across the propulsion phase. Mean system power across the propulsion phase was then calculated as the product of mean GRF and estimated mean COM velocity according to the sample rate from the force plates. Vertical GRF was used to calculate vertical instantaneous acceleration of the COM, therefore determining changes to COM displacement during the push-off phase. It has been suggested that changes to the relative vertical positions of the greater trochanter and the body centre of mass during a jump could be neglected (283).

***Samozino method***

The previously identified anthropometric variables ($h_s$, $h_{po}$) provide the foundation calculations for the SAM method. Jump height ($h$) was recorded from flight time ($t_F$) identified in the force-time signal from the force plates, as per the initial Samozino study (283), using the equation: height = $\left(\frac{1}{8}\right) g t_F^2$. Previous studies using the SAM method have also measured flight time using high-speed camera (240fps) (105) and an OptoJump device (174). Equations for the mechanical variables calculated across the propulsion phase of the CMJ trials include: mean force = $mg[\left(\frac{h}{hpo}\right) + 1]$, mean velocity = $\sqrt{gh}/2$, and mean power = $mg[\left(\frac{h}{hpo}\right) + 1]\sqrt{gh}/2$, where $m$ is the mass (BM or BM plus additional load), $g$ is gravitational acceleration, $h$ is jump height and $h_{po}$ is the height of push-off (283).

### *F-v relationships during countermovement jumps*

Computation of the F-v relationships were established by the equations in the SAM method spreadsheets (243). F-v relationships from force plate data were determined by least-squares linear regressions (358) using the trial at each load which demonstrated the highest jump height as identified in the original research by Samozino (283). The trial with the greatest jump height was selected as this could represent the current maximal capability of the lower limb neuromuscular system under each loading condition. Power-velocity relationships were described by second-degree polynomial functions. Other F-v variables calculated using force plate data and the SAM method included $F_0$ (N or N/kg), $v_0$ (m/s), which determined the intercepts at each respective axis, along with $P_{MAX}$ (W or W/kg) calculated as $F_0.v_0/4$ (288, 342). The F-v data achieved against each load established the linear relationship between the variables, also known as the slope of the profile, $S_{FV}$ (N. $s^{-1}.m^{-1}.kg^{-1}$).

### *Statistical Analyses*

Statistical analyses were determined from input into Microsoft Excel spreadsheets (154) plus coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages (smatr, bmbstats (178)). All descriptive data are presented as mean ± standard deviation (SD). Mean force, velocity and power, were calculated for all CMJ loading conditions using the force plate method, and the SAM method. The SAM method calculations were determined using freely available Microsoft Excel spreadsheets (243). A power analysis (109) was conducted prior to the study using the following test details: 'Means: Difference between two dependent means (matched pairs)', with an effect size of 0.5, alpha of 0.05 and power of 0.8 (276), which suggested the total sample size of the study should include 34 subjects.

Various statistical tests have been proposed and utilized to determine reliability and validity of measurements within the field of sport science (250). Although there is no gold standard test for comparative or agreement studies, there are known limitations to commonly used statistical approaches (27, 206). Further information detailing these limitations has been discussed previously (206), Therefore, it has been suggested for comparative or agreement studies the use of limits of agreement and ordinary least products regression analysis is preferred (26, 206, 207).

Limits of agreement analysis (26) and least products regression analysis were used to robustly determine fixed and proportional bias between methods and identify mean variable differences between methods. Both methods of analysis were used to test concurrent validity of the SAM method against the criterion (force plates). Least products regression analysis was used to account for random error in both the predictor and criterion (206).

Following analysis of normality, uniform distribution and linearity in each variable, least products regression analysis was performed against each load to assess between-trial reliability for fixed and proportional bias. Intraclass correlation coefficient (ICC) with 95% confidence limits, using a two-way random effect model (absolute agreement) and coefficient of variation (CV) were also used to assess relative and absolute reliability. Thresholds for evaluation of intraclass correlation coefficients were quantified using the following scale: 0.20-0.49 *low*, 0.50-0.74 *moderate*, 0.75-0.89 *high*, 0.90-0.98 *very high* and ≥ 0.99 *extremely high* (155). Previous biomechanical studies reported variables with a CV within the range of 10% as reliable (59). Therefore, acceptable reliability was determined with a coefficient of variation (CV) ≤10% (69) and ICC >0.70 (7, 59, 348). To analyse the validity of the SAM method, Pearson's product-moment correlation coefficient (Pearson's *r*) was used for mean force, velocity and power, along with all F-v related variables. The criteria to interpret the strength of the r coefficients were as follows:

*trivial* (<0.1), *small* (0.1–0.3), *moderate* (0.3–0.5), *high* (0.5–0.7), *very high* (0.7–0.9), or *practically perfect* (>0.9) (155). Limits of agreement analysis was used to plot the difference and average between two paired measurements (27), however not providing the means to account for the independent effect of the biases interacting with each other (250). Using the means of paired data, least products regression analysis states that if the 95% confidence interval for the intercept did not include zero, fixed bias was present. If the 95% confidence interval for the slope did not include 1.0, then proportional bias was present and therefore would identify the method could not accurately predict the criterion method (force plates). $R^2$ values within the least products regression analysis indicate the percentage of the variation of the dependent variable that is explained by changes to the independent variable. Higher $R^2$ values indicate the linear model explains the variability of the independent variable and its impact on the dependent variable. An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

## Results

### *Reliability*

Table 3.1 and Table 3.2 show the between-trial kinetic and kinematic concurrent reliability for mean force, velocity and power using traditional methods and least products regression analysis of the force plates and SAM method for both loading conditions. Relative and absolute reliability for the SAM method using the barbell was classified as *high* for mean force (ICC = 0.97, CV = 1.9%), velocity (ICC = 0.98, CV = 2.4%) and power (ICC = 0.94, CV = 4.2%), with similar results for mean force (ICC = 0.94, CV = 2.6%), velocity (ICC = 0.96, CV = 3.0%), and power (ICC = 0.90, CV = 5.5%), observed with the hexbar. Table 3.2 reports concurrent reliability for mean force, velocity and power using least products regression analysis of the force plates and SAM method for both loading conditions. Although subtle variations exist between trials, neither method or loading condition showed fixed or proportional bias due to the 95% confidence intervals for the intercept and slope including zero and one respectively, indicating reliability was acceptable.

### *Validity*

The results of the method comparison are highlighted in Table 3.3 and Figure 3.2, using limits of agreement and descriptive data for mean force, velocity and power. Acceptable limits should be defined by a priori, based on clinical understanding and biological considerations (126), while measurement tools in a clinical setting have been recommended to produce readings within 5% of gold standard values (277). Pearson's correlation coefficient was *moderate* to *high* (r = > 0.70) for mean force, velocity and power across all loads for both loading conditions. Limits of agreement plots and mean differences identified the SAM method overestimated mean force for both loading conditions (barbell -46.64N [2.7%], hexbar -32.27N [1.8%]). The SAM method also highlighted an underestimation of mean velocity (barbell 0.21m.s$^{-1}$ [15.4%], hexbar 0.17m.s$^{-1}$ [12.4%]), and mean power (barbell 156.42W [7.2%], hexbar 115.79W [5.0%]) across loading conditions, yet lower mean differences across all loads were identified for hexbar CMJ trials. Significant differences ($p \leq 0.05$) were identified for mean force, velocity and power using both the barbell and hexbar (Table 3.1). The mean bias for mean force across all loads was <5% between methods suggesting an acceptable level difference for this variable yet fixed and proportional bias was evident. Mean velocity and mean power showed >5% mean difference thereby demonstrating poor agreement between methods..

Limits of agreement data and descriptive data for $h_{po}$ and F-v variables ($F_0$ - N/kg), $v_0$ (m/s), $P_{MAX}$ (W/kg) and $S_{FV}$ (N.s-1.m-1.kg) between methods are highlighted in Table 3.3 and Figures 3.3 and 3.4. The mean differences between methods and percentage values expressed relative to mean criterion values for F-v variables highlighted stronger agreement when using the hexbar (1.7-5.2%) compared with using the barbell (8.2-37.2%) across all loading conditions  Pearson's correlation coefficient was *small* to *very high* (r = 0.07 – 0.75) for all F-v variables, with hexbar correlations showing a stronger relationship between criterion and predictor, however correlation coefficients for $h_{po}$ between methods was considered *trivial* to *small* (r = 0.05 – 0.30) for both loading conditions. Significant differences ($p \leq 0.05$) were identified for all F-v related variables using the barbell and only $h_{po}$ and $P_{MAX}$ (W/kg) when using the hexbar, highlighting poor agreement between criterion and predictor. Non-significant differences were evident for $F_0$ (N/kg), $v_0$ (m/s), and $S_{FV}$ (N.s$^{-1}$.m$^{-1}$.kg) suggesting acceptable agreement between methods.

Between methods, least products regression analysis identified fixed and proportional bias for mean force, velocity and power when incremental loads were combined for each loading condition (Table 3.4). Analysis of $h_{po}$ and F-v variables identified fixed bias for $v_0$ (m/s) and $S_{FV}$ (N.s$^{-1}$.m$^{-1}$.kg) for barbell CMJ trials, while proportional bias was identified for $h_{po}$, $S_{FV}$ (N.s$^{-1}$.m$^{-1}$.kg) and $P_{MAX}$ (W/kg) for barbell and hexbar CMJ trials respectively (Table 3.4). This was due to the slope and intercept showing significant differences from one and zero respectively. However, fixed and/or proportional bias was not evident for all incremental loads when analysed individually. Combined load data for barbell CMJ trials produced $R^2$ values of 0.70, 0.85 and 0.72 for mean force, velocity and power, while hexbar CMJ trials identified $R^2$ values of 0.68, 0.78 and 0.68 for mean force, velocity and power, highlighting *high* to *very high* relationships. Barbell F-v variables identified $R^2$ values ranging from  0.00-0.43, and hexbar F-v variables showed $R^2$ values ranging from of 0.00-0.56 for highlighting *trivial* to *moderate* relationships.

**Table 3.1.** Traditional measures of relative and absolute reliability for force plate and SAM method analysis across loading conditions.

| | Barbell | | | | Hexbar | | | |
|---|---|---|---|---|---|---|---|---|
| | **Mean Force (N)** | **Mean Velocity (m/s)** | **Mean Power (W)** | **$h_{po}$ (m)** | **Mean Force (N)** | **Mean Velocity (m/s)** | **Mean Power (W)** | **$h_{po}$ (m)** |
| **Force Plate** | | | | | | | | |
| ICC | 0.98 | 0.97 | 0.96 | 0.92 | 0.97 | 0.96 | 0.96 | 0.84 |
| (95% CL) | (0.97, 0.99) | (0.96, 0.98) | (0.95, 0.98) | (0.89, 0.95) | (0.96, 0.98) | (0.94, 0.97) | (0.94, 0.97) | (0.77, 0.89) |
| CV % | 2.0 | 2.7 | 3.7 | 4.1 | 2.4 | 4.2 | 4.7 | 5.0 |
| (95% CL) | (1.8, 2.3) | (2.4, 3.1) | (3.3, 4.3) | (3.6, 4.6) | (2.1, 2.7) | (3.8, 4.8) | (4.2, 5.3) | (4.5, 5.8) |
| **Field Method** | | | | | | | | |
| ICC | 0.97 | 0.98 | 0.94 | - | 0.94 | 0.96 | 0.90 | - |
| (95% CL) | (0.96, 0.98) | (0.97, 0.99) | (0.91, 0.96) | - | (0.92, 0.96) | (0.94, 0.97) | (0.85, 0.93) | - |
| CV % | 1.9 | 2.4 | 4.2 | - | 2.6 | 3.0 | 5.5 | - |
| (95% CL) | (1.7, 2.1) | (2.1, 2.7) | (3.8, 4.9) | - | (2.4, 3.0) | (2.7, 3.5) | (4.9, 6.3) | - |

ICC = intraclass correlation coefficient; CL = confidence limits; CV = coefficient of variation, *hpo* = height of push off.

**Table 3.2.** Results of the force plate and SAM method reliability least products regression analysis across loading conditions.

| | Barbell | | | Hexbar | | |
|---|---|---|---|---|---|---|
| | **Mean Force (N)** | **Mean Velocity (m/s)** | **Mean Power (W)** | **Mean Force (N)** | **Mean Velocity (m/s)** | **Mean Power (W)** |
| **Force Plate** | | | | | | |
| Intercept | -63.43 | 0.00 | 3.21 | -2.10 | 0.04 | 59.38 |
| (95% CL) | (-135.51, 8.64) | (-0.05, 0.95) | (-101.70, 108.13) | (-84.88, 8.67) | (-0.02, 0.12) | (-69.21, 187.99) |
| Slope | 1.03 | 0.99 | 0.99 | 1.00 | 0.96 | 0.97 |
| (95% CL) | (0.99, 1.08) | (0.95-1.03) | (0.94, 1.04) | (0.95, 1.04) | (0.91, 1.01) | (0.91, 1.02) |
| **Field Method** | | | | | | |
| Intercept | 13.99 | -0.01 | -8.15 | 38.96 | 0.06 | 91.63 |
| (95% CL) | (-69.50, 97.49) | (-0.06, 0.03) | (-143.81, 127.49) | (-106.40, 184.32) | (0.00, 0.12) | (-88.32, 271.59) |
| Slope | 0.98 | 1.00 | 0.99 | 0.97 | 0.94 | 0.94 |
| (95% CL) | (0.94, 1.03) | (0.96, 1.04) | (0.92, 1.06) | (0.89, 1.06) | (0.88, 1.00) | (0.86, 1.03) |

CL = confidence limits; if the 95% confidence interval does not include 0, then the difference is significant (*) (<0.05).

**Table 3.3.** Mean (SD) force plate and SAM method mean force, velocity, power, displacement and F-v variables for both loading conditions, and the mean (95% confidence limits [CL]) of the differences between them.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | **Barbell** | | | | |
| | **Force (N)** | **Velocity (m/s)** | **Power (W)** | $h_{po}$ **(m)** | **F0 (N/kg)** | **V0 (m/s)** | $P_{MAX}$ **(W/kg)** | **Sfv** $(N.m.s^{-1}.kg)$ |
| Force Plate | 1704.84 (229.08) | 1.36 (0.22) | 2165 (410.96) | 0.50 (0.07) | 32.04 (4.04) | 4.00 (0.52) | 31.98 (5.03) | -8.17 (1.76) |
| Field Method | 1751.48 (188.80) | 1.15 (0.16) | 2008.58 (318.45) | 0.37 (0.04) | 34.67 (5.05) | 3.28 (0.65) | 27.84 (3.78) | -11.21 (3.86) |
| Mean difference | -46.64 | 0.21 | 156.42 | 0.13 | -2.63 | 0.72 | 4.14 | 3.04 |
| % mean difference | 2.73 | 15.44 | 7.22 | 26.00 | 8.21 | 18.00 | 12.95 | 37.21 |
| (95% CL) | (-73.43, -19.18)* | (0.19, 0.23)* | (110.15, 204.40)* | (0.11, 0.14)* | (-4.53, -0.73)* | (0.35, 1.09)* | (1.80, 6.47)* | (1.28, 4.80)* |
| Pearson's R | 0.83 | 0.92 | 0.85 | 0.31 | 0.65 | 0.07 | 0.35 | 0.23 |
| | | | | **Hexbar** | | | | |
| | **Force (N)** | **Velocity (m/s)** | **Power (W)** | $h_{po}$ **(m)** | **F0 (N/kg)** | **V0 (m/s)** | $P_{MAX}$ **(W/kg)** | **Sfv** $(N.m.s^{-1}.kg)$ |
| Force Plate | 1786.82 (252.35) | 1.37 (0.23) | 2296.09 (457.17) | 0.46 (0.05) | 36.59 (5.32) | 3.57 (0.82) | 32.30 (6.40) | -10.79 (2.95) |
| Field Method | 1819.09 (201.49) | 1.2 (0.16) | 2180.3 (353.49) | 0.37 (0.04) | 34.94 (4.11) | 3.48 (0.69) | 29.98 (4.60) | -10.60 (3.22) |
| Mean difference | -32.27 | 0.17 | 115.79 | 0.09 | 1.64 | 0.09 | 2.32 | -0.19 |
| % mean difference | 1.80 | 12.40 | 5.04 | 19.57 | 5.29 | 2.52 | 7.18 | 1.76 |
| (95% CL) | (-63.03, -1.50)* | (0.14, 0.19)* | (59.47, 172.10)* | (0.08, 0.10)* | (-0.47, 3.77) | (-0.21, 0.40) | (0.39, 4.25)* | (-1.65, 1.26) |
| Pearson's R | 0.83 | 0.89 | 0.82 | 0.05 | 0.53 | 0.61 | 0.75 | 0.46 |

CL = confidence limits; if the 95% confidence interval does not include 0, then the difference is significant (*) (<0.05).

**Table 3.4.** Results of the method comparison least products regression analysis for mean force, velocity, power, displacement and F-v variables for both loading conditions, and the mean (95% confidence limits [CL]) of the differences between them.

| | Barbell | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Force (N)** | **Velocity (m/s)** | **Power (W)** | $h_{po}$ **(m)** | **F0 (N/kg)** | **V0 (m/s)** | $P_{MAX}$ **(W/kg)** | **Sfv (N.m.s$^{-1}$.kg)** |
| Intercept | -419.87 | -0.15 | -426.2 | -0.10 | 6.54 | 1.36 | -5.11 | -3.04 |
| (95% CL) | (-676.04, -163.70)^ | (-0.28, -0.02)^ | (-727.79, -124.60)^ | (-0.23, 0.02) | (-2.81, 15.9) | (0.06, 2.67)^ | (-22.01, 11.78) | (-5.65, -0.43)^ |
| Slope | 1.21 | 1.32 | 1.24 | 1.64 | 0.73 | 0.80 | 1.33 | 0.45 |
| (95% CL) | (1.07, 1.36)+ | (1.21, 1.43)+ | (1.15, 1.44)+ | (1.33, 2.02)+ | (0.51, 1.04) | (0.50, 1.27) | (0.86, 2.05) | (0.29, 0.71)+ |
| $R^2$ | 0.70 | 0.85 | 0.72 | 0.09 | 0.43 | 0.00 | 0.12 | 0.05 |
| | **Hexbar** | | | | | | | |
| | **Force (N)** | **Velocity (m/s)** | **Power (W)** | $h_{po}$ **(m)** | **F0 (N/kg)** | **V0 (m/s)** | $P_{MAX}$ **(W/kg)** | **Sfv (N.m.s$^{-1}$.kg)** |
| Intercept | -491.41 | -0.33 | -523.68 | -0.01 | -8.63 | -0.54 | -9.37 | -1.08 |
| (95% CL) | (-774.04, -208.77)^ | (-0.51, -0.16)^ | (-878.79, -168.57)^ | (-0.12, 0.09) | (-27.11, 9.84) | (-2.13, 1.04) | (-22.78, 4.03) | (-5.44, 3.27) |
| Slope | 1.25 | 1.42 | 1.29 | 1.29 | 1.29 | 1.18 | 1.39 | 9.10 |
| (95% CL) | (1.10, 1.41)+ | (1.28, 1.57)+ | (1.14, 1.46)+ | (1.04, 1.61)+ | (0.87, 1.92) | (0.81, 1.71) | (1.01, 1.90)+ | (0.60, 1.38) |
| $R^2$ | 0.68 | 0.78 | 0.68 | 0.00 | 0.28 | 0.37 | 0.56 | 0.21 |

CL = confidence limits; if the 95% confidence interval for the intercept does not include 0, then fixed bias is present; if the 95% confidence interval for the slope does not include 1.0, then proportional bias is present. + = proportional bias, ^ = fixed bias.

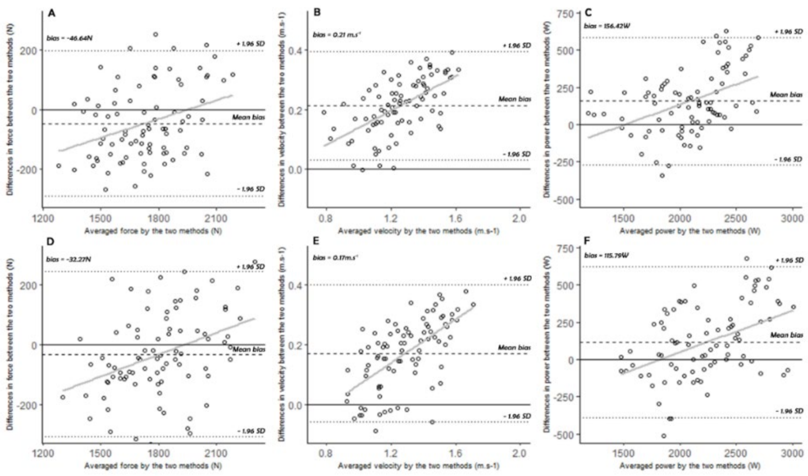

**Figure 3.2.** Limits of Agreement plots of differences between the force plate and field method for mean force (A), velocity (B) and power (C) using a barbell and mean force (D), velocity (E) and power (F) using a hexbar. Data combined from all incremental loads. The solid horizontal line corresponds to zero (no bias). The dashed line corresponds to the mean bias. Upper and lower horizontal dotted lines represent the limits of agreement (mean ±1.96 SD of the difference between methods). Regression line describes the relationship between criterion and predictor.

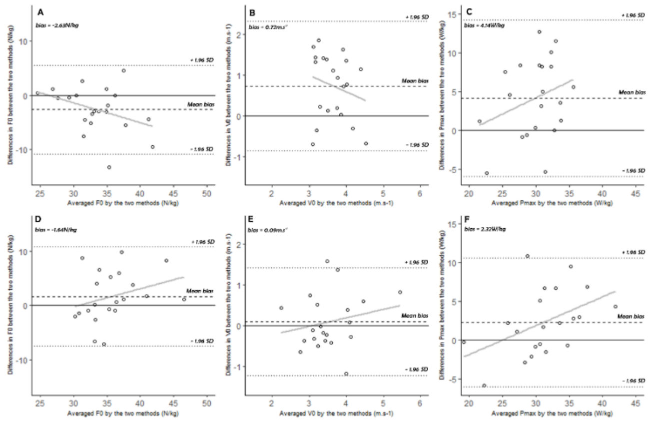

**Figure 3.3.** Limits of Agreement plots of differences between the force plate and field method for $F_0$ (A), $v_0$ (B), $P_{MAX}$ (C) using a barbell and $F_0$ (D), $v_0$ (E), $P_{MAX}$ (F) using a hexbar. The solid horizontal line corresponds to zero (no bias). The dashed line corresponds to the mean bias. Upper and lower horizontal dotted lines represent the limits of agreement (mean ±1.96 SD of the difference between methods). Regression line describes the relationship between criterion and predictor.

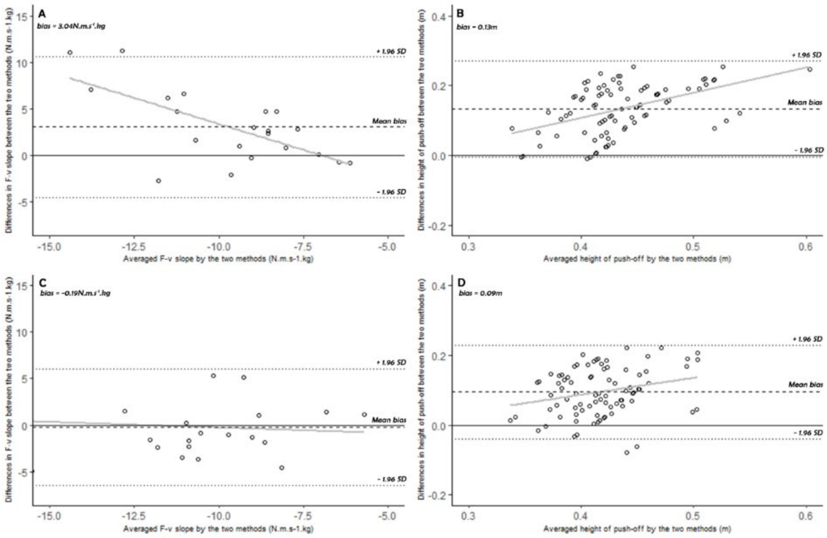


**Figure 3.4.** Limits of Agreement plots of differences between the force plate and field method for the force-velocity slope ($S_{FV}$) (A) and height of push-off ($h_{po}$) (B) using a barbell and the force-velocity slope ($S_{FV}$) (C) and height of push-off ($h_{po}$) (D) using a hexbar. The solid horizontal line corresponds to zero (no bias). The dashed line corresponds to the mean bias. Upper and lower horizontal dotted lines represent the limits of agreement (mean ±1.96 SD of the difference between methods). Regression line describes the relationship between criterion and predictor.

## Discussion

The purpose of this study was to assess the reliability and validity of the SAM method to determine mean force, velocity and power and associated F-v variables (($F_0$ (N/kg), $v_0$ (m/s), $P_{MAX}$ (W/kg), $S_{FV}$ (N.s-1.m-1.kg)) during the propulsion phase when performing loaded and unloaded barbell and hexbar CMJ actions. Displacement during the propulsion phase was also validated against $h_{po}$. With regards to the reliability of the SAM method, for both jump types, the results of this study support the work of the two previous validation studies (129, 176) highlighting acceptable between-trial absolute and relative reliability for mean force, velocity and power (ICC > 0.90, CV < 5.5%) (Table 3.1). The height of push off ($h_{po}$) for both loading conditions showed slightly lower levels of relative reliability, (barbell - ICC 0.92, CV of 4.1%, hexbar – ICC 0.84, CV of 5.0%)

(Table 3.1), yet still acceptable levels of absolute reliability. The results suggest the anthropometric inputs into the calculation of the SAM method ([mass (kg), height of take-off, squat depth ($h_s$) and height of push-off ($h_{po}$)]) provide reliable data to determine mean force, velocity and power values. Least products regression analysis also identified acceptable between-trial reliability using the SAM method for both loading conditions (Table 3.2). Neither fixed or proportional bias was evident between trials due to the 95% confidence intervals for the intercept and slope including zero and one, respectively.

When considering the results to determine the validity of the SAM method, limits of agreement analysis (Table 3.3) and least products regression analysis (Table 3.4) suggests significant differences exist for mean force, velocity or power, with similar findings evident for displacement during the propulsive phase and F-v variables across either loading condition. This was due to the level of mean bias observed in the limits of agreement plots (Figures 3.2-3.4) and the frequency of the 95% confidence intervals within the least products regression analysis excluding zero and one for the intercept and slope, identifying levels of fixed and proportional bias. The prevalence of fixed or proportional bias was however not evident in all incremental loading conditions (Supplemental material: Table 2). This contrasts the data presented in previous validation studies where the authors highlighted *negligible* systematic bias (% relative to mean value) between force plate analysis and the SAM method for measuring mean force (0.0% ± 1.0), velocity (0.0% ± 0.0) and power (0.2% ± 1.0) during the propulsive phase in CMJ actions using a smith machine (176).

The difference in findings between studies are important within the field of sports science since validation of the SAM method using common physical preparation loaded/unloaded exercises (barbell/hexbar jumps) is limited. This may, therefore, identify a significant limitation of the SAM method to estimate mean force, velocity and power, and establish a valid F-v profile, using a 'free-weight' CMJ protocol. The variance in which fixed or proportional bias appears in the least products regression analysis infers further analysis of possible causes across loading conditions.

One possible explanation for the differences identified in this study may be related to the key input into the SAM method; height of push-off ($h_{po}$). The between-trial reliability for $h_{po}$ (displacement during propulsion) was shown to be *high* across both loading conditions (barbell; ICC = 0.92 (0.89-0.95), CV = 4.1%, hexbar; ICC = 0.84 (0.77-0.89), CV = 5.0%)), with the coefficient of variation showing greater reliability with the barbell loading conditions. The mean percentage difference between methods for $h_{po}$, represented relative to the mean of the criterion, identified a 26.0% and 19.6% difference when performing barbell and hexbar CMJ trials respectively. This identifies a likely difference in the starting height ($h_s$) measured during the pre-assessment (and therefore $h_{po}$), and those achieved when performing the CMJ actions. Although $h_{po}$ is an easily measured input into the model, it directly affects the calculation of mean system force, and extrapolates to all key variables of the model. Moreover, an error in $h_{po}$, via anthropometric measurement or changes in the starting height of subject prior to the propulsive phase, will reduce validity of the SAM method.

The $h_{po}$ relies on the subject descending to and controlling the starting height of the propulsive phase, $h_s$, for each jump action. Although controlling $h_s$ during the CMJ increases the direct relationship between jump height and mechanical power (332), it has been noted this may reduce the ecological validity of the test due to restricting subjects from self-selecting the most appropriate depth at each load to maximise their jump performance (284, 332). This is an important consideration when applying the SAM method since it is designed for practitioners to determine the F-v profile without the level of equipment and technology freely available in a laboratory setting. As per a previous validation study using CMJ actions (176) in a smith machine, starting height was not constrained by a band or similar device . Due to the inconsistencies in the data, it is the authors hypothesis that the magnitude of differences which exist between displacement achieved during the propulsive phase measured via integration of the force-time signal, compared to the anthropometric measurements which provide $h_{po,}$ is likely a direct result of changes to $h_{s.}$ The SAM method under-estimated displacement during push-off, with significant mean differences identified for both loading conditions suggesting subjects descended to knee angles less than 90° at the knee joint. McBride et al. (217) has previously shown higher mean force values at higher starting height angles for CMJ actions. This may explain differences in mean force between methods as displacement values identified from integrating the force-time signal showed a larger distance covered during propulsion than anthropometric measures taken prior to testing. Table 3 identifies the mean and standard deviation starting height was similar between loading conditions and therefore may highlight greater familiarization of testing protocol was necessary to ensure the appropriate starting height, 90° at the knee joint, was achieved.

The validity of slope of the F-v profile and the differences between methods provides useful analysis considering this data is often used in training prescription for athletic populations (175) and can characterize performance (130, 174). Mean and individual F-v slope analysis is highlighted in Figure 3.5 and Figure 3.6. A closer analysis of the mean slope from combined subjects (Figure 3.5) highlights a closer agreement when using the hexbar compared to the barbell, while also showing the profiles between loading conditions should not be used interchangeably. For example, when using the barbell, the SAM method overestimates $F_0$ (N/kg) and underestimates $v_0$ (m/s), compared to the force plate, thereby creating a 'steeper' slope of the profile for each subject. This may therefore mislead sports scientists to  assume the subject has a velocity deficit and attempt to correct this F-v imbalance by targeting particular exercises on the F-v spectrum (175). Individual subject slope analysis (Figure 3.6) identifies the differences in the F-v slope between loading conditions and methods, with some subjects showing minimal variation (e.g. subjects #2, #18, #20), whereas other subjects showed much large variation (e.g. subjects #1, #11, #15). A closer analysis of individual loads using the hexbar (Supplemental material: Table 1) identifies minor mean % differences at higher loads, BM + 30kg = 0.81% and BM + 45kg = 0.51%, suggesting kinematic changes may have impact the subjects due the position of the load closer to the body centre of mass, see Swinton et al. (325).

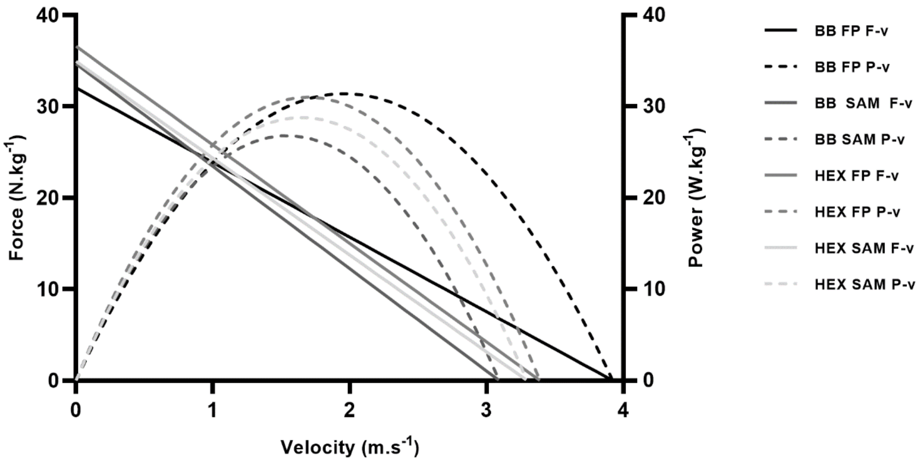


**Figure 3.5.** Mean force-velocity slope analysis between methods and loading conditions. (SAM = Samozino method, FP = force plate, BB = barbell, HEX = hexbar).

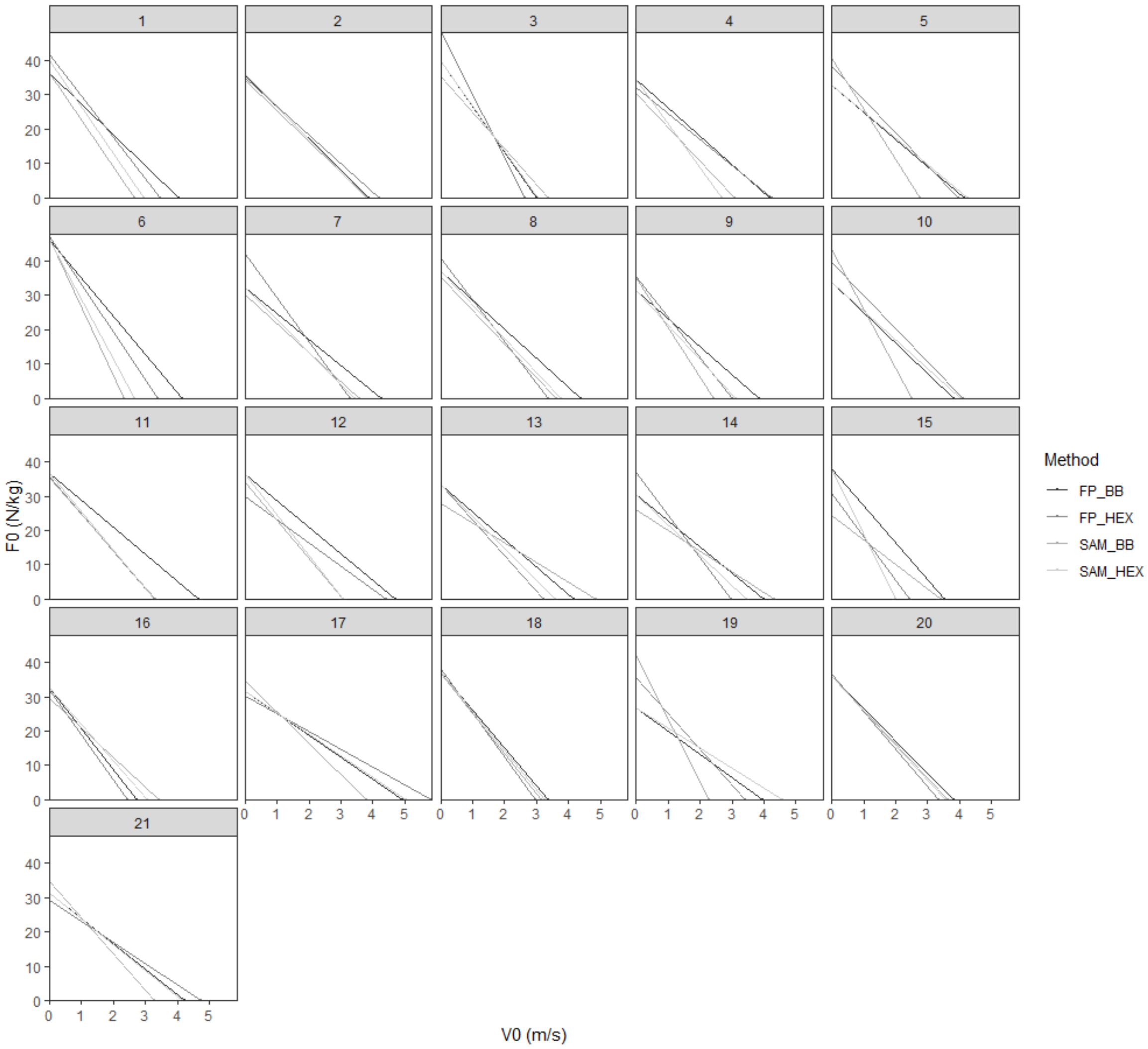


**Figure 3.6.** Individual subject (1-21) force-velocity slope analysis between methods and loading conditions. (SAM = Samozino method, FP = force plate, BB = barbell, HEX = hexbar).

Notwithstanding, previous research has shown changes to $F_0$ (N/kg), estimation of force intercept, will have a greater effect on the SAM method outputs than changes to $h_{po}$. For example, an approximately 10% change to $F_0$ (N/kg) results in a 10-15% increase in jump height, compared to the same percentage change in $h_{po}$, resulting in approximately 4.5-7.5% increase in jump height (284). This is an interesting consideration when analysing agreement between the methods since mean velocity is inversely calculated from the trial with the highest jump height. This suggests minor changes in $h_{po}$ will impact kinematic variables and therefore likely influence the validity of the SAM method, which confirms the findings in this study.

While determining reliability and validity of the SAM method was the focus of this study, the authors have identified potential limitations to the calculation method and study design. Although the SAM method is designed as a simple model for field conditions, practitioners should still be cognisant of potential errors in practical application. The mean differences (and % relative difference compared to the criterion) observed in $h_{po}$ between methods and loading conditions (barbell – 0.13m [26.0%], hexbar – 0.09m [19.6%]) suggests $h_s$ should be controlled by use of a band (or similar device) to elicit less jump variability (199, 336). Although starting height is *self-selected* by the athlete, they must still achieve a 90° angle at the knee, plus it should be consistent for each individual if jump assessment is frequent during training. Furthermore, real-time displacement data must be available from the force-time signal to ensure correct starting height, thereby reducing jump variability across loads. This did not occur during this study and does not appear to be a key recommendation in the initial SAM method literature. The considerable variation of $h_s$ evident in post-testing analysis was not expected by the authors yet appears to have greatly influenced agreement between methods. Another factor which potentially limited this study was the resistance training background of the subjects and familiarization of performing the movement under the direction of the lead author.

Although analysis for validity were grouped via combined loads and individual loads (Supplemental material: Table 1 and Table 2), fixed absolute loads for each bar condition did not occur in previous studies where loads were individualized based on a percentage of bodyweight (129, 176). This may have impact results and agreement between methods in the calculation of the intercepts of the linear F-v relationship, $F_0$

(N/kg) and $v_0$ (m/s). Therefore, for a given bodyweight, one subject jumped against a higher relative load than the next subject, thereby potentially impacting the slope of the F-v relationship (187, 336). The intercepts are extrapolated from the data points along the slope and are essentially estimates of theoretical maximal values, although frequently discussed as determinants of jump performance. The absolute and number of loads selected may also have prevented subjects expressing force close to the $F_0$ intercept; thereby potentially decreasing the validity of these theoretical values as suggested in previous research (1, 121, 172, 199). Notwithstanding, relative loads based on bodyweight percentages will remain estimated data points, albeit with likely greater validity.

One final limitation was the sample size of the study. A power analysis conducted prior to the study suggested 34 subjects was the ideal sample size (ES = 0.5, p = 0.05, power = 0.8), whereas only 21 subjects participated in this study. Post-hoc analysis using 21 subjects therefore provides a power level of only 0.57, which highlights differences between the means will only be detected 57% of the time. This may limit the conclusions outlined below as the study is underpowered.

Although there has been previous research validating Samozino's method during CMJ actions, to the best of our knowledge this is the only study which has reported the reliability and validity of establishing F-v profiles using CMJ actions with a barbell and hexbar.

## Conclusions

Providing practitioners with a simple approach to analyse the F-v capabilities of their athletes with limited technology is useful information to obtain current mechanical capabilities of the neuromuscular system. However, ensuring the methodological approach used provides valid data compared to the *gold* standard is essential. The results of this study suggest the SAM method to be reliable to determine mean force (N), velocity (m/s) and power (W) when performing barbell and hexbar CMJ actions. Therefore, from a practical point of view, coaches and scientists can use variables from the SAM method when monitoring the same athletes across the course of a season. Although the SAM method demonstrated acceptable levels of agreement (<5% mean difference) when measuring mean force, fixed and proportional bias was evident. This was also observed for mean velocity and mean power (>5% mean difference respectively) when compared to force plate analysis. In conclusion, the SAM method is a reliable, practical and time-efficient method to obtain lower-limb neuromuscular data, however differences exist between criterion and predictor when measuring mechanical variables thereby reducing validity between measures.

## PRELUDE

Chapter 3 demonstrated acceptable reliability of using a field method approach to determine force and velocity characteristics during free weight countermovement jump actions, while validity using the hexbar exceeded that of the barbell when compared to force plate analysis. However, there is limited research using a hexbar to determine vertical (i.e., jump) F-v characteristics in athletes. It would therefore be interesting to understand whether mechanical characteristics can differentiate between sex and positional demands from the same sporting background when using this as the primary neuromuscular tool for jump assessment. Therefore, the primary aim of the study was to evaluate jump-based mechanical characteristics in field hockey athletes and use the information to inform training-related interventions. We hypothesized athletes who were classified as primary attackers on the field would display a more velocity-oriented F-v profile when compared with defenders, thereby demonstrating significantly higher values in relative maximal power and mechanical differences would exist between sexes due to strength related factors. This chapter provides coaches with insight as to how to individualize and prescribe training demands based on sex and positional demands club-based field hockey players.

# CHAPTER 4: STUDY 2

## Force-velocity profiling in club-based field hockey players: Analyzing the relationships between mechanical characteristics, sex, and positional demands


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**Statement of co-authorship**: All authors were involved in formulating the concept and design of the study. Dylan Hicks and Roland van den Tillaar conducted the data collection. DH conducted the analysis and completed the initial draft of the manuscript. All authors edited multiple revisions of the manuscript.


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## Abstract

The purpose of this study was to investigate differences between sex and positional demands in club-based field hockey players by analyzing vertical F-v characteristics. Thirty-three club-based field hockey athletes (16 males - age: 24.8 ± 7.3yrs, body mass: 76.8 ± 8.2kg, height: 1.79 ± 0.05m; 17 females - age: 22.3 ± 4.2yrs, body mass: 65.2 ± 7.6kg, height: 1.66 ± 0.05m) were classified into two key positional groups (attacker or defender) based on dominant field position during gameplay. F-v profiles were established by performing countermovement jumps (CMJ) using a three-point loading protocol ranging from body mass (i.e., zero external mass, 0%) to loads corresponding to 25% and 50% of their own body mass. Across all loads, between-trial reliability of F-v and CMJ variables was determined by intraclass correlation coefficients (ICCs) and coefficient of variation (CV) and deemed to be acceptable (ICC: 0.87-0.95, CV% 2.8-8.2). Analysis by sex identified male athletes had significantly greater differences in all F-v variables (12.81-40.58%, $p \leq 0.001$, ES = 1.10-3.19), a more enhanced F-v profile (i.e., greater theoretical maximal force, velocity, and power values), plus overall stronger correlations between relative maximal power ($P_{MAX}$) and jump height ($r = 0.67$, $p \leq 0.06$) when compared to female athletes ($-0.71 \leq r \geq 0.60$, $p=0.08$). Male attackers demonstrated a more 'velocity-oriented' F-v profile compared to defenders due to significant mean differences in theoretical maximal velocity ($v_0$) (6.64%, $p \leq 0.05$, ES: 1.11), however differences in absolute and relative theoretical force ($F_0$) (15.43%, $p \leq 0.01$, ES = 1.39) led to female attackers displaying a more 'force-oriented' profile in comparison to defenders. The observed mechanical differences identify the underpinning characteristics of position specific expression of $P_{MAX}$ should be reflected in training programmes. Therefore, our findings suggest F-v profiling is acceptable to differentiate between sex and positional demands in club-based field hockey players. Furthermore, it is recommended field hockey

players explore a range of loads and exercises across the F-v continuum through on-field and gym-based field hockey strength and conditioning practices to account for sex and positional mechanical differences.

## Introduction

Field hockey is a high-intensity, intermittent-based team sport with high mechanical demands requiring players to accelerate, decelerate, change speed and direction quickly, and in addition requires advanced skill to be an effective player (300). Recent literature on field hockey has characterized movement patterns, activity profiles and repeated-sprint ability (311, 312) using time-motion analysis (i.e., global positioning systems [GPS] (118, 209, 346) which quantified different game-based demands based on specific positional groups including speed and distance of sprint efforts. Studies on age groups ranging from youth to international level field hockey also identified a significant demand for high-speed running during the game, with midfielders and attackers accumulating a greater number of high intensity actions compared to defenders (167, 208, 209, 219, 340). Despite extensive analysis of movement patterns within the sport of field hockey, mechanical characteristics contributing to on-field performance including force, velocity and power are yet to be fully explored.

Comparisons between high-intensity actions such as sprinting, and positional groups during field hockey games have previously highlighted significant differences between the number of sprints performed, velocities achieved during sprint efforts and the position of the player on the field (118, 209, 312, 346), suggesting the biomechanical demands and therefore F-v characteristics required at each position are different. For example, in elite women's hockey, midfielders spend a greater portion of game time at velocities greater than 7 $m.s^{-1}$, when compared to attackers and defenders, while midfielders and attackers spend a greater portion of game time above 5 $m.s^{-1}$, when compared with defenders (118). This comparison between position groups also identified attackers (also known as strikers) as likely to have a greater maximal velocity during game-play compared to midfielders and defenders, demonstrating their exposure to a greater mechanical load (209). Similarities have been observed in elite men's field hockey where differences between high intensity actions and positional groups identified inside-forwards (n=39 ± 1) and strikers (n=42 ± 15) performed a greater number of sprint actions when compared with full-backs (n=18 ± 1) and half-backs (n=22 ± 7) (312). Therefore, quantifying the on-field movement characteristics via time-motion analysis, along with analyzing the underpinning mechanical determinants and F-v relationship of the lower limbs contributing to performance may provide greater insight to further enhance field hockey strength and conditioning practice.

In sprint and team sport athletes, previous studies have demonstrated a significant correlation between the F-v characteristics of jumping and sprinting actions (202). The association between both actions has identified relative peak force, peak power and jump height in a countermovement jump (CMJ) action as strong predictors of maximal velocity at 10-metres and improved sprint times from 5-60-metres (215, 248), thereby highlighting similar neuromuscular qualities between actions. Due to the strong relationships between jump and sprint performance (72, 215), a CMJ is often an effective assessment of mechanical output to infer F-v characteristics across both actions. Furthermore, the simplicity of performing the jumping movement without the risk of injury associated with maximal velocity sprint testing may be more favourable from a coaching perspective (248). Despite the ease of testing, an isolated CMJ assessment is limited as it evaluates lower-limb function under a single mechanical condition; an athlete's body mass, and therefore the observed outcomes do not differentiate between different muscle capacities (i.e., force production at low and high velocities) (163). Therefore, to determine overall mechanical characteristics a F-v profile may be an alternative approach.

F-v profiling has previously shown strong utility in team sports (105, 106, 172, 174, 175, 212) to characterize the maximal mechanical capabilities of the lower limbs neuromuscular system (279). When performing a vertically oriented F-v profile, the athlete jumps (CMJ or squat jump) against a range of external loads (between 2-9 loads) (121, 242) from their own body mass only (i.e., zero external load) to potentially jumping with external load up to 75-100% of their body mass (122). Typically, the F-v profile provides comprehensive information about overall neuromuscular function including: the slope of the F-v profile ($S_{FV}$), theoretical maximal force at null velocity ($F_0$), theoretical maximal movement velocity up to which force can be produced ($v_0$) and theoretical external maximal power ($P_{MAX}$), the product of the two former variables (163). Potentially, athletes with different F-v profiles could produce similar levels of external $P_{MAX}$, yet with a different combination of vertical force and velocity, thereby offering insight to the practitioner about the strengths and weaknesses of their neuromuscular system (i.e., force-oriented or velocity-oriented) (172). F-v profiling in a range of tasks has shown to not only quantify current mechanical capabilities, but to distinguish between ability level (e.g. elite, non-elite)(170) and sport (130), while potentially being used to guide training interventions and programming decisions (175). Despite this, concerns have been raised about the reliability of using mechanical profiling to determine F-v variables through countermovement and squat jump actions, as well as the utility of these variables to inform performance. (199, 336). However, recent research has also challenged these concerns by demonstrating that improved methodological practices can produce reliable data.(290). Currently, there is limited information about the biomechanical demands of field hockey, suggesting a greater understanding of F-v characteristics between sex and positional demands within the sport may provide strength and conditioning practitioners with useful information to optimize and individualize training programmes to enhance on-field performance.

Therefore, the aim of the study was to evaluate vertically oriented F-v characteristics in male and female field hockey athletes and use the information to inform training-related interventions. Specifically, we aimed to determine and compare mechanical F-v relationships between sex and positional groups within a field hockey context. Due to achieving higher velocities during game-play as identified in time-motion analysis (167), we hypothesized athletes who were classified as primary attackers on the field would (1) display a more velocity-oriented F-v profile when compared with defenders, thereby demonstrating significantly higher values in relative maximal power (285) and (2), we hypothesized differences would exist in the F-v profile between males and females due to strength related factors (124, 189, 259, 326), and males would display an overall more enhanced F-v profile. The results of this study would allow for a more effective training design for field hockey athletes based on mechanical characteristics.

## Methods

We used a cross-sectional experimental design to investigate the relationship(s) between the vertical F-v profile using a CMJ, sex (male, female) and playing position (attackers and defenders). In consultation with the head coaches of the respective field hockey teams, subjects were classified as either an attacker or a defender based on where their coach most frequently positioned them on the field. Attacking positions included: attacking midfielder, left and right wing, inside left and right and striker. Defensive positions included: defensive midfield, outside and central defenders, sweeper and goalkeeper. It was reported by the coaching staff that some athletes played multiple attacking or defensive positions. All athletes were assessed for anthropometric measures (body mass, standing stature) along with a three-point F-v profile using incremental loads. The testing session for all athletes was conducted during the field hockey preseason period, approximately 8-weeks before the season began, with the intention the results would provide greater insight into training direction for specific positional groups across the preseason period. All CMJ measurements were recorded indoors with the same external environmental conditions and supervised by a certified strength and conditioning professional.

### *Subjects*

Thirty-three club-level field hockey athletes (male n=16, 8 attackers/8 defenders), age: 24.8 ± 7.3 years, body mass: 76.8 ± 8.2 kg, and height: 1.79 ± 0.05m, (female n=17, 9 attackers, 8 defenders), 22.3 ± 4.2 years, body mass 65.2 ± 7.6 kg, and height 1.66 ± 0.05 m, participated in the study (Table 4.1). Subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. The adult guardians or parents provided signed written consent for subjects under 18 years of age. Inclusion criteria included: subjects involved in state league level of competitive sport; a background in resistance training of greater than six months; and aged 15-35 years. Exclusion criteria maintained that subjects needed to be six-months free of musculoskeletal injuries which may prevent them from performing maximal effort CMJ actions against external loads. In their pre-testing questionnaire, subjects acknowledged their experience with exercises such as the vertical jump. Subjects were asked to refrain from physical training within the 24-hours prior to testing. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146).

**Table 4.1**. Descriptive statistics of anthropometric variables between sex and positional groups.

| Variable | Males | | | | | Females | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Attackers | Defenders | Mean difference (±95%CL) | Mean % difference | ES (90% CI) | Attackers | Defenders | Mean difference (±95%CL) | Mean % difference | ES (90% CI) |
| **Age (y)** | 24.50 ± 8.94 | 25.16 ± 4.91 | -0.66 (-8.10, 6.77) | 2.44 | -0.08 (-1.19, 1.02) | 23.10 ± 4.56 | 21.50 ± 4.44 | 1.61 (-3.05, 6.27) | 6.96 | 0.35, (-0.68, 1.40) |
| **Bodymass (kg)** | 75.64 ± 9.52 | 80.50 ± 3.53 | -5.85 (-13.09, 1.39) | 7.83 | -0.73 (-1.88, 0.40) | 66.86 ± 8.72 | 61.40 ± 4.56 | 5.46 (-1.4, 12.33) | 8.19 | 0.71 (-0.39, 1.83) |
| **Height (m)** | 1.77 ± 0.04 | 1.81 ± 0.08 | -0.04 (-11.8, 4.54) | 2.25 | -0.66 (-1.80, 0.46) | 1.64 ± 0.05 | 1.65 ± 0.05 | 0.01 (-6.1, 3.9) | 0.06 | -0.66 (-1.80, 0.46) |

*CL: confidence limits, ES: effect size, CI: confidence interval*

### *Procedures*

The vertical F-v profile assessment was performed on the same day for all subjects. The conditions observed on the day of testing included the following environmental variables: temperature min 21.5°C, max 33.0°C, SE winds 13km/h, 1017.5hPA.

### *Vertical force-velocity profile assessment*

Prior to jump testing, subjects completed a standardized warm-up consisting of three minutes of step-ups (cadence of 85 on metronome), dynamic movements, and preparatory vertical jumps including a series of maximal unloaded and sub-maximal (10-15kg) loaded CMJ trials (149). During all trials, internal cues such as "squat to a seated position then extend your hips, knees and ankles as fast as you can" (222), plus external cues such as "jump to the roof" were provided to subjects to ensure maximal intent was provided across the three loading conditions (136).

All assessments began with subjects standing with each foot on a separate portable force plate system (35cm by 35cm, PASPORT force plate, PS-2141, PASCO Scientific, California, USA), which directly measured left and right foot ground reaction forces (GRF). This type of portable force plate has previously been validated and deemed reliable against in-ground laboratory grade force plates (196). Prior to the initiation of the jump, subjects were instructed to stand still at full stature for at least 1-second with their left and right foot on the center of each force plate, to ensure the weighing phase could be calculated accurately (222). If there was movement prior to the initiation of the jump, the trial was repeated. Preceding the next trial, the force plate was zeroed. Vertical GRF was continuously sampled at 1000 Hz for each force plate, with vertical force-time data being stored within a local computer. The data was subsequently exported to a csv file for post-processing analysis.

Countermovement jump trials were performed either with body mass only (arms akimbo), a purpose-built polyvinyl chloride (PVC) hexagon made to the same inner dimensions as the free weight hexbar, which could hold light external load if required, or a 15kg free-weight hexbar with load added determined by percentage of body mass. Subjects used the high handles of the free-weight bar and were standing upright, within the hexagonal shape, with the bar sitting off the ground prior to descending into the CMJ. Each subject's arms remained extended throughout the duration of the jump. Countermovement depth was self-selected and was not constrained by a box or band to encourage individual jump strategy (221).

We used a three-point loading protocol for the F-v profile as this has been shown to provide reliable and valid data when compared to the more commonly used multiple point (load) approach (293). The multiple-point method although used extensively in the field, may be time-consuming on the practitioner, plus may also lead to athlete fatigue due to the necessity to perform multiple jumps at each incremental loading condition. Therefore, the three-point (body mass plus two external loads) approach was selected to obtain mechanical capabilities across the F-v spectrum. Each participant performed the trials using the same incremental loads and order; body mass (BM, 0%) (Load 1), then 25% (Load 2) and 50% (Load 3) externally added mass. Three trials were performed at each loading condition, assuming a successful jump. Upon landing for all loading conditions, subjects were asked to touch down with the same leg position as when they left the ground (i.e., plantar flexed ankle joint). Between each loading condition, there was a 3-minute passive recovery period to limit fatigue prior to the next series of jump trials.

To determine the F-v profile, mean values of force and velocity were determined using force-time data during the propulsive phase (concentric portion of jump) of the CMJ. Key phases of the CMJ were agreed upon using the force-time characteristics previously outlined (222). The propulsive phase was defined as the point at which centre of mass velocity becomes positive and the athlete begins moving vertically from the lowest point of the countermovement until the point of take-off (222). Mean vertical GRF was determined by averaging force from the dual force plate system across the time points established for the propulsive phase of the jump. The instantaneous vertical velocity across the propulsive phase of each jump type was determined via integration of the center of mass (COM) vertical acceleration signal over time via force plate data and then averaged across the propulsion phase. Mean external power across the propulsion phase was then calculated as the product of mean GRF and estimated mean COM velocity according to the sample rate from the force plates. Vertical ground reaction force was used to calculate vertical instantaneous acceleration of the COM, therefore determining changes to eccentric (braking phase) and concentric (propulsive phase) COM displacement during the countermovement. The braking phase (eccentric portion of jump) commenced from the instant of peak negative COM velocity through to when COM velocity increased to zero. Flight time was determined using the thresholds previously outlined and is characterized by the instant of take-off and landing on the force plates. Jump height (JH) was determined using the trapezoid rule in reference to flight time using the gold standard equation, JH = $v^2 2g$ (v=vertical velocity, g=gravitational constant)(230). Concentric and eccentric contraction times were established using the time-points outlined in the force-time characteristics. Take-off velocity was determined as the maximal velocity at the conclusion of the propulsion phase (220).

### *Force-velocity relationship during countermovement jumps*

F-v parameters were established using direct mean ground reaction force from the force plates and then input into a customised Microsoft Excel spreadsheet as outlined by Garcia-Ramos et al. (123). Descriptions of F-v and CMJ variables are shown in Table 4.2. The trial at each load which recorded the highest take-off velocity (maximum vertical velocity) was used for statistical analyses as this likely represents the current maximal capabilities of the neuromuscular system during the movement (270). A least squares linear regression model was then applied to the mean force and velocity data to determine the F-v relationship variables. Absolute (N) and relative theoretical maximal force ($N.kg^{-1}$) ($F_0$) and theoretical maximal velocity ($m.s^{-1}$) ($v_0$) were then established as the intercepts of the linear regression model, while absolute (W) and relative theoretical maximal power ($W.kg^{-1}$) were described as: $P_{MAX} = F_0.v_0/4$. The F-v data achieved across the three loading conditions describes the absolute ($N.s^{-1}.m^{-1}$) and relative ($N. s^{-1}.m^{-1}$.kg-1) slope of the F-v profile ($S_{FV}$) and is calculated as: $S_{FV} = F_0/v_0$.

### *Statistical analyses*

Statistical analyses were determined from input into custom built Microsoft Excel spreadsheets (154) plus coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages. The sample size used in this study was based on priori estimates used in previous research (total sample: n= ≤19, group comparisons: n= ≤9) using mechanical profiling suggesting the number of subjects is acceptable to detect true changes (18, 259, 316).

**Table 4.2**. Definition and practical description of vertical force-velocity and countermovement jump variables.

| Variable | Abbreviation | Practical Interpretation |
|---|---|---|
| **Theoretical maximal vertical force (intercept) production extrapolated from the linear loaded countermovement jumps F-v relationship** | Absolute $F_0$ (N)<br>Relative $F_0$ ($N.kg^{-1}$) | Maximal concentric force output in the vertical direction per unit of body mass. Describes the athlete's force capability to project the centre of mass in the vertical direction. |
| **Theoretical maximal movement velocity (intercept) extrapolated from the linear loaded countermovement jumps F-v relationship** | $v_0$ ($m.s^{-1}$) | Maximal movement velocity in the vertical direction during the countermovement jump. Describes the athlete's ability to produce force at high velocities in the vertical direction. |
| **Maximal mechanical external power output in the vertical direction ($P_{MAX} = F_0 \times v_0/4$)** | Absolute $P_{MAX}$ (W)<br>Relative $P_{MAX}$ ($W.kg^{-1}$) | Maximal external power-output capability during the concentric action of the countermovement jump per unit of body mass. |
| **Slope of the force-velocity relationship** | Absolute $S_{FV}$ ($N.s.m^{-1}$)<br>Relative $S_{FV}$ ($N.s.m^{-1}.kg^{-1}$) | Index of an athlete's individual balance between force and velocity capabilities. The more negative the value, and steeper the F-v slope, the more force-dominant the athlete is. |
| **Jump height** | JH (m) | The maximal centre of mass displacement achieved during the flight phase of the countermovement jump. |
| **Flight time** | FT (sec) | Arial time of the athlete between 'take-off' until 'landing' in the countermovement jump. |
| **Take-off velocity** | TOV ($m.s^{-1}$) | The maximal movement velocity at the conclusion of the propulsion phase |

All descriptive data are presented as mean ± standard deviation (SD) and were assessed for normality using the Shapiro-Wilks test. Mean force, velocity and power and associated F-v variables, plus vertical jump kinematics for all CMJ loading conditions, were calculated and derived using force-time characteristics previously detailed in recent literature (222). Intraclass correlation coefficient (ICC) with 95% confidence limits, using a 2-way random-effects model (absolute agreement) and coefficient of variation (CV) were used to assess relative and absolute reliability of CMJ variables. Reliability measures are important during multi-joint actions to ensure the linearity of the F-v relationship (123). Thresholds for evaluation of intraclass correlation coefficients were quantified using the following scale: 0.20-0.49 *low*, 0.50-0.74 *moderate*, 0.75-0.89 *high*, 0.90-0.98 *very high* and ≥ 0.99 *extremely high* (155). Biomechanical literature have previously reported variables with a CV within the range of 10% as reliable (59). Therefore, acceptable reliability was determined with a coefficient of variation (CV) ≤ 10% (69) and ICC > 0.70 (7, 59, 348).

To assess the effect of positional demands and sex on vertical F-v profile variables, a 2 (position) x 2 (sex) ANOVA for each variable was used. Furthermore, a one-way ANOVA was used for each sex to determine significant differences based on positional demands. To analyse the associations between F-v and CMJ variables, Pearson's product-moment correlation coefficient (Pearson's *r*) was utilized. Thresholds for evaluation of Pearson's correlation coefficients (*r*) were quantified using the following scale: weak (≤0.39), moderate (≥0.40–0.69), or strong (≥0.70) (52). Effect sizes (Cohen's d) were determined from both sexes and positional groups with 95% confidence limits. Magnitudes of effect size changes were interpreted using the following values: trivial (< 0.20), small

($0.20 \leq 0.60$), moderate ($0.60 \leq 1.20$), large ($1.20 \leq 2.00$) and extremely large (> 2.00)(52). An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

## Results

Table 4.1 highlights descriptive statistics for anthropometric variables between sexes and playing positions with moderate, non-significant effects reported for body mass (kg) between positional groups in both sexes ($-0.73 \leq ES \geq 0.71$). Table 4.3 reports the between-trial reliability for kinetic and kinematic variables established from the force-time data. Relative and absolute reliability for males across all key variables were classified as high, (ICC: 0.95-0.97, CV% 2.7-6.9), while females demonstrated slightly lower yet acceptable reliability values, (ICC: 0.87-0.95, CV% 2.8-8.2). The linearity ($R^2$) of F-v profiles for males and females was 0.99 (Figure 4.1), suggesting strong reliability across the selected loads and no significant difference between sexes. Figure 4.2 identifies Pearson's correlation coefficients between all mechanical variables and vertical jump performance (i.e., jump height). Male and female attackers reported a slightly stronger, more dominant relationship between relative $P_{MAX}$ and $v_0$ ($r \geq 0.91$, $p \leq 0.01$) compared to relative $F_0$, whereas male defenders only displayed a strong association with relative $P_{MAX}$ and relative $F_0$ ($r \geq 0.94$, $p \leq 0.01$). Female defenders presented balanced correlations between relative $F_0$, $v_0$ and relative $P_{MAX}$. More details on correlation and significant relationships between F-v variables can be found in supplemental files (S1). Figure 4.3 identifies the linear regression model between jump height and relative $P_{MAX}$ highlighting weak to moderate R-squared values between sex and positional group (males: $R^2 \geq 0.45$; females: $R^2 \geq 0.35$). Female defenders only demonstrated a negative linear relationship between jump height and relative $P_{MAX}$.

**Table 4.3.** Traditional measures of relative and absolute reliability between sex for force-velocity and countermovement jump variables.

| Variables | Male | | Female | |
|---|---|---|---|---|
| | ICC (± 95%CL) | CV (± 95%CL) | ICC (± 95%CL) | CV (± 95%CL) |
| **Mean force (N)** | 0.97 (0.94, 0.98) | 2.7 (2.2, 3.4) | 0.92 (0.86, 0.95) | 4.5 (3.7, 5.6) |
| **Mean velocity ($m.s^{-1}$)** | 0.97 (0.94, 0.98) | 3.4 (2.8, 4.3) | 0.92 (0.86, 0.95) | 4.9 (4.1, 6.1) |
| **Mean power (W)** | 0.95 (0.92, 0.97) | 4.2 (3.5, 5.4) | 0.87 (0.78, 0.92) | 5.7 (4.8, 7.2) |
| **Jump height (m)** | 0.95 (0.91, 0.97) | 6.9 (5.7, 8.8) | 0.90 (0.83, 0.94) | 8.2 (6.8, 10.3) |
| **Flight time (sec)** | 0.97 (0.94, 0.98) | 2.8 (2.3, 3.6) | 0.95 (0.92, 0.97) | 2.8 (2.3, 3.5) |
| **Take-off velocity ($m.s^{-1}$)** | 0.96 (0.92, 0.98) | 3.2 (2.6, 4.0) | 0.90 (0.83, 0.94) | 4.0 (3.4, 5.1) |

*ICC = intraclass correlation coefficient, CL = confidence limits, CV = coefficient of variation*

The analysis of variance across all F-v variables identified no significant effects based on position except for relative $F_0$ ($F = 4.41$, $p = 0.04$, ES= −0.80), Significant effects between sex were reported for most F-v variables ($F \geq 4.53$, $p \leq 0.04$, ES≥ 0.76), excluding absolute and relative $S_{FV}$. A significant position-sex interaction effect was also evident for $F_0$ and mean force produced across CMJ trials ($F \geq 4.34$, $p \leq 0.04$, ES≥ 0.88). Furthermore, post hoc comparison revealed that greater absolute and relative force differences were observed between female positional groups when compared to males. Table 4.4 highlights descriptive statistics for positional group and sex. Regarding male athletes, significant differences were evident for $v_0$ with attackers demonstrating higher values than defenders (6.64%, $p \leq 0.05$, ES = 1.11). Female attackers showed significantly higher values for both absolute and relative $F_0$ (14.59-15.43%, $p \leq 0.01$, ES ≥ 1.35), when compared to defenders. Figure 4.4 highlights the differences in sex and positional groups in F-v and power-velocity (P-v) characteristics. Male attackers demonstrated a more ‘velocity-oriented’ profile compared to defenders due to significant differences in $v_0$ ($p \leq 0.05$, ES: 1.11) however differences in absolute and relative $F_0$ ($p \leq 0.01$, ES = 1.39) led to female attackers displaying a ‘force-oriented’ profile in comparison to defenders. Non-significant moderate effects was reported for $S_{FV}$ (Es = 0.73) and $P_{MAX}$ (ES = 0.93) for male and female positional groups respectively (Figure 4.5).

**Table 4.4.** Descriptive statistics and mean differences between positional groups across all loads in force-velocity and countermovement jump variables.

| Variable | Males | | | | | Females | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Attackers | Defenders | Mean difference (±95%CL) | Mean % difference | ES (90% CI) | Attackers | Defenders | Mean difference (±95%CL) | Mean % difference | ES (90% CI) |
| **Absolute $F_0$ (N)** | 3085.18 ± 309.64 | 3079.48 ± 484.44 | 5.70 (-430.28, 441.68) | 0.18 | 0.01 (-1.36, 1.39) | 2368.09 ± 297.44 | 2002.62 ± 234.19 | 365.47 (89.83, 641, 09) | 15.43** | 1.35 (0.20, 2.50) |
| **Relative $F_0$ ($N.kg^{-1}$)** | 40.29 ± 2.02 | 40.03 ± 5.03 | 0.26 (-3.84, 4.37) | 0.64 | 0.07 (-1.09, 1.23) | 36.51 ± 2.78 | 31.18 ± 4.73 | 5.33 (1.12, 9.53) | 14.59** | 1.39 (0.24, 2.54) |
| **Theoretical maximal $v_0$ ($m.s^{-1}$)** | 3.31 ± 0.17 | 3.09 ± 0.20 | 0.22 (0.009, 0.42) | 6.64* | 1.11 (-0.08, 2.31) | 2.72 ± 0.50 | 2.87 ± 0.40 | 0.15 (-0.62, 0.32) | 5.51 | -0.31 (-1.35 0.72) |
| **Absolute $P_{MAX}$ (W)** | 2555.07 ± 257.83 | 2398.95 ± 482.90 | 156.12 (-258.99, 571.23) | 6.11 | 0.41 (-0.98, 1.81) | 1589.43 ± 198.62 | 1433.43 ± 235.06 | 156.00 (-72.15, 384.16) | 9.81 | 0.72 (-0.34, 1.78) |
| **Relative $P_{MAX}$ ($W.kg^{-1}$)** | 33.45 ± 3.08 | 31.12 ± 5.21 | 2.33 (-2.26, 6.92) | 6.96 | 0.54 (-0.62, 1.71) | 24.68 ± 3.63 | 22.06 ± 1.33 | 2.62 (-0.24, 5.51) | 10.61 | 0.93 (-0.15, 2.03) |
| **Absolute $S_{FV}$ ($N.s^{-1}.m^{-1}$)** | -933.69 ± 120.35 | -991.97 ± 128.55 | 58.28 (-75.25, 191.82) | 6.24 | 0.46 (-0.90, 1.84) | -915.93 ± 317.01 | -712.88 ± 164.96 | 203.05 (-465.29, 59.20) | 22.16 | -0.78 (-1.86, 0.28) |
| **Relative $S_{FV}$ ($N.s^{-1}.m^{-1}.kg^{-1}$)** | -12.16 ± 0.53 | -12.92 ± 1.41 | 0.76 (-0.38, 1.90) | 6.25 | 0.73 (-0.59, 2.05) | -13.97 ± 3.69 | -11.22 ± 3.34 | 2.75 (-6.39, 0.88) | 19.68 | -0.77 (-1.85, 0.29) |
| **Mean force (N)** | 1843.44 ± 210.09 | 1808.64 ± 285.63 | 34.80 (-346.21, 201.47) | 1.88 | -0.28 (-1.18, 0.61) | 1386.51 ± 111.71 | 1296.68 ± 157.50 | 89.83 (-102.49, 210.81) | 6.47 | 0.37 (-0.66, 1.42) |
| **Mean velocity ($m.s^{-1}$)** | 1.35 ± 0.09 | 1.26 ± 0.12 | 0.09 (-0.09, 0.15) | 6.66 | 0.26 (-0.50, 1.04) | 1.09 ± 0.09 | 1.04 ± 0.02 | 0.05 (-0.007, 0.14) | 4.58 | 0.93 (-0.15, 2.02) |
| **Mean power (W)** | 2380.04 ± 255.64 | 2226.28 ± 483.13 | 153.76 (-464.24, 393.29) | 6.46 | -0.08 (-0.98, 0.81) | 1466.88 ± 135.28 | 1327.52 ± 156.03 | 139.36 (-35.40, 287.57) | 9.50 | 0.82 (-0.25, 1.89) |
| **Jump height (m)** | 0.33 ± 0.04 | 0.29 ± 0.04 | 0.04 (-0.04, 0.30) | 12.12 | 0.23 (-0.74, 0.92) | 0.22 ± 0.03 | 0.21 ± 0.02 | 0.01 (-0.01, 0.04) | 4.54 | 0.46 (-0.58, 1.51) |
| **Flight time (sec)** | 0.50 ± 0.03 | 0.48 ± 0.04 | 0.02 (-0.04, 0.05) | 0.04 | 0.17 (-0.60, 0.96) | 0.42 ± 0.03 | 0.41 ± 0.01 | 0.01 (-0.01, 0.03) | 2.38 | 0.31 (-0.72, 1.35) |
| **Take-off velocity ($m.s^{-1}$)** | 2.52 ± 0.17 | 2.40 ± 0.16 | 0.12 (-0.17, 0.25) | 4.76 | 0.43 (-0.68, 1.55) | 2.06 ± 0.16 | 2.01 ± 0.10 | 0.05 (-0.08, 0.20) | 2.42 | 0.44 (-0.60, 1.49) |

** $p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$, CL: confidence limits, ES: effect size, CI: confidence interval*

Significant mean differences were also evident between males and females for mean force, velocity, and power variables, along with CMJ variables including jump height, flight time and take-off velocity (12.81-40.58%, ES ≥ 1.10, p ≤ 0.001).

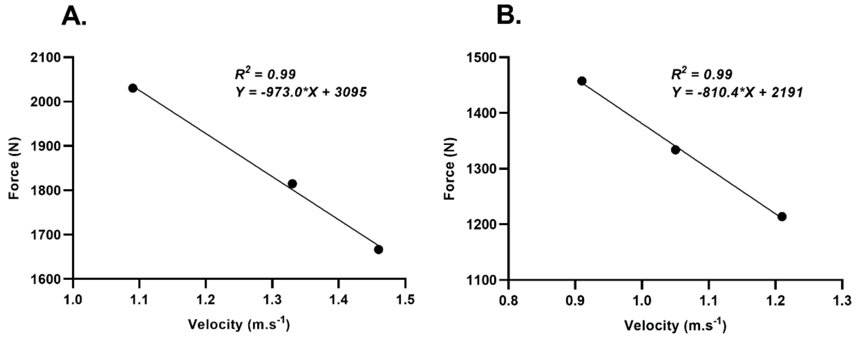


**Figure 4.1.** Linearity of the force-velocity profile across countermovement jump loading parameters. A: males; B: females.

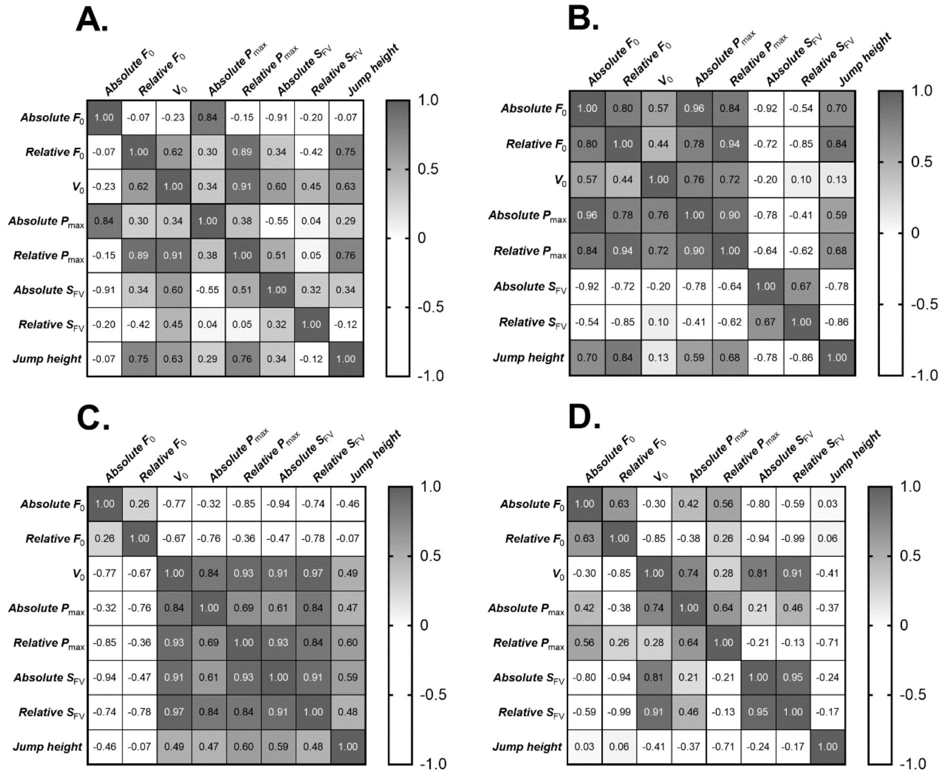


**Figure 4.2.** Correlation matrices of force-velocity and countermovement jump variables between sex and positional group. A: male attacker; B: male defender; C: female attacker; D: female defender.

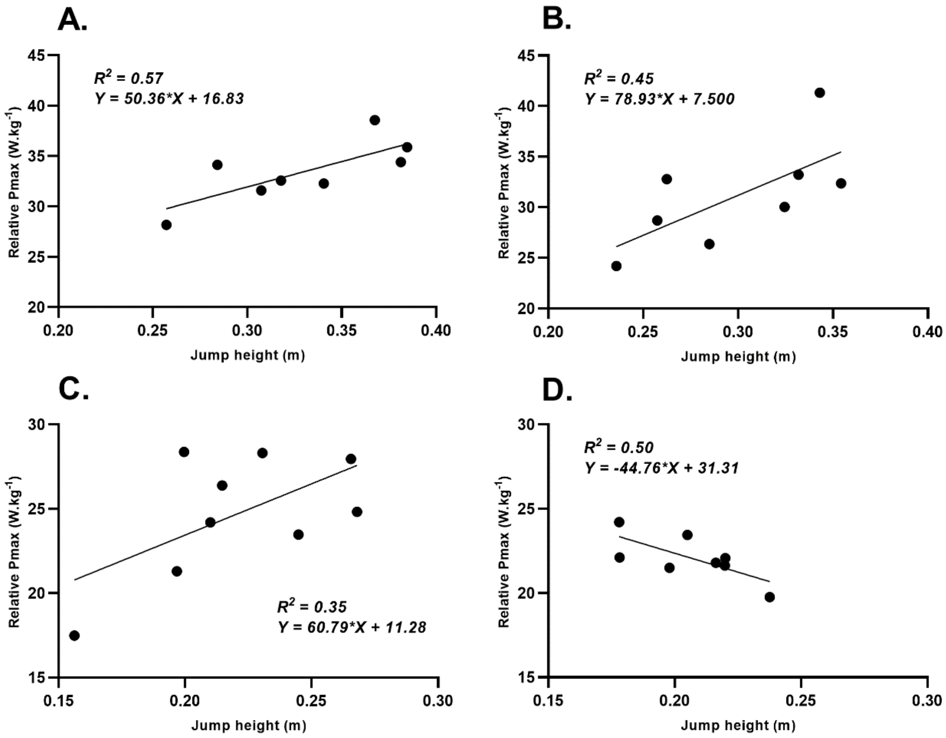


**Figure 4.3**. Linear regression model showing the relationship between jump height (metres) and relative maximal power (W.kg$^{-1}$) between sex and positional group. A: male - attackers; B: male - defenders; C: female – attackers; D: female - defenders.

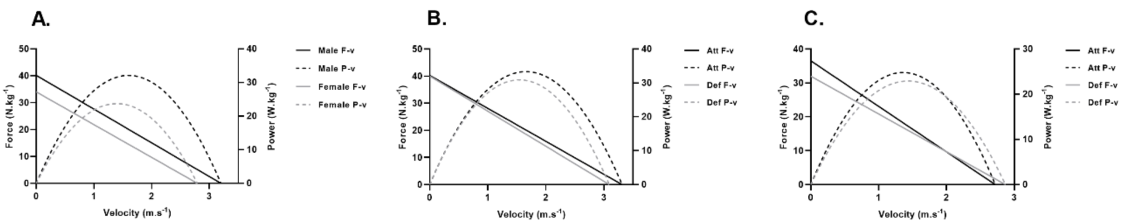


**Figure 4.4**. Mean force-velocity profiles from the countermovement jump loading protocol. A: between sex; B: males; C: females. F-v = force-velocity, P-v = power-velocity. Att = attacker, Def = defender.

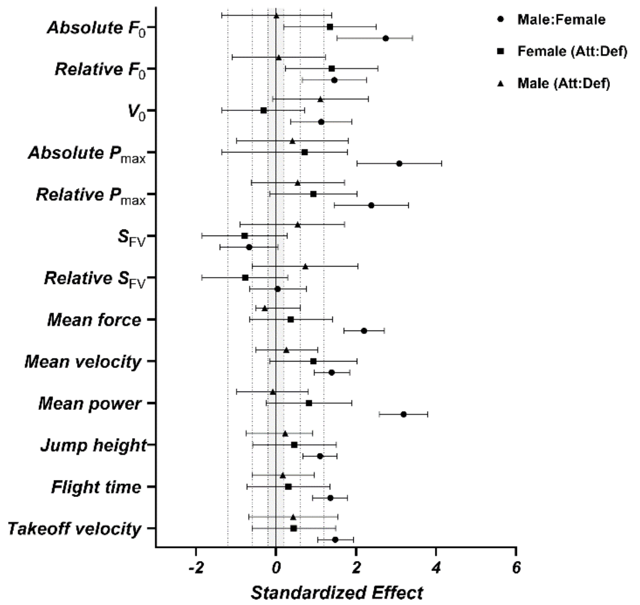


**Figure 4.5**. Standardized effect sizes (90% confidence intervals) in force-velocity and countermovement jump characteristics between sex and positional group.

## Discussion

The purpose of this study was to identify the relationship(s) between sex, positional demands, and vertical F-v profiles in field hockey players to improve the individualization of training interventions by physical preparation coaches. To the authors knowledge, this is the first study to report on the sex-specific associations of the vertical F-v profile with positional demands in field hockey. The main findings of this study indicate that overall, (1) F-v characteristics and positional demands appear to be sex-specific suggesting different strength and conditioning strategies are likely required to improve mechanical output, (2) the relationship between sex and force production during CMJ actions is positional dependent, and (3) male players display a more enhanced F-v profile likely due to musculotendinous and structural differences between sexes.

The acceptable relative (ICC) and absolute (CV) reliability measures (Table 4.3) of this investigation suggests within this population of field hockey players, a three-point loading protocol provides reliable data (Figure 4.1) to establish a linear F-v relationship in a loaded CMJ action. Previous research using a two-point method, an unloaded jump and a heavy load of approximately 75-100% of a participants' body mass, has highlighted this approach to assessing force, velocity and power capabilities of the lower limbs to be reliable and valid (ICC≥ 0.72, CV≤ 12.1%). However, it is recommended to select distal loads due to reliability and validity of measures decreasing with the proximity of applied loads (121). Similar reliability results using a CMJ have been observed when establishing a 2-point load-velocity relationship ICC≥ 0.63, CV≤ 7.30%) (261), with researchers highlighting the quick and safe nature of evaluating neuromuscular characteristics with this approach compared to a multiple load assessment.

In line with our first hypothesis, due to the greater demands for high-speed running and sprint efforts (118, 167) and despite the orientation for force being directed vertically during testing, we postulated attackers would display greater velocity characteristics than defenders. This hypothesis was confirmed in male subjects only, with both positional groups displaying similar levels of absolute and relative $F_0$, however attackers displayed higher a $v_0$, thereby creating a more 'velocity-oriented' profile (Figure 4.4). The differences observed in male subjects highlights the positional F-v requirements of attackers to produce and express force at high velocities. Research from elite level men's field hockey (167) supports these findings, where attackers performed more high-speed running meters compared to defenders (-26.6 ± 8.2%, ES = -2.43), while during under-18 competition, attackers covered approximately 29% more distance (≥ 380m) during gameplay at ≥ 24.7 km/hr compared to defenders.

When comparing female positional groups, our hypothesis did not agree with the findings. Female attackers presented higher levels of absolute and relative $F_0$, therefore displaying a more 'force-oriented' profile and defenders a more 'velocity oriented' profile. Between female positional groups, the differentiating factor was therefore the ability produce and express force at low velocities. In elite women's hockey, significant differences have not been reported between positional groups in high-velocity and high-acceleration efforts up to distances of 20-meters (118), suggesting our results may not be unusual and may infer game dynamics within women's field hockey differs to that of their male counterparts. Previous research focused on women's field hockey identified attackers performed 21 high velocity actions and 16 acceleration actions from 6-20m, whereas defenders performed 19 and 13 high velocity and accelerations actions over the same distance respectively, suggesting the mechanical demands are similar between positional groups (118). However, midfielders were also included as a sub-category in this study which may have distorted the utility of comparing results to those found within this study. Although the movement characteristics of positional demands within male and female field hockey research appear to be similar, we must also be careful inferring data between competitions and ability levels.

Given the significant differences reported for F-v characteristics, along with mean differences between other F-v and CMJ variables, it raises an interesting question as to what type of training each positional group should be involved in to improve mechanical performance based on the F-v characteristics? If force production at high velocities is a key requirement of field hockey players i.e., male attackers, strength and conditioning coaches should aim to support the mechanical characteristics of the position and prescribe exercises which develop or expose players to this quality such as assisted jumping (214) and sprinting actions (337). Whereas, if force production at low velocities is a characteristic of positional play i.e., female attackers, then exercises which require the player to express force at a slower velocity such as resisted sprint training (241) or back squat (64) at higher percentages of one repetition maximum, would be useful to prepare for the positional demands of gameplay. Similar studies aimed at improving jump performance, have demonstrated individualized training based on F-v characteristics was attributed to significant changes in the performance outcome compared with a non-individualized, traditional resistance training approach (105, 172, 174).

Further to our first hypothesis, despite not achieving significance ($p \geq 0.07$), large mean differences in relative $P_{MAX}$ (6.96-10.61%) were evident between positional groups (Table 4.4 and Figure 4.4). Previous research (212) with other team sport athletes has highlighted maximal power in jumping ($r = 0.84$) and sprinting ($r = 0.99$) (285) actions strongly correlated with its associated performance outcome, which is supported in this study by small differences in jump height. However, the mechanisms driving $P_{MAX}$ characteristics appear to differ between sexes due to different combinations of force and velocity. Correlation coefficients between relative $P_{MAX}$ and jump height for male ($r \geq 0.68$) and female ($r \geq -0.71$) positional groups (Figure 4.3) are similar to previous studies (201), however greater relative $P_{MAX}$ values are evident in both attacking groups and would seem advantageous during short sprint actions on the field (i.e., acceleration actions). Previous findings (285) support this where it is highlighted when attempting to improve maximal external power during sprinting, relative horizontal $F_0$ is of greater importance to sprint efforts <15-meters, i.e., force-oriented profile, whereas sprint efforts which exceed 15-meters are more reliant on $v_0$, i.e., velocity-oriented, which appears to be reflected in position-specific time motion analysis. Although female positional groups reported F-v characteristics which differ from their male counterparts, this may be explained through differences in tactics, technical abilities and overall skill level of the players as this has been shown to influence mechanical demands (340). This is an interesting finding for practitioners and compared to solely using time-motion analysis to understand and quantify the on-field game demands of sex and positional groups in field hockey, it may identify a new approach for individualizing training to improve $P_{MAX}$ based on F-v characteristics.

Regarding our second hypothesis, we aimed to determine and compare the vertical F-v profile between men and women competing at the same level in club field hockey. In line with literature regarding sex differences and mechanical variables (124, 189, 326), our results demonstrate males showed an overall more enhanced F-v profile due to higher values of both relative $F_0$ and $v_0$ (Figure 4.4: A), plus showed significantly superior CMJ variables at the same loads relative to bodyweight. When comparing sexes, large effect sizes were reported for absolute $F_0$ and $P_{MAX}$ (Figure 4.5) which were likely due to musculotendinous structural characteristics and differences between sex (186, 193). Although specific to sprint F-v characteristics, previous comparisons between males and females in soccer, a similar field sport, found the ability to produce force at high velocities i.e., $v_0$, was a limiting factor for female subjects (170). Furthermore, studies on high level sprint athletes identified significant differences in sprint mechanical properties (15-46%, $ES \geq 1.98$, $p \leq 0.01$), with greater differences observed for $v_0$ than $F_0$ between males and females, along with moderate correlations evident between lower limb muscle and sprint outcomes (259). Differences in force-time characteristics between sexes during the CMJ has also previously been shown due to higher relative peak concentric force, concentric impulse and eccentric rate of force-development, therefore leading to increased vertical velocity at take-off; the key determinant in jump height (221). These findings were supported in this study with males demonstrating a 23.3% greater take-off velocity compared to females. It has been proposed changes to negative centre of mass displacement (i.e., countermovement squat depth) between sexes as a key determinant of CMJ performance (221). Despite not reporting all kinematic jump variables, as it was not the primary focus of this study, structural differences including segmental lengths and muscle volumes may further explain sex differences between F-v profiles, however force-time characteristics are proposed to be important also (221, 259).

When analyzing the performance outcome between sexes, male subjects displayed a 31% mean difference in jump height compared to females, which is a similar difference to previous studies (25-33% difference) and supported in the data due to higher relative vertical ground reaction forces (141, 193). Differences observed between F-v characteristics and jump height highlights a greater reliance on relative $F_0$ in male subjects ($r \geq 0.75$). These observations were not made with female subjects ($r \geq -0.07$) highlighting potential sex-differences in jump strategy as external load increases (221), while also inferring training design to increase $P_{MAX}$ between groups would likely be sex-specific. Lower correlations between jump height and $P_{MAX}$ as observed in the female cohort may also be explained in reference to variations in countermovement depth, one's own body mass independent of strength levels and heterogenous individual F-v profiles (162, 238). Furthermore, it has been reported approximately only 40-80% of differences in jump performance can be explained via differences in $P_{MAX}$, suggesting the results in this study may not be atypical (279). The training history, ability level and age of subjects in this study may also present potential interactions with covariant variables, therefore creating a level of uncertainty when attempting to link neuromuscular capability with jump performance (279). Therefore, this further supports the utility of using a F-v profile to understand mechanical variables rather than performance outcomes such as jump height to infer mechanical characteristics of athletes.

In other movement tasks, the linear relationship between force and velocity (i.e., $S_{FV}$) has been shown to be more individual (139) than sport specific suggesting mechanical demands at each position group in field hockey may not fully explain the underpinning mechanisms of jump performance. Although $S_{FV}$ differences were evident between attackers and defenders (i.e., force or velocity oriented), it may also be the case of athletes or coaches selecting positions on the field which match their biomechanical strengths and avoiding positions which may highlight a weakness. For example, male athletes who can express force at low velocities but limited in their ability to express force at high velocities may choose to position themselves in the defensive half of the field to ensure their biomechanical limitations match the lower demand of high intensity actions at this end of the pitch. Nonetheless, irrespective of the initial $S_{FV}$, interventional approaches in jump and sprint studies have highlighted the adaptability of the $S_{FV}$ to respond to targeted training i.e., high force training addressing a force deficit (172, 175, 195), suggesting that individual F-v characteristics should always be a consideration when determining training interventions.

Overall, there were several strengths to this cross-sectional study. Firstly, there is a paucity of research investigating mechanical demands within field hockey and therefore this study adds new reference data for practitioners. Secondly, despite attackers and defenders essentially performing the same tasks in both men’s and women’s field hockey (i.e., moving the ball forward for an attacking play on goal, or defending the opposing team’s attack on goal), the findings suggest physical preparation coaches working with male and female players should design training programmes to reflect the different mechanical demands required in each field position. Finally, this study provides a suggested training design framework for attackers and defenders to focus on during their preseason period, plus also highlights the utility of vertical F-v profiling within this field hockey context.

There were some limitations in the current study identified by the authors. F-v profiles created using only three incremental loads (bodyweight + two external loads) and the proximity of the loads in reference to each other and the axis intercepts ($F_0$, $v_0$) may limit the findings. Although the mechanical variables in the three-point loading protocol used this study were shown to be reliable between sexes (ICC: 0.87-0.97, CV% 2.7-5.7), the highest external added load, body mass + 50% externally added mass relative to body mass, was likely not distal enough across the F-v spectrum to provide a true representation of $F_0$ capabilities. Concerns with linear regression models using moderate forces to predict characteristics at high forces have previously been raised (1). Despite this, external loads in this study were selected due the ability level and resistance training competency of the subjects, plus provide a safer expression of force for subjects. Furthermore, if a greater duration of time was allocated to testing, a multiple-point F-v assessment could have been performed therefore providing more distal F-v characteristics (123, 261). Secondly, the cross-sectional approach and competition level of subjects used in this study may hinder the transfer of findings to higher level field hockey athletes. Although inferences were made between time-motion analysis of elite level players and F-v characteristics of club-based players in this study, exploration of F-v profiles in national or international level field hockey athletes and creating individualized training interventions to optimize mechanical characteristics for specific positional groups would further research in the field.

One final limitation may be sample size of the study, which may reduce statistical power for some variables and increase the margin of error, which can affect results or interpretation to higher level field hockey athletes.

## Conclusions

Understanding the relationships between sex and positional demands in field hockey athletes appears to identify vertical F-v profiles can provide new insight about individualizing strength and conditioning programs based on mechanical characteristics. Based upon the findings of the present study, when analysed by positional group, male attackers displayed a more 'velocity-oriented' profile compared to defenders, whereas female attackers displayed a more 'force-oriented' profile in comparison to defenders. The significant differences evident between male players suggests the positional F-v requirements of attackers is their ability to express force at high velocities, however between female positional groups, the ability to produce and express force at low velocities differentiates attackers from defenders, thereby highlighting the dominant mechanical characteristic underpinning expression of maximal power at each position. Between sexes, males displayed an overall more enhanced F-v profile likely due to musculotendinous and structural differences. Overall, we recommend practitioners working with field hockey players to utilize a range of loads and exercises which span the F-v continuum however account for specific F-v differences between positional group and sex within the training program. We conclude that the F-v profile assessment is acceptable to distinguish between positional group and sex in club-based field hockey athletes and provides guidance for training interventions to enhance mechanical characteristics.

## PRELUDE

A key finding of the narrative review (Chapter 2) was the overall lack of consensus whether mechanical characteristics transfer between human movements and more specifically whether the orientation of movement influences this relationship. Chapter 3 quantified the reliability and validity of using a hexbar to determine jump-based mechanical characteristics, whereas Chapter 4 extended on this research demonstrating the utility of this data to inform training and programme design for field hockey athletes. However, limited research exists investigating the relationships between jump and sprint mechanical characteristics in field hockey athletes. With this knowledge, coaches could use mechanical profiling methods interchangeably and prescribe physical preparation interventions to assess neuromuscular function plus mechanical strengths and weaknesses by performing one F-v assessment only. Therefore, the primary aim of the study was to analyse the relationships and mechanical transfer of characteristics in jumping and sprinting actions using F-v profiling methodology in field hockey athletes. Second, the aim was to analyse the influence of force and velocity, as predictor variables for explaining variability in jump and sprint performance (i.e., jump height, 30m sprint time) from both F-v profiles. We hypothesized that limited transfer would exist between matched mechanical characteristics in jump and sprint profiles due to the specificity of the movement task and variability in performance would be explained by the same mechanical characteristic. This chapter provides coaches with insight as to whether both profiling methods are necessary to inform future training interventions.

# CHAPTER 5: STUDY 3

## Investigating vertical and horizontal force-velocity profiles in club-level field hockey athletes: Do mechanical characteristics transfer between orientation of movement?

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**Statement of co-authorship**: All authors were involved in formulating the concept and design of the study. Dylan Hicks and Roland van den Tillaar conducted the data collection. DH conducted the analysis and completed the initial draft of the manuscript. All authors edited multiple revisions of the manuscript.

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**Abstract**

To inform physical preparation strategies in field hockey athletes, this cross-sectional study investigated the transfer of mechanical characteristics in different force-vectors and determined the correlations between vertical and horizontal F-v profiles and performance outcomes (i.e., jump height, sprint time). Thirty-one club-level field hockey athletes (age: 23.1 ± 4.3yrs, body mass: 70.6 ± 10.3kg, height: 1.72 ± 0.09m) performed vertical F-v profiles by completing countermovement jumps at three incremental loads (bodymass[BM], BM+25% externally added mass relative to BM, BM+50% externally added mass relative to BM), and horizontal F-v profiles by performing maximal 30-meter sprint efforts. When comparing matched mechanical variables between F-v profiles in each force orientation, small to moderate significant correlations r = (0.37−0.62, $p \leq 0.03$) were observed for relative theoretical maximal force ($F_0$), power ($P_{MAX}$) and theoretical maximal velocity ($v_0$). The performance outcomes of both F-v profiles highlighted a large, significant negative correlation ($r = -0.86$, $p = 0.001$) between variables. Multiple linear regression analysis of F-v profiles identified $F_0$ and $v_0$ accounted for 74% and 94% of the variability in jump height and sprint time respectively; however, $v_0$ appeared to be a greater predictor of both performance outcomes. Due to the significant relationships between variables, the results of this study suggest vertical and horizontal F-v profiling may explain the same key lower-limb mechanical characteristics, despite the orientation of the movement task. With club-level field hockey athletes, coaches could potentially use mechanical profiling methods interchangeably to prescribe physical preparation interventions, however for greater neuromuscular and mechanical insight, it is likely worthwhile to assess mechanical strengths and weaknesses in both force-vectors.

## Introduction

Field hockey is a team-based sport which relies on skills, team tactics and strategy but also has strong requirements of high-intensity movement demands (167). In elite men's and women's field hockey, typical distances covered during high-velocity and high-acceleration efforts are approximately 10−20-meters thereby relying on the player to express their lower body mechanical characteristics including force, velocity, and power (118, 167, 343). One neuromuscular diagnostic assessment which can be utilized to describe mechanical limits of the neuromuscular system in jumping and sprinting actions is known as F-v profiling. Despite typical team sport strength, power and fitness test batteries providing quantitative outcome measures of performance (i.e., jump height and sprint time)(333), these fail to explain the underpinning characteristics contributing to performance. Whereas F-v profiling models and describes mechanical characteristics across the entire F-v continuum thereby providing practitioners with actionable data to inform on and on and off-field training interventions. To date, most studies in field hockey have relied on time-motion analysis (i.e., global positioning systems) to quantify different physiological demands during competition in an attempt to prepare players for match demands (167, 208, 209, 219, 340), however, there is limited information about mechanical characteristics required in the sport and how this information could be utilized to inform monitoring and physical preparation strategies (242).

Mechanical profiling in other team sports including soccer and netball have described the underpinning mechanical characteristics of jump (i.e., vertical force vector) and sprint performance (i.e., horizontal force vector), using the same three key variables; theoretical maximal force ($F_0$), theoretical maximal velocity ($v_0$), and theoretical maximal external power ($P_{MAX}$), plus the performance outcome (i.e., jump height and sprint time). These variables describe the F-v and power-velocity (P-v) relationships of each action.

Vertical F-v profiles determine jump-specific mechanical characteristics of the propulsive phase of a loaded or unloaded countermovement or squat jump (121) from the inverse dynamics of the centre of mass (283) or ground reaction force (GRF) using force plates (122), while horizontal F-v profiles provide sprint-based mechanical characteristics derived from modeled velocity-time (or position-time) data of maximal effort sprint accelerations using inverse dynamics (286). Furthermore, analyzing the mechanical relationships which exist between actions in field hockey players would therefore identify a level of *mechanical transfer*.

When exploring mechanical transfer (i.e., matched variables between each action [vertical/horizontal directed force production]) between vertical and horizontal based actions in amateur, national and elite level team sports (113, 174, 180, 361), research has demonstrated maximal external power showed the strongest significant relationship ($r$ = 0.40−0.75, $p \leq 0.04$) between jumping and sprinting actions (107, 180, 212, 305, 317), however this is yet to be explored in field hockey. Despite strong associations with external maximal power, force ($r$ =-0.12−0.58) and velocity ($r$ =-0.31−0.71) demonstrated trivial to moderate, and often non-significant mechanical transfer between actions, potentially highlighting greater independent neuromuscular and physiological characteristics of these two variables (281). Previous research studies (174, 212, 317) suggested the performance level of the athlete, training and chronological age, homogeneity of participants, sport and position influenced the mechanical relationships between matched variables, but a consensus was not reached on the *transference of training effect* (299). In addition, it is of interest to strength and conditioning coaches to understand, (1) whether both vertical and horizontal F-v profiling assessments are necessary to understand the current mechanical characteristics of the athlete, and (2) whether mechanical characteristics are independent of orientation of force and therefore require specific physical preparation training interventions to improve neuromuscular output.

Training studies investigating the development and transfer of strength and power adaptations between exercise types have typically focused on vertical force and power production and sprint performance (13, 56, 204, 205, 269, 361). The rationale for using exercises oriented vertically (i.e., loaded jumps) to improve performance in exercises oriented horizontally (i.e., sprinting) assumes that improvement in absolute GRF production will positively transfer between both actions. For example, significant negative correlations in team sport and sprint athletes have been reported for relative squat strength and sprint times between 5-60 meters ($r \geq -0.55$) (56, 57), while the level of one repetition-maximum (1-RM) in the back squat relative to body mass correlated strongly with lower sprint time (<36.6m) and increased vertical jump height ($r \geq 0.78$)(216, 357). Barr et al. (13) also reported greater levels of strength in one repetition maximum power clean and front squat positively influenced sprint kinematics ($r = 0.70$, $d = 0.6-0.81$) in elite rugby players. Despite evidence identifying relationships between force production and performance outcomes in the vertical and horizontal orientation, the underpinning mechanical determinants of performance in each orientation must be considered. Vertical impulse (force*time) is the primary variable influencing take-off velocity and therefore jump height (332), whereas in sprinting, the athlete's mechanical effectiveness to produce and apply a greater ratio of antero-posterior GRF, compared to total GRF, across each ground contact as running velocity increases limits sprint performance (150). Furthermore, since mechanical and technical differences in force application exist between both actions, transfer of characteristics should be limited and therefore oppose the force-vector theory (114).

The force-vector theory states that sports skills can be classified based on the direction of force expression relative to the global (world fixed) coordinate frame (58, 114, 202, 367). In this regard, jumping actions would be classified as a vertical movement activity and sprint actions a horizontal movement activity. Despite this, the expression of force between vertical and horizontal actions has been described as similar relative to the local coordinate system of the athlete (114), where both actions rely on lower limb triple extension yet with different muscle recruitment patterns (i.e. knee dominant [quadriceps] vs hip dominant [hip extensors]). Therefore, according to the theory, vertical force expression during a back squat will show greater neuromuscular transfer in unloaded movements such as a vertical jump, yet limited transfer to a horizontal-based movement such as a maximal sprint effort i.e., dynamic correspondence (320). Consequently, this would infer matched mechanical characteristics would show low associations due to the technical application of force into the ground i.e., expressing force vertically versus expressing force horizontally (236).

Therefore, the aim of this study was twofold. First, we analysed the relationships and mechanical transfer of characteristics in jumping and sprinting actions using F-v profiling methodology in field hockey athletes. Second, the aim was to analyse the influence of force and velocity, as predictor variables for explaining variability in jump and sprint performance (i.e., jump height, 30m sprint time) from both F-v profiles. It was hypothesized that (a) limited transfer would exist between mechanical variables and performance outcomes in vertical and horizontal F-v profiles due to the specificity of the movement task (113, 366) thereby adhering to the force-vector theory, and (b) multiple linear regression models should provide similar prediction values to explain variability in performance, as they are based on the same characteristics of the neuromuscular system. The results of this study are expected to inform practitioners working with club-level field hockey athletes about the most appropriate mechanical profiling methodology to inform physical preparation strategies and potentially influence exercise selection to improve jump and sprint performance, plus may also provide neuromuscular reference data for field hockey athletes.

## Methods

### *Subjects*

A power analysis was conducted prior to the study (G*Power 3)(109) using the following test details: 'Correlation: bivariate normal model', an effect size of 0.5, alpha of 0.05 and power of 0.8 (276), which suggested the total sample size of the study should include 29 subjects. Thirty-one club-level field hockey athletes (male n=15: 23.2 ± 4.7 years, body mass 75.6 ± 8.2 kg, and height 1.79 ± 0.06 m; female n=16: 23.1 ± 4.0 years, body mass 64.7 ± 7.6 kg, and height 1.65 ± 0.06 m) volunteered to participate and provided their written informed consent before beginning the study. Inclusion criteria included: subjects involved in club-level sport; a background in resistance training of greater than 12 months; and aged 15-35 years. Exclusion criteria maintained that subjects needed to be six-months free of musculoskeletal injuries which may prevent them performing maximal effort jump squats or maximal effort sprints. If under 18 years of age (males[n=2], female [n=1], the adult guardian acknowledged the participants experience with jumping and sprinting actions and provided written informed consent before beginning the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146).

### *Experimental Design*

This investigation was a cross-sectional study design focussed on the transfer of mechanical characteristics between vertical and horizontal F-v profiles in club-level field hockey athletes. The familiarization period occurred during the pre-season period when participants were engaged in two training sessions per week (1 x on-field hockey session, 1 x running-based conditioning). Gym-based and sprint-based familiarization session were performed with the subjects two weeks prior to the testing date and led by the primary investigator, specifically focussing on jump squats using a hexbar across key loading parameters and maximal effort sprinting over distances between 10-30 meters. as these would be the testing methods for the vertical and horizontal F-v profiles respectively. The environmental conditions observed on the day of testing included: Temperature (min 21.5°C, max 33.0°C, SE winds 13km/h, 1017.5hPA. Vertical F-v profiling was performed approximately 60 minutes prior to horizontal F-v profiling. Testing was performed in this order to limit fatigue when completing sprint efforts.

### *Testing procedures*

#### *Vertical force-velocity profiling*

A warmup consisting of three minutes of metronome paced step-ups, dynamic movements plus a series of sub-maximal and maximal effort countermovement jumps were completed prior to the jumping protocol. All subjects then completed three maximal effort jump trials at three incremental loading conditions; body mass (BM) (LO1), 25% externally added mass relative to BM (LO2) and 50% externally added mass relative to BM (LO3). This approach to F-v profiling was selected as this has been shown to provide reliable and valid data when compared to a multiple point (5-9 loads) approach (121). Upon landing for all loading conditions, subjects were asked to touch down with the same leg position as when they took off, (i.e., with an extended leg and maximal foot plantar flexion). If all requirements were not met, the trial was repeated. During all trials, the research staff made an effort to ensure maximal intent by providing subjects with internal and external verbal cues such as “squat to your preferred depth then rapidly extend your hips, knees and ankles” (222) and “jump towards the ceiling” (136). A two minute of recovery period was taken between trials and 4–5 minute recovery period between different loads (149).

Countermovement jump (CMJ) trials were performed using the high handles of a 15kg free-weight hex bar (or purpose-built polyvinyl chloride [PVC] hexagon equivalent) with subjects standing upright holding the bar off the ground prior to descending into the countermovement jump. Arms remained extended during all CMJ trials. Subjects self-selected the countermovement depth and were not constrained by a box or band, to encourage individual jump strategy (262).

To measure vertical ground reaction force (GRF) data, jump trials were conducted with the subject standing with each foot on a separate portable force plate system levelled on a concrete floor (35cm by 35cm, PASPORT force plate, PS-2141, PASCO Scientific, California, USA). This model of portable force plate has previously been validated and deemed reliable against in-ground laboratory grade force plates (196). Before initiating the jump action, subjects were required to stand stationary at full stature for at least 1-second with their left and right foot on the centre of each force plate, to ensure the weighing phase could be calculated accurately (222). Identification of vertical jump take-off and touch-down was determined using a threshold of vertical ground reaction force equal to 5 times the standard deviation of flight force (i.e., when the force plate was completely unloaded)(222). Movement prior to the initiation of the jump would void the trial and the jump would be repeated. Prior to the next trial, the force plates were zeroed. Vertical GRF was continuously sampled at 1000 Hz for each force plate, with vertical force (Fz)-time data being stored within a local computer.

To determine the jump F-v profile, mean values of force and velocity were determined using unfiltered ground reaction force-time data during the concentric portion of the countermovement jump. Key phases of the countermovement jump were outlined using the force-time characteristics described by McMahon et al. (222). The concentric phase was defined as the point at which centre of mass velocity becomes positive and the athlete begins moving vertically from the lowest point of the countermovement until the point of take-off (222). Mean vertical GRF was calculated by averaging vertical force from the dual force plate system across the time points established for the concentric phase of the jump. The instantaneous vertical velocity across the concentric phase of each jump type was calculated via integration of the centre of mass (COM) vertical acceleration signal over time, via force plate data and then averaged across the concentric phase. Mean system power across the propulsion phase was then determined as the product of mean GRF and estimated mean COM velocity according to the sample rate from both force plates.

F-v variables were established using mean vertical ground reaction force values which were entered into a customised Microsoft Excel spreadsheet as outlined by Garcia-Ramos et al. (123). At each load, the jump trial which recorded the highest take-off velocity (maximum vertical velocity) was used for statistical analyses, since this likely represents the overall maximal capabilities of the neuromuscular system during the jumping action (270). A least squares linear regression model was then applied to the mean force and velocity data to determine the F-v relationship variables. Absolute (N) and relative theoretical maximal force ($N.kg^{-1}$) ($F_0$) and theoretical maximal velocity ($m.s^{-1}$) ($v_0$) were then established as the intercepts of the linear regression model, while absolute (W) and relative theoretical maximal power ($W.kg^{-1}$) were described by the polynomial power-velocity (P-v) relationship (Figure 5.1: A). The F-v data achieved across the three loading conditions describes the absolute ($N.s^{-1}.m^{-1}$) and relative ($N. s^{-1}.m^{-1}.kg^{-1}$) slope of the F-v profile ($S_{FV}$) and is calculated as: $S_{FV} = F_0/v_0$.

*Horizontal force-velocity profiling*

Sprint testing was performed on an artificial turf surface. The standardized warm-up included 5 minutes of light jogging, dynamic running-based drills (i.e., A-skips, high-knees, scissor bounds) and movements, and 4-8 linear accelerations from 10-40m progressing from sub-maximal to maximal. Following the warmup, subjects performed two 30-metre maximal sprint efforts from a 2-point staggered stance (dominant foot forward) wearing typical athletic footwear. To initiate the start of the sprint effort, subjects were given a verbal countdown of "3, 2, 1, sprint". A 5-minute passive recovery period occurred following each sprint to reduce fatigue prior to the next maximal effort.

The MuscleLab™ is a system which uses an optical laser to measure sprint distance over and time and automatically calculates sprint mechanical properties. During each sprint attempt, speed measurements were recorded continuously using a laser gun (CMP3 Distance Sensor, Noptel Oy, Oulu, Finland), sampling at 2.56 KHz (Figure 5.2). The laser was positioned 5 m directly behind the starting position and at a vertical height of 1 m to approximately align with the subject's centre of mass. Testing was performed by R.VT who is experienced using this technology. A polynomial on distance over time was fitted, and automatically resampled over 1000Hz by MuscleLab v10.212.98 (Ergotest Technology AS, Langesund, Norway). The in-built software automatically calculates peak velocity ($m.s^{-1}$), the distance at which peak velocity was reached, peak force per body mass

(N.kg$^{-1}$), peak power per body mass (W.kg$^{-1}$) and the strength–speed factor (ratio of force and velocity capabilities). Graphical representation of the F-v and power-velocity relationships evident in the sprint F-v profile is shown in Figure 5.1: B.

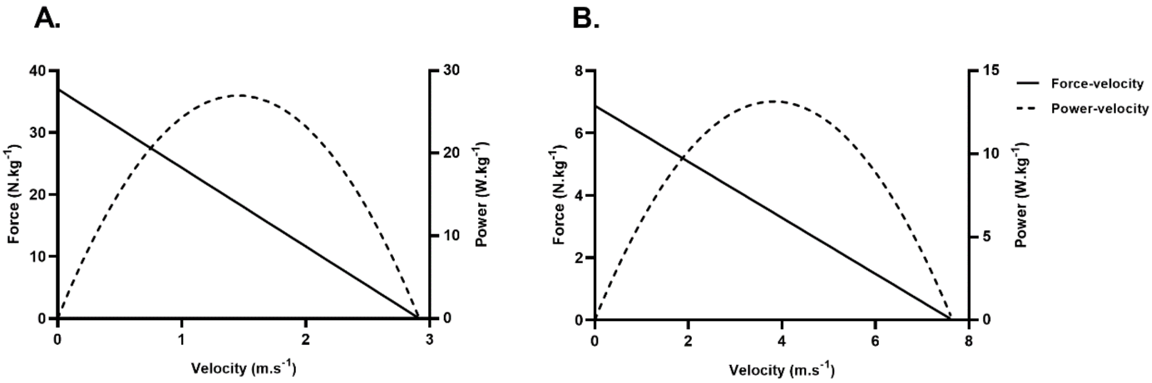


**Figure 5.1.** Mean force-velocity and power-velocity characteristics of field hockey athletes obtained during vertical (A) and horizontal (B) force-velocity profiles.

**Figure 5.2.** MuscleLab$^{TM}$ is a system which uses an optical laser to measure sprint distance over time and automatically calculates sprint mechanical properties.

### *Statistical Analysis*

Statistical analyses on all F-v data were determined from input into custom built Microsoft Excel spreadsheets (154) plus coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages. All descriptive data are presented as mean ± standard deviation (SD) and were assessed and confirmed for normality using the Shapiro-Wilks test. Pearson's product-moment correlation coefficients ($r$) and linear regression models were selected to compare, analyse and determine relationships between matched variables in both profiling assessments (i.e., vertical, and horizontal). Performance outcomes (i.e., jump height and sprint time) were labelled as dependent variables and then analysed with multiple linear regression models using $F_0$ and $v_0$ as independent variables. Relative maximal power ($P_{MAX}$) was not used as an independent variable due to its multicollinearity with other variables. Thresholds for evaluation of Pearson's correlation coefficients ($r$) were quantified using the following scale: (0-0.09, trivial; 0.10-0.29, small; 0.30-0.49, moderate; 0.50–0.69. large; 0.70-0.89, very large; ≥0.90, nearly perfect (155). An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

## Results

Descriptive statistics for all variables between F-v profiling assessment in each force orientation are highlighted in Table 5.1. Correlational data and linear regression analysis of theoretical relative maximal force and power and theoretical maximal velocity for each mechanical profile showed moderate to large, significant correlations ($r$ = 0.38−0.61, $p \leq 0.03$) between jump and sprint F-v variables (Table 5.1, Figure 5.3). Trivial, non-significant relationships ($r = 0.06$, $p = 0.72$) were reported for the $S_{FV}$ between profiling assessments. The performance outcome (i.e., jump height, sprint time) in each orientation showed a significantly large, negative correlation with each other ($r$ = -0.86, p $\leq$ 0.01) (Table 5.2).

When analyzing mechanical characteristics and performance outcomes, jump height showed moderate to large correlations with relative $F_0$, $v_0$ and relative $P_{MAX}$ from the vertical F-v profile ($r$ = 0.63−0.87, $p \leq 0.01$). Thirty-meter sprint time showed moderate to large ($r$ = -0.40− -0.73, $p \leq 0.01$) negative correlations with relative $F_0$, $v_0$ and relative $P_{MAX}$ in the horizontal direction (Table 5.2, Figure 5.4). Moderate to large significant correlations were also reported for performance outcomes using the mechanical variables from the opposite F-v profile (Table 5.2, Figure 5.4) (i.e., relationship between vertical variables and horizontal performance outcome and vice versa). Relative $F_0$, $P_{MAX}$ and $v_0$ in the horizontal direction were significantly correlated with jump height ($r$ = 0.59−0.89, p $\leq$ 0.001), whereas $F_0$, $P_{MAX}$ and $v_0$ in the vertical direction were also significantly correlated with 30-meter sprint time ($r$ = -0.75− -0.94, p $\leq$ 0.001). The slope of the F-v profile in both orientations showed trivial, non-significant relationships with the performance outcomes ($r$ = -0.003 −0.01, $p \geq 0.95$).

Multiple linear regression models for prediction of the performance outcome from each F-v profile identified $F_0$ and $v_0$ accounted for 74% and 94% of the variability of jump height and sprint time respectively (Table 5.3). Both mechanical variables were deemed significant predictors of performance outcomes when modeling jump height and sprint time. Specifically, we found the regression model for the vertical F-v profile predicted $v_0$ would increase jump height (0.12cm) to a greater degree compared to $F_0$ (0.009cm). Similarly, multiple regression model for prediction of sprint time identified $v_0$ (-0.40sec) explained greater sprint performance variability than $F_0$ (-0.11sec).

**Table 5.1.** Descriptive statistics for mechanical variables from vertical and horizontal force-velocity profiles.

| Variables | Abbreviation | Action | Mean ± SD | r (95% CI) | *p* |
|---|---|---|---|---|---|
| **Relative maximal force ($N.kg^{-1}$)** | $F_0$ | Jump | 37.02 ± 5.31 | 0.37 (0.02, 0.64) | 0.03* |
| | | Sprint | 6.88 ± 1.05 | | |
| **Theoretical maximal velocity ($m.s^{-1}$)** | $v_0$ | Jump | 2.97 ± 0.41 | 0.47 (0.14, 0.70) | ≤ 0.01* |
| | | Sprint | 7.69 ± 0.78 | | |
| **Relative maximal power ($W.kg^{-1}$)** | $P_{MAX}$ | Jump | 27.59 ± 5.92 | 0.62 (0.32, 0.79) | ≤ 0.01* |
| | | Sprint | 13.19 ± 3.28 | | |
| **Relative force-velocity slope ($N.s^{-1}.m^{-1}.kg^{-1}$)** | $S_{FV}$ | Jump | -12.70 ± 2.78 | 0.06 (-0.29, 0.41) | 0.72 |
| | | Sprint | 0.90 ± 0.10 | | |
| **Performance outcome (i.e., jump height, sprint time)** | metre | Jump | 0.32 ± 0.08 | -0.86 (-0.92, -0.72) | ≤ 0.01* |
| | sec | Sprint | 4.68 ± 0.41 | | |

**Table 5.2**. Correlation coefficient data between mechanical characteristics and performance outcome from vertical and horizontal force-velocity profiles.

| Variable | Jump Height (m) | |
|---|---|---|
| | *r* | *p* |
| **VTC $F_0$ ($N.kg^{-1}$)** | 0.63 | ≤ 0.001* |
| **VTC $v_0$ ($m.s^{-1}$)** | 0.62 | ≤ 0.001* |
| **VTC $P_{MAX}$ ($W.kg^{-1}$)** | 0.87 | ≤ 0.001* |
| **VTC $S_{FV}$** | -0.003 | 0.98 |
| **HZT $F_0$ ($N.kg^{-1}$)** | 0.59 | ≤ 0.001* |
| **HZT $v_0$ ($m.s^{-1}$)** | 0.89 | ≤ 0.001* |
| **HZT $P_{MAX}$ ($W.kg^{-1}$)** | 0.77 | ≤ 0.001* |
| **HZT $S_{FV}$** | -0.04 | 0.81 |
| **Variable** | **Sprint Time (sec)** | |
| | *r* | *p* |
| **VTC $F_0$ ($N.kg^{-1}$)** | -0.75 | ≤ 0.001* |
| **VTC $v_0$ ($m.s^{-1}$)** | -0.94 | ≤ 0.001* |
| **VTC $P_{MAX}$ ($W.kg^{-1}$)** | -0.88 | ≤ 0.001* |
| **VTC $S_{FV}$** | 0.03 | 0.84 |
| **HZT $F_0$ ($N.kg^{-1}$)** | -0.62 | ≤ 0.001* |
| **HZT $v_0$ ($m.s^{-1}$)** | -0.40 | 0.02* |
| **HZT $P_{MAX}$ ($W.kg^{-1}$)** | -0.73 | ≤ 0.00*1 |
| **HZT $S_{FV}$** | 0.01 | 0.95 |

*VTC = vertical, HZT = horizontal, * =* $p \leq 0.05$

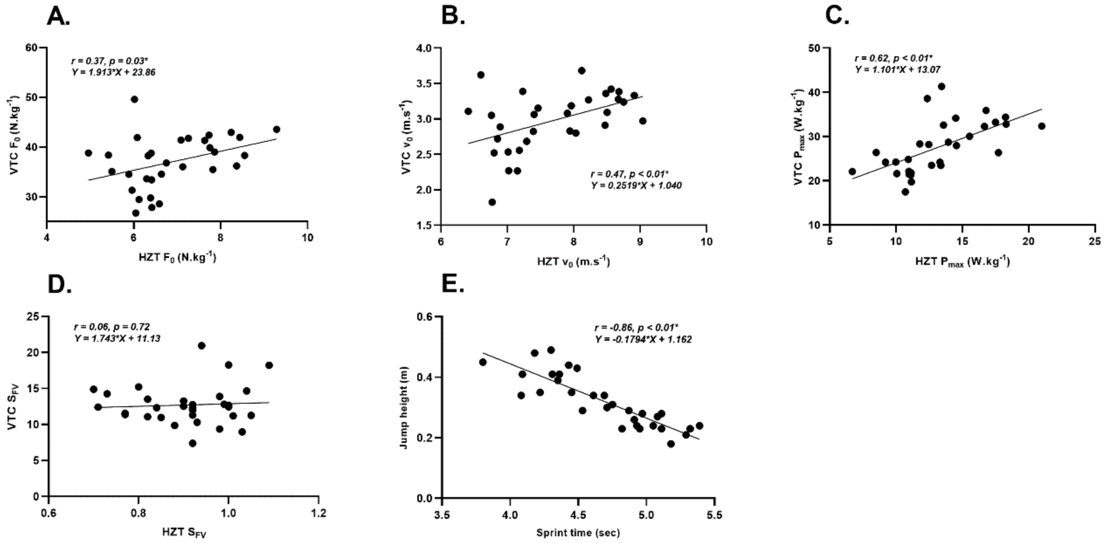


**Figure 5.3.** Linear regression models showing the relationships between matched mechanical variables across vertical and horizontal force-velocity profiles. A: Relative maximal force; B: Theoretical maximal velocity; C: Relative maximal power; D: Slope of the force-velocity profile; E: Performance outcome for each profile. VTC = vertical, HZT = horizontal.

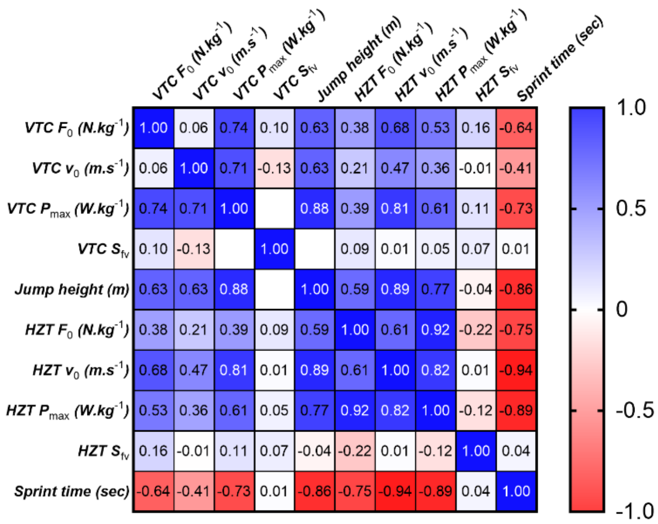


**Figure 5.4.** Correlation matrices of vertical and horizonal force-velocity variables. VTC = vertical, HZT = horizontal.

**Table 5.3.** Multiple linear regression analysis performance outcome predictor variables from vertical and horizontal force-velocity profiles.

| Variable | Jump height (m) | | | | | |
|---|---|---|---|---|---|---|
| | $R^2$ | Coefficient | Standard error | 95% CI | t | *p* |
| | 0.74 | | | | | |
| **Intercept** | | -0.40 | 0.08 | -0.56, -0.24 | 5.04 | <0.0001** |
| **VTC $F_0$ ($N.kg^{-1}$)** | | 0.009 | 0.001 | 0.006, 0.01 | 6.27 | <0.0001** |
| **VTC $v_0$ ($m.s^{-1}$)** | | 0.12 | 0.02 | 0.08, 0.16 | 6.21 | <0.0001** |
| **Variable** | **Sprint time (sec)** | | | | | |
| | $R^2$ | Coefficient | Standard error | 95% CI | t | *p* |
| | 0.94 | | | | | |
| **Intercept** | | 8.58 | 0.18 | 8.20, 8.96 | 45.78 | <0.0001** |
| **HZT $F_0$ ($N.kg^{-1}$)** | | -0.11 | 0.02 | -0.16, -0.06 | 5.02 | <0.0001** |
| **HZT $v_0$ ($m.s^{-1}$)** | | -0.40 | 0.03 | -0.46, -0.34 | 13.30 | <0.0001** |

*VTC = vertical, HZT = horizontal, CI = confidence interval, * $p \leq 0.05$, ** $p \leq 0.01$*

## Discussion

The purpose of this cross-sectional study was to investigate the transfer of mechanical characteristics between vertical and horizontal F-v profiles, analyse F-v variables to explain variability in jump and sprint performance and potentially provide some reference data for field hockey practitioners using mechanical profiling as part of their neuromuscular assessments. Despite various studies providing insight to the intensity of running demands during competition field hockey (118, 167), to the best of our knowledge, this is the first study to analyse mechanical profiling within a field hockey context. We believe the information presented about mechanical profiling in different force orientations suggests within a context of club-level field hockey players, this information can provide strong utility for sports practitioners when developing physical preparation strategies across the field hockey season.

Our key findings are as follows: (a) when comparing matched mechanical characteristics, significant moderate to large relationships are evident between vertical and horizontal mechanical profiles, (b) the performance outcomes (i.e., jump height and sprint time) showed moderate to very large (positive and negative) significant relationships with mechanical variables in both the vertical and horizontal orientation, and (c) furthermore, $v_0$ showed greater utility in explaining the variability in jump and sprint performance compared to $F_0$. Therefore, vertical and horizontal F-v profiles present similar mechanical characteristics and can potentially infer performance outcomes in each force orientation.

In reference to our first hypothesis, we identified matched mechanical characteristics including force, velocity and power demonstrated significant relationships between vertical and horizontal F-v profiles, thereby highlighting a strong *transference effect*. This contradicted our initial hypothesis and previous studies in other team and individual sports (174, 212, 317) which identified limited transfer between matched mechanical characteristics in jump and sprint actions, specifically for $F_0$ and $v_0$. Related research on multi-sport athletes (n=553) (174) reported trivial to large (positive and negative) correlation coefficients for $F_0$: $-0.12 \leq r \geq 0.58$; $v_0$: $-0.31 \leq r \geq 0.71$; $P_{MAX}$: $-0.10 \leq r \geq 0.67$; and performance outcomes: $-0.92 \leq r \geq -0.23$, however no consensus was reached to explain trivial or strong associations or lack of significance between mechanical characteristics. Despite not being confirmed, it has been has proposed the transfer of mechanical qualities is greater for athletes of lower ability levels (174) suggesting training absolute force qualities would positively influence neuromuscular output in all force orientations, which opposes the force-vector theory. At a lower 'training age', the trainability of the athlete is potentially higher therefore non-specific training methods may have greater impact on performance (174). Furthermore, previous studies focussed on the transfer of mechanical qualities between horizontal and vertical actions have also suggested, gender, bodymass, lower limb neuromuscular properties (i.e., intramuscular coordination) and resistance training background may influence the correlation between variables (13, 205, 299, 361), which may be the case in this study. Therefore, for club-level field hockey athletes. these findings highlight physical preparation strategies including exercise selection should likely span the F-v continuum using exercises oriented both vertically and horizontally, regardless the targeted movement pattern (150).

Without identifying results within a field hockey context, an analysis of matched mechanical characteristics across a range of individual and team sports suggests the cohort within this study (Table 5.1) have similar mechanical and performance characteristics in vertical and horizontal F-v profiles as medium level/semi-professional soccer players and low-level sport science students (i.e. amateur) respectively (vertical [VTC] $F_0$: 31.8N.kg$^{-1}$, horizontal [HZT] $F_0$: 6.45N.kg$^{-1}$; VTC $v_0$: 2.88m.s$^{-1}$, HZT $v_0$: 7.60m.s$^{-1}$; VTC $P_{MAX}$:

22.8W.kg$^{-1}$, HZT $P_{MAX}$: 12.2W.kg$^{-1}$; jump height: 0.29m, 20m sprint time: 3.78sec (174). When comparing correlations between matched mechanical characteristics, soccer athletes displayed slightly lower associations than field hockey athletes ($F_0$: $r \leq 0.42$; $v_0$: $r \leq 0.27$; $P_{MAX}$: $r \leq 0.44$; performance outcome: $r \leq -0.59$), whereas sport science students displayed similar matched mechanical characteristics ($F_0$: $r \leq 0.57$; $v_0$: $r \leq 0.48$; $P_{MAX}$: $r \leq 0.78$; performance outcome: $r \leq -0.83$). Greater correlations and similarities between club-level field hockey athletes and sport science students, rather than higher level soccer athletes, is likely explained by the heterogeneity of the population.

Within this study, maximal external power demonstrated the strongest relationship between jumping and sprinting actions highlighting the importance of this mechanical quality to field hockey athletes. Relative to distance, it has been suggested greater intensities and running velocities are achieved in field hockey compared to other field sports such as soccer (343). Samozino et al. (285) recently identified acceleration performance less than 30m largely depends on $P_{MAX}$ and individual mechanical characteristics, further identifying the necessity to develop and express this mechanical quality to be an effective field hockey player. These findings have been supported in similar studies, but not all ($r = 0.27$) (258) involving amateur netball players, academy rugby players, high-level sprint athletes and professionl male and female football players, ($r = 0.40–0.75$) (107, 180, 212, 317), further highlighting the need for power development expression in field and court sports. However, across these studies, most force variables ($F_0$) did not achieve significance ($r \leq 0.27$), thereby demonstrating a greater emphasis on movement velocity capabilities to express maximal external power. This was not the case in this study, as both $F_0$ and $v_0$ achieved significance however stronger associations are evident between movement velocity in both jump and sprint actions.

Non-significant relationships were evident between slope of the jump and sprint F-v profile ($S_{FV}$) suggesting independent characteristics of this mechanical variable (Table 5.2). Although differences in ability level are evident, low correlations between the jump and sprint $S_{FV}$ have previously been reported in elite female soccer players (212) (r =-0.09) and high-level sprint athletes (317) (r =0.17). Previous studies have raised concerns regarding the reliability (ICC: ≤ 0.50, CV%: ≤ 29.3) of the $S_{FV}$ using countermovement and squat jump actions from F-v profiles (199, 336), along with the utility of the mechanical variable to inform performance, however other studies have recently questioned the methodological rigors to obtain reliable data (290).

Regarding our second hypothesis, we aimed to determine whether the same mechanical variable would explain performance variability in each force orientation. Multiple linear regression analysis identified $F_0$ and $v_0$ had a significant influence on jump height and sprint time explaining 74% and 94% of the variance in outcome respectively. When analyzing jump height and sprint time as the dependent variables, vertical F-v regression model coefficients showed $v_0$ had greater effects on performance outcome compared to $F_0$. Similarly, increases in horizontal $v_0$ had a greater effect on reducing sprint time over 30-meters compared to increases in $F_0$. This identifies the underpinning mechanical characteristics explaining the performance outcome is the same between jumping and sprinting actions, thereby confirming our hypothesis. Furthermore, it may also identify this population group exhibits a force-dominant F-v profile and the subjects require greater exposure to maximal movement velocity during training (i.e., sprint training), which would influence the approach to development and expression of maximal power.

From a physical preparation perspective, club-level field hockey athletes could target power development (310) to improve jump height, plus select exercises which target high movement velocities and optimal loads to improve sprint performance (75, 150). Previous studies with elite youth soccer players identified high-velocity training improved adaptations to the high-velocity/low-force end of the F-v continuum, which lead to improved power expression (203). The present study highlighted relative $P_{MAX}$ showed slightly stronger relationships to sprint time than was evident for jump height however the correlations between force and velocity to express $P_{MAX}$ are different between actions (Figure 5.4). The stronger kinematic relationship between relative $P_{MAX}$ and $v_0$ in sprinting compared to jumping is likely due to the necessity to achieve maximal power expression in early acceleration (75) plus the overall duration of the task places a greater emphasis on velocity qualities. Similar $P_{MAX}$ correlations in other population groups including netball, soccer and ballet suggests this relationship may be typical amongst athletes irrespective of their ability level or sport (i.e., novice vs elite) (107, 180, 212, 305, 317).

Overall, this cross-sectional study has several strengths. Although suggestions the magnitude of transfer may be dependent on the task (366) therefore adhering to the force-vector theory and dynamic correspondence (114, 320), this study identifies vertical F-v profiles can potentially infer performance in horizontal F-v profiles and vice versa. Moreover, if practitioners working with field hockey athletes should only choose one F-v assessment to determine mechanical characteristics, the authors of this study recommend horizontal F-v profiling. Despite similar expression of force relative to the local coordinate system of the athlete (114), the technical component of applying horizontally directed force at increasing running velocities during sprinting i.e., mechanical effectiveness (150), typically requires greater segmental coordination (233) than vertical force expression and therefore may provide greater mechanical insight for the practitioner. Finally, there are few studies exploring mechanical profiling in field hockey populations and therefore this adds original knowledge towards biomechanical and strength and conditioning practices within the sport.

There are also limitations in this study which should be acknowledged. Firstly, although significant relationships were evident between vertical and horizontal F-v profiles, a closer analysis of the loads selected in the vertical F-v profile and distance in the horizontal F-v profile may have improved the correlation between matched mechanical variables. For example, stronger relationships with relative $P_{MAX}$ and the vertical F-v profile may exist due to the selected loads which may have optimized external mechanical power (310) for subjects, rather than exposure to loads spanning the F-v continuum (1). Moreover, the slightly greater relationship with $v_0$ than $P_{MAX}$ in the horizontal F-v profile is likely a result of the overall sprint distance and potentially individual subject F-v characteristics. In most team sports, including field hockey, acceleration and sprint distances are generally less than 15-meters where maximal force qualities in the horizontal direction are dominant, whereas velocity qualities are dominant when sprint distances are greater than 15-meters (285, 343). Therefore, the selected sprint testing distance placed a greater reliance on velocity capabilities to achieve a faster 30-meter time. Secondly, the cross-sectional approach, heterogenous population and competition level of participants (i.e., club-level, novice) used in this study may limit findings and transfer of understanding in higher ability athletes (i.e., elite level). Finally, stronger correlations between mechanical characteristics and performance outcomes (i.e., vertical characteristics and horizontal performance outcome, and vice versa) may have been observed due to greater variability in the mechanical dataset compared to previous studies (132). Greater information could be provided to practitioners by analyzing longitudinal changes to the relationships between matched characteristics obtained from mechanical profiles across a competitive field hockey season and determine how this might assist strength and conditioning practice.

## Conclusions

This is the first cross-sectional study to investigate the transfer of mechanical characteristics between vertical and horizontal F-v profiles and performance outcomes in club-level (i.e., novice) field hockey athletes. Matched variables from jump and sprint mechanical profiles revealed significant correlations between force, velocity, and power suggesting they explain similar mechanical characteristics irrespective of force orientation. Relative maximal power demonstrated the greatest correlation to the performance outcome in jumping and sprinting respectively, however the contribution of force and velocity differed between actions. In addition, multiple linear regression models indicated $v_0$ was a greater predictor of jump and sprint performance variability compared to $F_0$. This information may have implications on physical preparation strategies and exercise selection along with identifying which aspect of the F-v continuum to target. Trivial correlations for the vertical and horizontal $S_{FV}$ suggest the linear F-v relationship is unrelated between actions. Overall, strength and conditioning coaches working with club-level field hockey athletes could potentially use mechanical profiles interchangeably to determine current mechanical strengths, weaknesses, and imbalances, yet due to technical differences when expressing force in the horizontal direction, greater mechanical insight may be provided by performing mechanical profiling in both force-vectors.

## PRELUDE

Chapter 4 and chapter 5 used a cross-sectional study design and identified the effectiveness of mechanical profiling in jumping and sprinting actions to differentiate between sex and positional groups in field hockey athletes, plus also identified the level of mechanical transfer between actions and whether profiling methods could be used interchangeably. The results suggested a level of mechanical transference and sprint profiling should be used in favour of jump profiling if selecting only one assessment. Despite previous chapters highlighting key diagnostic information for sport practitioners, there is currently limited research examining the longitudinal effects to the F-v profile in response to specific training methods. This information provides practitioners with the knowledge of how specific training methods influence mechanical characteristics in an athletic population. Therefore, the primary aim of this study was to quantify changes to sprint mechanical characteristics in junior Australian Football (AF) players by using a 7-week combined sprint training methodology (i.e., assisted sprint training and maximal sprint training) which focussed on enhancing the velocity component of the F-v continuum. We hypothesized a combined sprint training methodology would improve sprint mechanical characteristics in unassisted sprinting and create a more velocity-oriented F-v profile compared to maximal sprinting only. This chapter provides coaches with insight to how mechanical characteristics will adapt in response to sprint specific training methods.

# CHAPTER 6: STUDY 4

## The effect of a combined sprint training intervention on sprint force-velocity characteristics in junior Australian football players

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**Statement of co-authorship**: All authors were involved in formulating the concept and design of the study. Dylan Hicks conducted the data collection and analysis and completed the initial draft of the manuscript. All authors edited multiple revisions of the manuscript.

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**Abstract**

Sprint performance in junior Australian football (AF) players has been shown to be a differentiating quality in ability level therefore developing sprint characteristics via sprint-specific training methods is an important aspect of their physical development. Assisted sprint training is one training method used to enhance sprint performance yet limited information exists on its effect on sprint F-v characteristics. Therefore, the main aim of this study was to determine the influence of a combined sprint training intervention using assisted and maximal sprint training methods on mechanical characteristics and sprint performance in junior Australian football players. Upon completing familiarization and pre-testing, twenty-two male junior Australian football (AF) players (age: 14.4 ± 0.3 years, body mass 58.5 ± 10.0 kg, and height 1.74 ± 0.08 m) were divided into a combined sprint training (CST) group (n= 14), and a maximal sprint training (MST) group (n=8) based on initial sprint performance over 20-meters. Sprint performance was assessed during maximal 20-meter sprint efforts via a radar gun (36Hz), with velocity-time data used to derive F-v characteristics and split times. All subjects then completed a 7-week in-season training intervention consisting of maximal sprinting (MST and CST groups) and assisted sprinting (CST only), along with their usual football specific exercises. Moderate to large pre-post within group effects ($-0.65 \leq ES \geq 0.82$. $p \leq 0.01$) in the CST group for relative theoretical maximal force ($F_0$) and power ($P_{MAX}$) were reflected in improved sprint performance from 0-20 meters, thereby creating a more force-oriented F-v profile. The MST group displayed statistically significant pre-post differences in sprint performance between 10-20 meters only (ES = 0.18, p = 0.04). Moderate to high relative reliability was achieved across all sprint variables (ICC=0.65-0.91), except for the F-v slope ($S_{FV}$) and decrement in ratio of forces ($D_{RF}$) which reported poor reliability (ICC=0.41-0.44), while the CST group exceeded the pre-post minimal detectable change (MDC) in most sprint

variables suggesting a ‘true change’ in performance across the intervention. It is concluded that implementing a short-term, combined sprint training intervention consisting of assisted and maximal sprint training methods may enhance sprint mechanical characteristics and sprint performance to 20-meters in junior Australian football players.

## Introduction

High-speed running and sprinting are key requirements in Australian football (AF) (70). Within a junior AF setting, sprint characteristics and performance have been shown to differentiate between ability levels including those drafted and non-drafted into the professional ranks of the sport (i.e., Australian Football League; AFL) (35, 103, 265). Sprint performance (20-meter) is also measured in the standardized test battery for those athletes who attend the annual AFL draft combine (265), therefore exploring sprint characteristics and specific training methods to improve sprint performance in aspiring junior AF players would be useful for practitioners.

Typically, sprint characteristics in team sport fitness batteries, including the AFL, are described by intermediate split times (i.e., 5-meter and 10-meter time) and overall sprint time, thereby providing a quantitative measure of performance (265). However, this approach to sprint assessment is limiting in nature as it does not explain the underpinning biomechanical and neuromuscular mechanisms contributing to performance. More recently, a macroscopic inverse dynamics approach to sprint assessment known as sprint F-v profiling has been utilized in team sport settings to explain and quantify the force, velocity and power characteristics contributing to sprint performance (99, 248, 351). This approach has helped practitioners better understand the individual F-v characteristics of the athlete and the influence mechanical characteristics have on sprint performance. The key mechanical variables obtained from sprint F-v profiles include theoretical maximal force ($F_0$), theoretical maximal velocity ($v_0$) and theoretical maximal power ($P_{MAX}$)(286), each of which characterize independent neuromuscular characteristics.

Training methods to enhance sprint performance are often focussed on applying progressive overload to a component of the F-v continuum via modalities such as resisted sprint training, plyometrics and traditional strength training (101, 143), however no previous research has investigated the effect of using assisted sprint training within a junior AF cohort and its long-term benefit to improving sprint mechanical characteristics. Assisted sprint training is based on overloading the velocity component of the F-v relationship (337) and is a term often used synonymously with overspeed or supramaximal training, where the aim is to create running velocity greater than what can be achieved in unassisted voluntary conditions (190). Seminal studies in assisted sprint training identified supramaximal velocities ($10.36 \pm 0.31$m/s) was significantly correlated with stride rate ($r=0.63$, $p<0.01$), while average net resultant force in the concentric phase correlated with stride length ($r=0.65$, $p<0.01$) (224); this is thought to serve as a specific force indicator in sprinting. It was highlighted by the same authors that electromyography (EMG) increases in lower limb muscles prior to ground contact provided a higher level of muscle stiffness and pre-activation of lower limb muscles was a result of centrally driven recruitment of motor units upon ground contact to withstand supramaximal velocities (224, 226, 227). Collectively, it is suggested that assisted sprint training may provide and additional stimulus for the neuromuscular system during training to achieve higher running velocities when unassisted (225).

Assisted sprint training methods include running downhill (97), using a horizontal pulley system (44, 190), a portable robotic resistance device e.g. 1080 Sprint™ (195), MuscleLab DynaSpeed™ (337), or elastic pulling cords, which are a cost effective option to enhance sprint speed (14, 44, 68, 210, 225, 334). Several research studies have focussed on the acute effects of assisted sprint training using elastic pulling cords with results identifying positive changes to sprint performance (14, 44, 68, 210, 225). However, limited studies exist on the same training methodology within an interventional setting (210, 334) and the influence on sprint mechanical characteristics and performance. In this regard, previous research has (334) reported increased acceleration performance to 15-yards (13.7-meters), specifically in the first 5-yards (4.6m), when using an assisted training protocol with elastic pulling cords across a 4-week period. Furthermore, using a similar protocol across a 5-week period (210), significant ($p<0.05$) interactions have been identified for running velocity, stride frequency, ground contact time and flight time. Despite the implementation of sprint training methods into various football codes (257), knowledge about the effects of assisted sprint training are limited yet may be a viable form of non-traditional sprint training for AF players.

Therefore, the purpose of this study was to quantify changes to sprint mechanical characteristics in junior AF players by using a combined sprint training (i.e., assisted and maximal sprinting) methodology which focussed on enhancing the velocity component of the F-v continuum. Our primary aim was to determine the influence of a 7-week combined sprint training intervention on sprint F-v characteristics and performance. We hypothesized that 1), a combined sprint training methodology would enhance sprint mechanical characteristics in unassisted sprinting and create a more velocity-oriented profile compared to maximal sprinting only, due to enhanced neural activation (225), and 2) due to the pulling force assisting athletes to achieve greater velocities (14), reduction in overall sprint times would be a result of higher velocities achieved from 10-20m, compared to 0-10m.

## Methods

### *Study design and participants*

A pre-test versus post-test experimental design with two groups was selected to investigate the effects of a combined sprint training intervention (7-weeks) in junior AF players. A power analysis was conducted prior to the study (G*Power 3) (109) using the following test details: 'ANOVA: Repeated measures, within-between interaction', with an effect size of 0.3, alpha of 0.05 and power of 0.8 , which suggested the total sample size of the study should include 24 participants. Twenty-eight junior male AF players from the same specialist sport academy focussing on Australian Football, volunteered to participate in this study. Twenty-two (age: 14.4 ± 0.3 years, body mass 58.5 ± 10.0 kg, and height 1.74 ± 0.08 m) met the inclusion criteria of completing 10-12 sessions (2 sessions per week; ≥70%) within 7 weeks, excluding familiarization and pre and post testing. From these participants, 6 completed 100% of sessions, 5 completed 91% of sessions, 7 completed 83% of sessions and 4 completed 75% of all sessions. The data from participants who could not complete post-testing was removed from all statistical analysis. Inclusion criteria included: participants involved in AF and aged under 18 years of age. Exclusion criteria maintained that participants needed to be six-months free of musculoskeletal injuries which may prevent them from performing maximal effort sprints. In their pre-testing questionnaire, the adult guardian acknowledged the participant's experience with sprinting actions and provided written informed consent before beginning the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146).

The 7-week training intervention was created with a combined sprint training [CST] group and maximal sprint training [MST] group. The CST group completed maximal assisted sprint efforts and maximal unassisted sprint efforts, while the MST group performed maximal unassisted sprint efforts only. Depending on the structure of the training session, specific sprint-based exercises (maximal and assisted sprint training) were performed on an indoor basketball court or outdoors on a football field. The MST group did not participate in any assisted sprint training protocols. Familiarization of the sprint training assessment and intervention began four weeks prior to testing and included 4-6 x

10-30m maximal effort unassisted sprint efforts for both groups and assisted sprint efforts for the CST group once per week. This timeline was selected to ensure participants were exposed to the assisted sprinting stimulus in small doses prior to testing and beginning the intervention and to reduce the risk of injury using this training method (147). During familiarization sessions for assisted sprinting, players practiced sprinting over distances between 10-20 meters with the elastic cord at pulling forces progressing from sub-maximal (50-75% stretch on cord; ~30-75N) to maximal (100% stretch on cord; ~90N) using a progressive overload approach. Elastic cord tension was measured using a spring balance at various distances (i.e., 10m, 12.5m, 15m) to determine the percentage of maximal pulling force. No changes were observed when measuring pre and post cord tension. Pre-testing coincided with the conclusion of the pre-season period and start of the competitive season for junior AF teams, while post-testing occurred during the middle of the competitive season.

### *Testing procedures*

#### *Force-velocity profile assessment*

The sprint F-v profile assessment was performed on an indoor basketball court with participants wearing standard athletic clothing and shoes. Prior to the first sprint trial, participants performed a series of six sprint efforts over 10-20m progressing from sub-maximal to near-maximal. Participants then performed three 20-meter maximal sprint efforts from a standing start (staggered stance; dominant foot forward) and were encouraged to sprint maximally past the 20-meter marker. Between each sprint attempt there was 5-minute passive recovery period to limit fatigue prior to the next sprint effort. Participants were ranked (1-fastest time, 28-slowest time) according to their mean sprint performance (0-20m) during pre-testing and then pairwise matched to the CST or MST group creating two balanced groups of 14 participants. Unfortunately, injuries and COVID-19 related health concerns impacted 6 participants who started the intervention study in the MST group, therefore reducing this group number to 8 participants. Pre and post sprint assessments occurred on a single day.

Velocity measurements were recorded continuously during each attempt using a radar gun. Software provided by the radar device manufacturer (STATs software, Stalker ATS I Version 3.0, Applied Concepts Dallas, Dallas, TX, USA) was used to collect raw velocity-time data across each sprint trial. The radar device (Model: Stalker ATS I, 36.6Hz, Applied Concepts, Dallas, TX, USA) was positioned 5 m directly behind the starting position and at a vertical height of 1 m to approximately align with the subject's centre of mass. Participants bodymass was assessed using dual force plates (35cm by 35cm, PASPORT force plate, PS-2141, PASCO Scientific, California, USA), while standing stature was determined using a stadiometer. Individual data files, anthropometric variables and environmental conditions (i.e. barometric pressure, temperature) were then processed and imported into the 'shorts' package (179) written in R language (R 203 Development Core Team, 2020). The 'shorts' package uses non-linear least squares regression implemented in the 'nls' function in R (15, 16)). Both R and the 'shorts' package are open-source software. Any velocity-time data before the onset of movement or past the total sprint distance was filtered from the analysis. Using an inverse dynamics approach of the subject's center of mass locomotion, the 'shorts' package (179) fits an exponential function to the raw velocity-time data from the radar gun to establish all variables. The biomechanical model and equations of this approach have previously been reported (286) and validated (246) when compared with direct measurement of ground reaction forces (GRF) from in-ground force plates and has been used in previous interventional studies (195). Sprint position-time data (i.e., split times) were derived from velocity-time data from the radar and were analysed separately for each participant to establish sprint F-v profiles, and associated sprint mechanical characteristics by following previously validated methods (286). The mean of three maximal sprint trials from each participant was used for statistical analysis.

***Intervention protocol***

Assisted sprinting was performed using a 6-meter elastic cord (HART Catapult Trainer) harnessed to the waist of the runner. The elastic cord was fully stretched prior to a sprint, thereby establishing a pulling force of approximately 97.5N (± 15N) at 15-meters, as measured by a spring balance, and held in position by the accredited strength and conditioning coach (Australian Strength and Conditioning Association Level 2, ASCA). Cords could not be stretched greater than 15-meters. Upon receiving a 3-second countdown, the harnessed athlete would sprint maximally up to a distance of approximately 20-30m. Once the harnessed athlete began to sprint, the coach holding the other end of the elastic cord must also run for approximately 10-15m in the same direction to maintain the highest level of tension on the cord to assist the runner until they reach the required distance (Figure 6.1). The coach ran a slight angle (5-10°) to the athlete to ensure the athlete was not impeded by running over the elastic cord. Despite the coaches best efforts, it is acknowledged the tension on the cord is reduced once the athlete begins to accelerate (14). After sprinting using the elastic cords, several players provided feedback to the coaches including '*I felt like I was catapulted off the start line'* and '*sprinting is so easy with the cords.'*

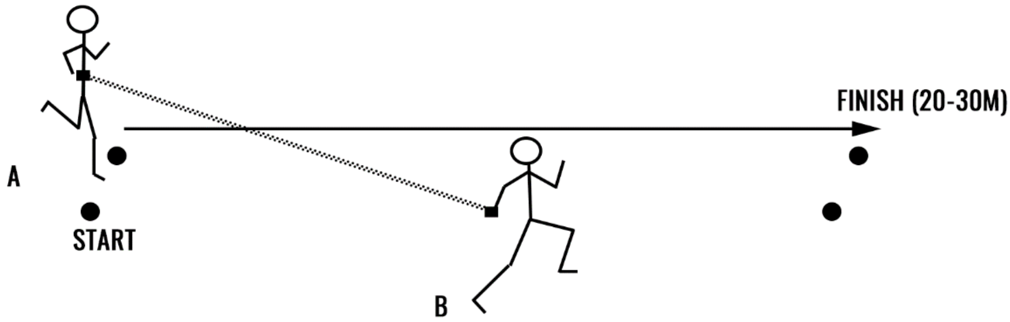


**Figure 6.1.** Visual description of assisted sprinting design. A: subject pulled by elastic cord (attached around the waist); B: subject pulling the elastic cord (cord held outstretched in hand).

Sessions for all participants (i.e., CST and MST) were conducted and supervised by ASCA coaches and completed twice weekly prior to on-field technical and tactical football session. Prior to all intervention-based training sessions, participants performed a 10-minute warm-up consisting of linear and multi-directional movement patterns, dynamic stretches, mobility, and activation exercises, and progressed from general to more sprint specific exercises (i.e., marching, A-skip, scissor bound). There was no added sprint specific training included in the on-field sessions and overall training volume remained stable across the intervention, thereby maintaining a level of consistency across the study. At the conclusion of each sprint effort, each participant undertook a rest period of approximately 3-5 minutes to limit fatigue prior to the next sprint. All protocols specific to the 7-week training intervention are outlined in Table 6.1. Sprint volume between both groups were matched across the duration of the intervention.

**Table 6.1.** Description of sprint training intervention.

| Week | Group | | Volume/session | Weekly volume |
|---|---|---|---|---|
| | CST (Combined sprint training: Assisted and maximal sprint training) | MST (Maximal sprint training) | | |
| | **Session** | **Session** | | |
| -4 Familiarization | Sub-maximal to maximal unassisted and assisted sprint efforts over 10-30-metres. | | 100m | 200m |
| -3 Pre-Testing | 3 x 20-metre sprint efforts. Velocity-time data collected via radar device. | | 60m | 120m |
| -2 and -1 | Technical and tactical football sessions only | | - | - |
| 1 | 2 x 20m AST / 1 x 20m MST | 3 x 20m MST | 60m | 120m |
| 2 | 3 x 20m AST | 3 x 20m MST | 60m | 120m |
| 3 | 3 x 25m AST | 3 x 25m MST | 75m | 150m |
| 4 | 3 x 25m AST / 1 x 15m MST | 1 x 15m, 3 x25m MST | 90m | 180m |
| 5 | 3 x 30m AST | 3 x 30m MST | 90m | 180m |
| 6 | 3 x 30m AST / 1 x 30m MST | 4 x 30m MST | 120m | 240m |
| 7 | 4 x 30m AST | 4 x 30m MST | 120m | 120m |
| 8 Post-Testing | 3 x 20-metre sprint efforts. Velocity-time data collected via radar device. | | 60m | 60m |

AST: Assisted sprint training

### ***Statistical analysis***

Statistical analyses were performed in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages. All descriptive data are presented as mean ± standard deviation (SD) and were assessed for normality and variance using the Shapiro-Wilks and Levene's test respectively. Independent samples t-tests were used to determine between group differences at pre-test for sprint F-v characteristics and split-times. Intraclass correlation coefficient (ICC) with 95% confidence limits were used to assess relative reliability of F-v and split times for sprint trials (152). To account for typical fluctuations in sprint performance between testing sessions, the MDC at 90% confidence intervals, was used to determine the minimum level of change necessary to represent a 'true' performance change, rather than random measurement error and was calculated as 1.645 x Standard error of measurement (SEM) x $\sqrt{2}$ (116, 135). The MDC% was defined as (MDC/$\bar{x}$ ) x 100 (115). Thresholds for evaluation of intraclass correlation coefficients were quantified using the following scale: 0.20-0.49 *poor,* 0.50-0.74 *moderate*, 0.75-0.89 *high*, 0.90-0.98 *very high* and ≥ 0.99 *extremely high* (155). To assess the effect of assisted sprint training a 2 (pre-post-test: repeated measurements) x 2 (group: CST, MST) ANOVA was performed. Standardized effect sizes (Cohen's *d*) were assessed pre-post training for all sprint F-v variables and split-times were determined using a pooled standard deviation approach from both groups with 95% confidence limits. Magnitudes of effect size changes were interpreted using the following values: trivial (< 0.20), small (0.20 ≤ 0.60), moderate (0.60 ≤ 1.20), large (1.20 ≤ 2.00) and extremely large (> 2.00) (52). In addition, a one-way ANOVA with repeated measures per group was conducted to identify changes per group. An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

## Results

Shapiro-Wilks and Levene's test confirmed normality and homogeneity of variance for all F-v variables. All results are reported in Tables 2-3 and Figures 6.2-6.4. The mean session completion rate in the CST and the MST group were 78.6% and 85.7% respectively. At the pre-test, no significant differences were observed between groups (MST vs CST) for all sprint F-v ($t \leq 1.87$, $p \geq 0.07$) or split-times variables ($t \leq 1.59$, $p \geq 0.12$).

Reliability measures, SEM and MDC data for sprint mechanical characteristics and split times are presented in Table 6.2. The intraclass correlation coefficients (ICC) for sprint mechanical characteristics and split times ranged from moderate to high (ICC=0.65-0.91), except for the F-v slope ($S_{FV}$) and decrement in ratio of forces ($D_{RF}$) which both reported poor reliability measures (ICC=0.41-0.44). The MDC (%) across sprint mechanical variables and split times ranged from 2.59-6.88%. The CST group exceeded the MDC for most variables suggesting a 'true change' in performance across the intervention except for $v_0$, split time to 15m, 20m and 10-20m. Changes in the MST group did not exceed those of the MDC.

Significant time*group interaction effect was found for relative $F_0$, relative $S_{FV}$, $RF_{MAX}$, $D_{RF}$ and split time to 5-meters and 10-meters ($F \geq 3.96$, $p \leq 0.05$, $-0.80 \leq ES \geq 0.84$) (Table 6.3, Figure 6.2-6.3). Changes to absolute values of mechanical characteristics can be found in supplemental files (Table_S1), highlighting no significant group effects were found between variables ($F \leq 3.07$, $p \geq 0.08$) (Table 6.3). Post hoc comparison revealed the MST group significantly increased $v_0$ and split time from 10-20m only ($0.18 \leq ES \geq 0.39$, $p \leq 0.04$), while significant increases in sprint mechanical characteristics and sprint performance were reported in the CST group for almost all variables ($-0.64 \leq ES \geq 0.82$, $p \leq 0.01$) (Table 6.3, Figure 6.2-6.3). Analysis of sprint performance in the CST group showed significant pre-post % changes at all sprint distances to 20-meters (2.78-4.49%)(Table 6.3, Figure 6.2). No significant differences ($p > 0.05$, ES = -0.10) were noted for body mass (ES=-0.10, 95%CI [-0.12, -0.06], $p = 0.06$) between testing days. Mean group pre-post changes between sprint F-v profiles over 20-meters are presented in Figure 6.4. Pre-post analysis of the F-v profile identified 12/14 participants (85%) in the CST group had a more force-oriented profile post-intervention, compared with 3/8 of participants (38%) in the MST group.

**Table 6.2.** Reliability measures and minimal detectable change for sprint force-velocity variables and split-times.

| Variable | Relative $F_0$ ($N.kg^{-1}$) | $v_0$ ($m.s^{-1}$) | Relative $P_{MAX}$ ($W.kg^{-1}$) | Relative $S_{FV}$ ($N.s.m^{-1}.kg^{-1}$) | $RF_{MAX}$ (%) | $D_{RF}$ ($\%.m.s^{-1}$) | 5m (s) | 10m (s) | 15m (s) | 20m (s) | 10-20m (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ICC | 0.65 (0.29, 0.83) | 0.72 (0.41, 0.88) | 0.85 (0.62, 0.96) | 0.44 (0.20, 0.74) | 0.71 (0.41, 0.90) | 0.41 (0.16, 0.72) | 0.65 (0.47, 0.76) | 0.79 (0.65, 0.88 | 0.85 (0.75, 0.91 | 0.89 (0.80, 0.95) | 0.91 (0.83, 0.96) |
| SEM | 0.10 | 0.15 | 0.30 | 0.01 | 0.005 | 0.001 | 0.01 | 0.02 | 0.03 | 0.04 | 0.02 |
| MDC | 0.24 | 0.36 | 0.72 | 0.04 | 0.01 | 0.003 | 0.05 | 0.08 | 0.10 | 0.13 | 0.05 |
| MDC% | 4.71 | 4.54 | 6.88 | 6.30 | 3.36 | 6.27 | 2.65 | 2.59 | 2.60 | 2.65 | 3.17 |

(ICC = intraclass correlation coefficient [95% confidence intervals]; SEM: standard error of measurement; MDC = minimal detectable change; $F_0$: theoretical maximal force; $v_0$: theoretical maximal velocity; $P_{MAX}$: theoretical maximal power; $S_{FV}$: force-velocity slope; $RF_{MAX}$: maximum ratio of forces; $D_{RF}$: decrement in ratio of forces.

**Table 6.3.** Pre-post sprint force-velocity variables and split times for within and between-group comparisons.

| Variable | Group | PRE Mean ± SD | POST Mean ± SD | Within-group ES (pre-post) P value | %Δ ± SD | Between-group-time ES ± 95% CL, F value, P value |
|---|---|---|---|---|---|---|
| **Relative $F_0$ ($N.kg^{-1}$)** | CST | 5.18 ± 0.49 | 5.76 ± 0.84 | 0.74 (0.22, 1.26), 0.005** | 11.19 ± 12.52 | Group ES: -0.11 (-0.95,0.73), F=0.07, p=0.78<br>Time ES: 0.84 (0.12,1.55), F=5.57, p=0.02* |
| | MST | 5.10 ± 0.51 | 5.07 ± 0.59 | -0.05 (-0.68, 0.57), 0.85 | -0.40 ± 8.47 | Int ES: -0.88 (-2.06,0.31), F=2.24, p=0.14 |
| **$v_0$ ($m.s^{-1}$)** | CST | 8.31 ± 0.83 | 8.25 ± 0.60 | -0.06 (-0.41, 0.27), 0.69 | -0.25 ± 6.08 | Group ES: -0.77 (-1.66,0.12), F=3.07, p=0.08<br>Time ES: -0.08 (-0.84,0.67), F=0.04, p=0.82 |
| | MST | 7.80 ± 0.43 | 8.01 ± 0.52 | 0.39 (0.04, 0.73), 0.03* | 2.60 ± 2.87 | Int ES: 0.39 (-0.86,1.65) F=0.40, p=0.53 |
| **Relative $P_{MAX}$ ($W.kg^{-1}$)** | CST | 10.75 ± 1.47 | 11.80 ± 1.86 | 0.60 (0.18, 1.02), 0.007** | 10.04 ± 11.56 | Group ES: -0.46 (-1.30,0.38), F=1.22, p=0.27<br>Time ES: 0.61 (-0.10,1.33), F=2.99, p=0.09 |
| | MST | 9.96 ± 1.36 | 10.15 ± 1.57 | 0.12 (-0.27, 0.51), 0.52 | 1.94 ± 7.28 | Int ES: -0.50 (-1.69,0.68), F=0.73, p=0.39 |
| **Relative $S_{FV}$ ($N.s.m^{-1}.kg^{-1}$)** | CST | -0.63 ± 0.09 | -0.70 ± 0.12 | -0.64 (-1.23, 0.15), 0.01* | 12.96 ± 16.33 | Group ES: -0.26 (-1.13,0.62) F=0.35, p=0.55<br>Time ES: -0.79 (-1.53,-0.04), F=4.57, p=0.03* |
| | MST | -0.65 ± 0.05 | -0.63 ± 0.07 | 0.27 (-0.55, 1.10), 0.48 | -2.46 ± 10.24 | Int ES: -0.50 (-1.69,0.68), F=2.53, p=0.11 |
| **$RF_{MAX}$** | CST | 0.39 ± 0.02 | 0.42 ± 0.03 | 0.69 (0.18, 1.21), 0.008* | 6.06 ± 7.31 | Group ES: -0.23 (-1.08, 0.62), F=0.30, p=0.58<br>Time ES: 0.71 (-0.01, 1.43), F=3.96, p=0.05* |
| | MST | 0.39 ± 0.02 | 0.39 ± 0.03 | -0.02 (-0.55, 0.51), 0.91 | -0.14 ± 5.21 | Int ES:-0.74 (-1.94, 0.46), F=1.54, p=0.22 |
| **$D_{RF}$** | CST | -0.05 ± 0.01 | -0.06 ± 0.01 | -0.65 (-1.19, -0.12), 0.01* | 11.91 ± 15.48 | Group ES: -0.30 (-1.18,0.62), F=0.47, p=0.49<br>Time ES: -0.75 (-1.50,0.00), F=4.09, p=0.04* |
| | MST | -0.06 ± 0.01 | -0.06 ± 0.01 | 0.31 (-0.52, 1.14), 0.44 | -2.63 ± 9.73 | Int ES: 0.96 (-0.29, 2.20), F=2.41, p=0.12 |
| **Split time 0-5 meters (sec)** | CST | 1.72 ± 0.09 | 1.64 ± 0.09 | 0.82 (-0.04, 1.64), 0.02* | -4.39 ± 7.31 | Group ES: 0.11 (-0.72,0.95), F=0.07, p=0.78<br>Time ES: -0.80 (-1.51,-0.09), F=5.16, p=0.02* |
| | MST | 1.74 ± 0.09 | 1.75 ± 0.09 | -0.19 (-0.87, 0.48), 0.55 | 1.09 ± 4.39 | Int ES: 0.97 (-0.21,2.15), F=2.75, p=0.10 |
| **Split time 0-10 meters (sec)** | CST | 2.60 ± 0.14 | 2.50 ± 0.13 | 0.75 (0.00, 1.51), 0.02* | -3.76 ± 6.15 | Group ES: 0.24 (-0.60,1.07), F=0.33, p=0.56<br>Time ES: -0.73 (-1.44, -0.01), F=4.23, p=0.04* |
| | MST | 2.64 ± 0.13 | 2.65 ± 0.11 | -0.12 (-0.69, 0.44), 0.65 | 0.69 ± 3.60 | Int ES: 0.84 (-0.35,2.02), F=2.04, p=0.16 |
| **Split time 0-15 meters (sec)** | CST | 3.36 ± 0.18 | 3.24 ± 0.16 | 0.66 (0.01, 1.30), 0.02* | -3.24 ± 5.25 | Group ES: 0.34 (-050,1.18), F=0.67, p=0.41<br>Time ES: -0.64 (-1.36,0.08), F=3.25, p=0.07 |
| | MST | 3.42 ± 0.17 | 3.43 ± 0.13 | -0.06 (-0.53, 0.41), 0.79 | 0.37 ± 2.99 | Int ES: 0.70 (-0.49,1.89), F=1.39, p=0.24 |
| **Split time 0-20 meters (sec)** | CST | 4.05 ± 0.22 | 3.94 ± 0.19 | 0.55 (0.02, 1.09), 0.02* | -2.78 ± 4.54 | Group ES: 0.43 (-0.42,1.28), F=1.04, p=0.31<br>Time ES: -0.55 (-1.27,0.17), F=2.37, p=0.13 |
| | MST | 4.15 ± 0.20 | 4.15 ± 0.17 | 0.00 (-0.40, 0.38), 0.96 | 0.10 ± 2.55 | Int ES: 0.56 (-0.64,1.76), F=0.88, p=0.25 |
| **Split time 10-20 meters (sec)** | CST | 1.45 ± 0.09 | 1.43 ± 0.07 | 0.15 (-0.10, 0.41), 0.23 | -1.05 ± 3.09 | Group ES: 0.65 (-0.22, 1.53), F=2.27, p=0.03*<br>Time ES: -0.17 (-0.92, 0.58), F=0.21, p=0.57 |
| | MST | 1.51 ± 0.07 | 1.48 ± 0.07 | 0.18 (-0.01, 0.39), 0.04* | -0.96 ± 1.36 | Int ES: 0.01 (-1.23,1.25), F=0.00, p=0.98 |

ES: effect size; CL: confidence limits; CST: combined sprint training; MST: Maximal sprint training; $F_0$: theoretical maximal force; $v_0$: theoretical maximal velocity; $P_{MAX}$: theoretical maximal power; $S_{FV}$: force-velocity slope; $RF_{MAX}$: maximum ratio of forces; $D_{RF}$: decrement in ratio of forces, * $p \leq 0.05$, ** $p \leq 0.01$.

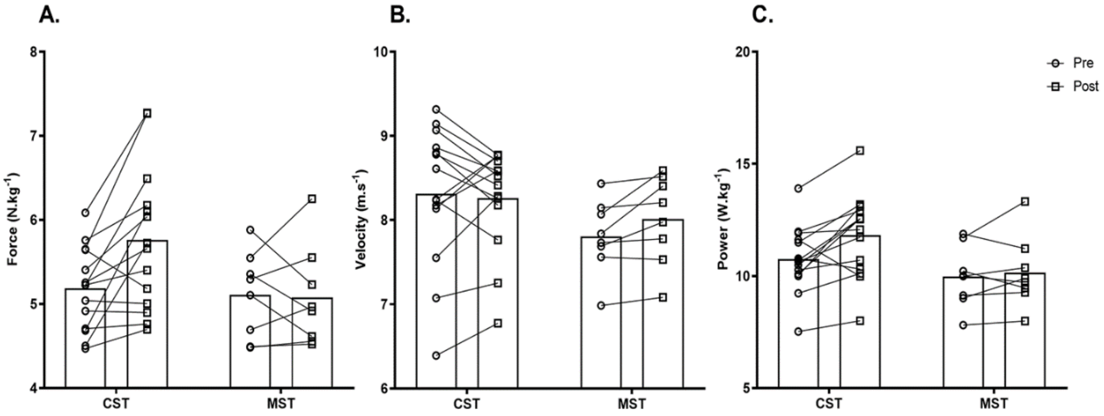


**Figure 6.2**. Pre-post changes to sprint force-velocity characteristics and split times after the 7-week training intervention. A: Relative maximal force; B: Theoretical maximal velocity; C: Relative maximal power. (CST: combined sprint training group; MST: Maximal sprint training group).

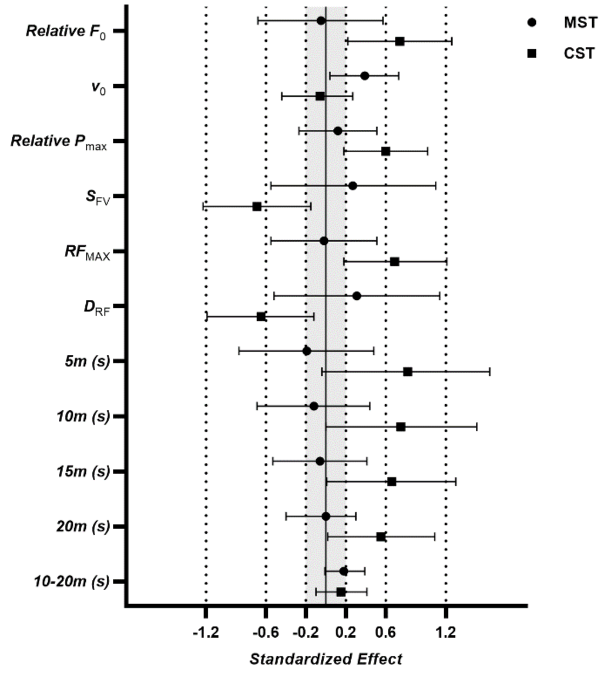


**Figure 6.3**. Within-group pre-post effect sizes for sprint force-velocity characteristics and split times across the 7-week intervention. ($F_0$: theoretical maximal force; $v_0$: theoretical maximal velocity; $P_{MAX}$: theoretical maximal power; $S_{FV}$: force-velocity slope; $RF_{MAX}$: maximum ratio of forces; $D_{RF}$: decrement in ratio of forces; CST: combined sprint training group; MST: Maximal sprint training group).

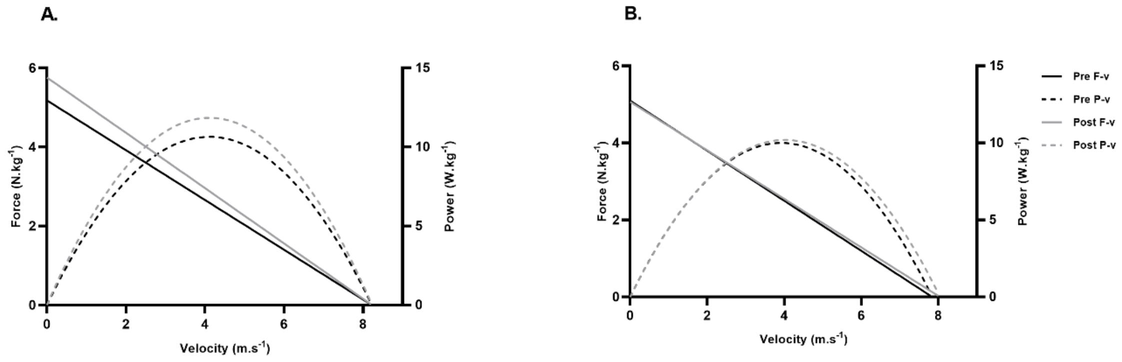


**Figure 6.4**. Mean pre-post sprint force-velocity-power profile of 20-meter sprint performance. A: Combined sprint training (CST) group; B; Maximal sprint training (MST) group. (F-v: force-velocity; P-v: power-velocity).

## Discussion

The purpose of this study was to investigate the effects of a 7-week combined sprint training intervention (assisted sprint and maximal sprint training) on sprint mechanical characteristics and performance in junior AF players. To the best of our knowledge this is the only study which has reported the effects of this type of training intervention in conjunction with a focus on the mechanical characteristics of the sprint F-v profile. The main findings of this study identified a combined sprint training approach significantly improved sprint performance (i.e., reduced sprint time over 20-meters), whereas minor changes were observed for mechanical and performance characteristics in the maximal sprint training group. Reduced sprint times across all distances (2.78-4.49%) in the CST group were reflected in significant changes to relative theoretical maximal force (10.04%) and power (11.19%), which were greater than the minimal detectable change for each variable. Maximal sprint training only elicited significant changes to $v_0$ (2.60%) and split time from 10-20m (0.96%) in the MST group, highlighting the effectiveness and utility of this training method to improve maximal velocity in field-based sports. The results from this intervention study suggests a combined sprint training approach may be a viable option for junior AF players when attempting to improve sprint performance during the in-season period.

Although sprint performance is not the sole predictor of success in Australian football (i.e., tactical and technical abilities, physiological qualities), developing this quality appears conducive for progressing to higher levels of the sport suggesting understanding and then developing sprint mechanical characteristics is important for sports performance coaches (35, 103, 273). In reference to our first hypothesis, we identified that a combined sprint training approach created a more force-dominant F-v profile, leading to greater acceleration ability due to pre-post changes to relative theoretical maximal force (ES: 0.74) and power (ES: 0.60) (Figure 6.4). This contradicted our initial hypothesis as it appears significant changes to mechanical and performance characteristics in the initial steps of the sprint (i.e., 0-10m) is due to the transfer of training effect of the supramaximal velocity stimulus from the elastic cord in the early acceleration phase. This biomechanical change in performance is supported in the results by the moderate effect sizes for relative maximal force and split time from 0-5 meters ($-0.80 \leq ES \geq 0.84$). Furthermore, motor learning research details greater transfer or 'crossover' to normal sprinting occurs when the biomechanics target specific technical sprint elements (143), in this case a greater exposure to supramaximal velocities at the start of the sprint effort. As previously reported (14), the pulling force of the elastic cord most likely lost tension relative to the athlete's bodyweight at distances greater than 15-meters. suggesting the stimulus was likely negligible when in an upright position, i.e., approximately 10-20 meters. It can therefore be inferred that the mechanical changes affecting early acceleration has led to faster split times across the sprint effort except for the 10-20m flying segment. These findings are important considering previous studies in Australian football have reported high numbers of acceleration-based efforts in elite male players identifying the importance of developing mechanical characteristics (344).

Previous intervention studies involving male AF players of similar ages as those in this study (37, 101), have reported resisted sprint training using sleds had significant effects on relative theoretical maximal force values (ES: 0.63-1.19) with the greatest performance change occurring in the first 10m of the sprint. It was also suggested to improve sprint performance, junior AF players should develop a force-oriented mechanical profile (102); which occurred in the CST group during this study, despite using velocity as a speed specific stimulus (190). This is a new finding and suggests a CST approach to sprint performance may provide a similar neuromuscular adaptation to resisted sprint training in adolescent AF populations. Furthermore, large changes to $P_{MAX}$ in the CST group suggests over this sprint distance, the improvements in $F_0$ may be of greater importance compared to $v_0$ when trying to improve $P_{MAX}$ and sprint performance. This may therefore inform practitioners which side of the F-v continuum to place a greater focus on when attempting to improve sprint performance in junior AF players.

F-v profiles and their associated variables have not previously been reported in assisted sprint training interventions using elastic pulling cords, however the sprint performance changes in this study as measured via split times align with previous findings (210, 334). Other studies have reported significant effects to early acceleration (<15m) performance with female college sport athletes using this approach, yet with no reference to the F-v profile, along with an increased mean centre of mass velocity (6.37%Δ), increases in stride frequency (Hz) (5.48%Δ), and decreases in contact time (ms) (8.39%Δ) following a 5-week assisted sprint training programme. Across studies, elastic pulling cords increased mean velocity to 5-yards (10.07%Δ), yet relatively small velocity changes to 25-yards (2.07%Δ )(334). These changes were thought to be the result of enhance neuromuscular response in the early steps of acceleration across the 4-week (12-session) intervention. The difference in our findings compared to previous studies (210, 334) may also be due to a measure of mean velocity across the sprint effort, differences in pulling force, the experience level of the participants (i.e., junior AF players compared to College level athletes) or training volume and intensities used within the intervention.

Our second hypothesis was not confirmed as sprint performance in the CST group did not achieve statistical significance for the split time from 10-20m. Changes in sprint performance between 10-20m were evident in the MST group only. These results identify how pulling force from the elastic cords has likely influenced the rate of acceleration at the instant the athlete overcomes inertia yet provided limited assistance to improve velocity adaptations in this segment of the sprint. This was not the case in the MST group where significant changes to $v_0$ and split time from 10-20m were identified, suggesting greater volume and exposure to maximal sprint training performed by these players established greater neuromuscular adaptations impacting this aspect of sprint performance (143), along with velocity specific adaptations, such as greater vertically directed support forces which have been shown to enhance maximal velocity (191, 352). While not the focus of this study, this finding is a consideration for speed development in AF due to the demand for high-speed running (>5.5m.s$^{-1}$) across the duration of the game (70-110m.min$^{-1}$) which has been reported to differentiate between ability levels (177). Although our pre-testing data did not show significant between-group differences for $v_0$ ($p = 0.07$), the lower initial values for this variable in the MST group may also suggest participants may have had a velocity-deficit when compared with the CST group and by engaging in maximal sprint training, reduced this mechanical imbalance across the 7-week intervention.

It should be noted that improved sprint performance along with increased relative maximal power in the CST group may have established a more *optimal* F-v profile for this cohort of junior AF players (285). The individual optimal sprint F-v profiles depends largely on $P_{MAX}$ and to a lesser degree on sprint distance and the interindividual variability in F-v characteristics. Recent research (285) identified as sprint distance was reduced (< 15-meters) the optimal F-v profile would become oriented towards force capabilities (i.e., force dominant), whereas, as sprint distance increased (>15-meters) velocity capabilities would be of greater importance to sprint performance and the optimal profile would orient towards being velocity dominant. This is largely supported in our findings when considering pulling force in the CST group appears to be maximized in the initial stages of the sprint effort, however, may also identify this particular group of adolescent AF players exhibit a force-deficit in a sprint context. From a practical perspective, this identifies a potential *window of trainability* to improve maximal power by targeting the force side of the F-v continuum using a combined sprint training approach to *optimize* the mechanical sprint F-v profile.

Investigating the associated sprint mechanical characteristics influencing performance was also important to consider in this study. Significant within-group effects and pre-post changes in the CST group to the maximum ratio of forces ($RF_{MAX}$) suggests changes to force application during sprint performance may have occurred across the training intervention. Previous research (236) suggests the increase in $RF_{MAX}$ would result in a more horizontally directed ground reaction force in the initial steps of the acceleration thereby directly affecting acceleration capabilities according to Newton's laws of motion. Furthermore, Morin et al. (236) reported an increase in ratio of force (%) is a result of improving the angle and technical ability at which antero-posterior force compared to the corresponding total ground reaction force ($F_{TOT}$) is averaged over the support phase.

Therefore, for the same magnitude of force applied to the ground, the horizontal change in velocity during the stance phase will improve due the orientation of the ground reaction force vector (22) which may have led to a  reduction in all split times in the CST group. Significant changes to decrement of ratio of forces ($D_{RF}$) and relative F-v slope ($S_{FV}$) were reported in the CST group. Changes to $D_{RF}$ highlight how the natural decrease in ratio of forces as running velocity increases has likely been altered due to the assistive pulling force from the elastic cord, whereas the $S_{FV}$ describes the athlete's individual ratio of force (i.e., acceleration) in reference to velocity (i.e., maximal speed). However, due to the absolute reliability confidence intervals of these variables, we cannot make conclusive statements concerning the utility for the $D_{RF}$ (ICC=0.41) and $S_{FV}$ (ICC=0.44) to inform practice within this intervention study only.

This experimental study has several strengths. Sprint mechanical characteristics on junior Australian football players can provide valuable insights into the physical capabilities of these athletes, specifically in regard to their neuromuscular output. Such a study can help the sport and strength and conditioning coach design more effective training programs, as well as identify areas where individual players may need to focus on improvement across the F-v continuum. Additionally, the results of the study may identify how mechanical profiling can be used to track and monitor changes in the players' biomechanical and technical sprint abilities across the competitive season. This study has also identified alternate sprint-specific training methods to enhance performance within a football context. Finally, there are a limited number of studies exploring sprint mechanical profiling in youth populations and therefore this adds original knowledge to the growing literature.

There are also limitations in this study which should be acknowledged. Across the duration of the intervention there was limited monitoring of velocity changes in assisted sprint conditions in the CST group. Although the elastic cord tension was measured during the intervention, individual velocity data was not measured for each participant which would have provided greater information about the percentage above maximal velocity each player achieved during the training sessions, thereby potentially highlighting the variability of the training method. Furthermore, despite previously identifying the non-constant pulling force on the athlete while using elastic cords to achieve a supramaximal stimulus, without having a budget to purchase several portable robotic devices with constant pulling force, i.e., 1080Sprint™, elastic cords may still be a viable option for AF coaches. Also, a power analysis was conducted prior to the study and the desired number of subjects was initially met (n=28), however due to injuries and COVID-19 health implication several participants could not complete the intervention (n=22) and the study became underpowered which may undermine some of the results. Post-hoc analysis using 22 subjects therefore provides a power level of only 0.76, which highlights differences between the means will only be detected 76% of the time. Future studies using a larger sample size would therefore provide greater certainty of results. We were also concerned with the poor reliability (ICC=≤0.44) regarding $S_{FV}$ and $D_{RF}$, which is in line with previous research (142). The $D_{RF}$ is the combination of maximum velocity and relative acceleration, and therefore has an interdependence on the individual slope of the F-v ($S_{FV}$) relationship. Typically, as one value moves up (i.e., relative force), the other value will likely move down (i.e., velocity) changing the $S_{FV}$ value. Therefore, slight changes in initial acceleration of the sprint effort, i.e., 0-5m, will reduce the reliability of the velocity-time data from the radar gun (or laser gun), which has previously been identified as a methodology concern (24). Furthermore, small changes in velocity-time data between trials will likely be amplified in derived F-v values, which again places an importance on participant familiarization of the testing protocol. Also, the adolescent aged population group involved in this study may limit the transfer of findings to senior level AF players. Although maturation is highly individual, studies have shown changes to sprint performance can be influenced by an individual's chronological age relative to their age at peak height velocity (PHV) and maturation offset (54, 99, 104, 211, 229). A final limitation was that we did not directly measure pre-post stride kinematics (step-length / step frequency) or muscle activity (EMG) of the lower limbs as has occurred in previous assisted sprint training studies (224, 227, 337). This information would have provided a greater understanding of how variables such as stride length, stride frequency, contact time, flight time, joint-segment changes and motor unit recruitment were influenced by mechanical changes due to assisted and maximal sprint training. Combining the mechanical data from F-v profiling, use of a portable robotic device with constant pulling force, plus obtaining stride kinematics and EMG data, would provide greater insight into adaptations caused across the intervention and is worthy of future research.

## Conclusions

Developing sprint ability in junior Australian football players appears to be advantageous for on-field performance and potential selection in the annual Australian Football League national draft, therefore understanding the most effective training methods to improve this quality is important for practitioners. Based upon the findings of the present study, we conclude that a 7-week combined sprint training intervention using assisted (elastic pulling cord) and maximal sprint training methods, may be a more appropriate methodology to enhance various sprint mechanical characteristics and improve sprint performance over 20-meters compared to a traditional maximal sprint training approach. Upon completing familiarization, a progressive overload approach of combined sprint training lasting approximately 15-20 minutes, starting at 40-meters (total volume) of assisted sprinting and progressing to 120-meters (total volume) of assisted sprinting, could be implemented in the warm-up period prior to football-specific exercises. Practitioners are encouraged to use assisted and maximal sprint training methods in a combined training protocol to create a more force-oriented F-v profile due to significant changes to relative theoretical maximal force and power in junior Australian football players. Coaches should however be cautious when implementing this training modality and ensure familiarization has been performed by all players to reduce the risk of injury.

## PRELUDE

Chapter 6 highlighted the mechanical changes to force, velocity, power and sprint performance in response to a specific sprint training intervention across a 7-week period in team sport athletes. This provided a platform to further explore changes to the sprint mechanical characteristics in track and field athletes, i.e., athletes who perform this task as their main performance. To date, no study has investigated changes to F-v characteristics using a longitudinal approach. The results in Chapter 6 suggests sprint mechanical characteristics will adapt to a specific stimulus but it would be of interest to sport practitioners to understand how these characteristics adapt and change across an entire track and field season. Therefore, the primary aim of this case study was to investigate how force, velocity and power variables expressed during sprinting change across a track and field season (~45 weeks) in two male sprint athletes who qualified for their national championships. A secondary aim was to explore how periodised sprint training influences mechanical and spatio-temporal characteristics, step kinematics and their effect on sprint performance outcomes. We hypothesized as the periodisation model changed between training phases within the track and field season and the mechanical load was reduced, it would likely result in improved sprint outcomes due to an enhanced F-v profile, plus optimized step kinematics for each athlete during 100-meter performance. However, inter-athlete differences would be evident based on initial mechanical characteristics and level of performance. This chapter provides insight to coaches about the underpinning mechanical characteristics influencing sprint performance outcomes during specific training periods.

# CHAPTER 7: STUDY 5

## Exploratory analysis of sprint force-velocity characteristics, kinematics, and performance across a periodised training year: A case study of two national level sprint athletes

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## Abstract

Objective: This case study aimed to explore changes to sprint F-v characteristics across a periodised training year (45-weeks) and the influence on sprint kinematics and performance in national level 100-meter athletes. F-v characteristics have been shown to differentiate between performance levels in sprint athletes (235), yet limited information exists describing how characteristics change across a season and impact sprint performance, therefore warranting further research. Methods : Two male national level 100-meter athletes (Athlete 1: 22yrs, 1.83m, 100m time: 10.47sec; Athlete 2: 19yrs, 75.3kg, 100m time: 10.81sec) completed 12 and 11 F-v assessments respectively, using electronic timing gates. Sprint mechanical characteristics were derived from 30-metre maximal sprint efforts using split times (i.e., 0-10m, 0-20m, 0-30m) whereas step kinematics were established from 100-meter competition performance using video analysis (278). Results: Between the preparation (PREP) and competition (COMP) phase, Athlete 1 showed significantly large within-athlete effects for relative maximal power ($P_{MAX}$), theoretical maximal velocity ($v_0$), maximum ratio of force ($RF_{MAX}$), maximal velocity ($V_{MAX}$), and split time from 0-20m and 0-30m ($-1.70 \leq ES \geq 1.92$, $p \leq 0.05$). Athlete 2 reported significant differences with large effects for relative maximal force (F0) and $RF_{MAX}$ only (ES: $\leq -1.46$, $p \leq 0.04$). In the PREP phase, both athletes reported almost perfect correlations between $F_0$, $P_{MAX}$ and 0-20m ($r = -0.99$, $p \leq 0.01$), however in the COMP phase, the relationships between mechanical characteristics and split times were more individual. Competition performance in the 100-meter sprint (10.64 ± 0.24sec) showed a greater reliance on step length ($r \geq -0.72$, $p \leq 0.001$) than step frequency to achieve faster performances. The minimal detectable change (%) across mechanical variables ranged from 1.3-10.0% while spatio-temporal variables were much lower, 0.94-1.48%, with Athlete 1 showing a higher 'true change' in performance across the season compared

to Athlete 2. Conclusions: The estimated sprint F-v data collected across a training year may provide insight to practitioners about the underpinning mechanical characteristics which affect sprint performance during specific phases of training, plus how a periodised training design may enhance sprint F-v characteristics and performance outcomes.

## Introduction

Across a training year, sprint athletes typically progress through a periodised training programme aimed at peaking towards major competitions including national championships. Training components within a sprint programme generally include acceleration and maximal velocity sprinting, resistance training and plyometrics (43) which aim to enhance neuromuscular, biomechanical and technical sprint characteristics. However, the overall aim of all sprint programmes should be to improve an athlete's ability to run fast. Sprint running requires athletes to overcome inertia and accelerate from a stationary start to a high maximal velocity (233). From a mechanical perspective, the ability to complete this movement task requires the athlete to apply a large amount of force and power in the horizontal direction at an increasing running velocity (286). Although sprint mechanical characteristics have been assessed in various athletic populations in cross-sectional studies (104, 351), there is a paucity of longitudinal research investigating individual mechanical changes in sprint athletes in response to specific periods of training. An analysis of sprint mechanical characteristics and performance is therefore of interest to practitioners as it may provide greater insight into training programme design and periodisation structure of sprint training and competition.

To quantify the mechanical determinants which underpin sprint performance a field method known as F-v profiling has been proposed by Samozino et al (286). Using an inverse dynamics approach to the body center of mass, the field method describes the mechanical output of over-ground maximal sprint running by modelling position-time data to indirectly estimate the underlying mechanical properties (i.e., forces) which produced the sprint performance (51). The key mechanical variables obtained from sprint F-v profiles include theoretical maximal force ($F_0$), theoretical maximal velocity ($v_0$) and theoretical maximal power ($P_{MAX}$)(286), which determine the intercepts of the inverse linear F-v relationship, and the parabolic relationship between power and velocity (P-v) (286).

The mechanical characteristics obtained by from sprint F-v and power-velocity data can be used as a quantitative approach to improve the planning of sprint training to influence sprint outcomes during competition. The aim of sprint athletes who compete in traditional track events is to cover the competition distance (i.e., 100-meter) in the shortest time possible, however the aim of the coach is to periodize the training load and content to ensure the athlete produces their best performance at key times in the year, for example national championships. Furthermore, at different stages of the year the training focus will likely change from attempting to improve various bio-motor abilities including strength and power, to more sprint-specific foci including acceleration, maximal velocity and speed endurance (31), a planning process known as periodisation. Periodisation of physical training has been identified as key to developing physiological and neuromuscular adaptations to maximize performance at specific periods during the training year (31). Despite its recent widespread use in team sport to differentiate between ability level, field position and to individualize training strategies (99, 248, 304, 351), an investigation into changes to mechanical characteristics in sprint athletes across a training year is yet to be explored.

Recent evidence has highlighted the importance of maximal power ($P_{MAX}$) during the sprint action and the influences of individual F-v characteristics (i.e., $S_{FV}$) to sprint acceleration performance (285). Therefore, it would be useful information for sprint practitioners to understand mechanical changes across the training year and the relationships with sprint outcomes. Previous longitudinal case studies of junior (7-weeks, 100-meter personal best: 10.89 ± 0.21sec) and senior level (5-months, 100-meter personal best: 10.16 ± 0.16) sprinters focussed on strength training and its effect on sprint performance (28), plus changes to step kinematics in response to periodised training (21). Sprint performance changes in junior athletes were deemed inconclusive; however, it was hypothesized changes to performance in senior elite athletes was explained by the periodisation of specific training components which was associated with an increase in force production, along with the ability to produce force rapidly leading to increases in step velocity and frequency during phases of low volume resistance training and high-intensity sprint training (21). However, to the authors' knowledge no research exists examining changes to mechanical characteristics and the sprint F-v profile in national level sprint athletes across a training year.

Therefore, the aim of this case study was to investigate how sprint mechanical characteristics change across a track and field season (~45 weeks) in two male sprint athletes who qualified for their national championships. A secondary aim was to explore how periodised sprint training influences mechanical and spatio-temporal characteristics, step kinematics and sprint performance outcomes. We hypothesized that, as the periodisation model changed between training phases and the mechanical load was reduced (31), it would likely result in improved sprint outcomes due to an enhanced F-v profile, plus optimized step kinematics for each athlete during 100-meter performance, however inter-athlete differences would be evident based on initial F-v characteristics and level of performance.

## Methods

### *Participants*

Two male sprint athletes who qualified for their national track and field championships (2021-22) in the 100-meter sprint event volunteered to participate in this study. Both athletes (Athlete 1: 22yrs, 1.83m, 100-meter time: 10.47sec; Athlete 2: 19yrs, 75.3kg, 100-meter time: 10.81sec) met the inclusion criteria of completing a minimum of 10 sprint force velocity assessments across the training and competition period. Further inclusion criteria included participants aged over 18 years of age. Exclusion criteria maintained that participants needed to be six-months free of musculoskeletal injuries which may prevent them from performing maximal effort sprints. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146). Personal best data and World Athletics points during the past 12 months of competition was collected from World Athletics (313) to establish a baseline for the performance levels of both athletes (100-meter: 10.81 ± 0.42 / 895 ± 56.5 points, 200m: 21.98 ± 1.01 / 898 ± 91.9 points).

***Study Design***

A case study design was used to monitor the sprint athletes from when they began their general preparation phase training at the end May 2021 and were followed through to the national championships at the start of April 2022 (~45-weeks). During this period the athletes completed 12 (Athlete 1) and 11 (Athlete 2) F-v assessments respectively, while also competing in 100-meter and 200-meter events (Table 7.1).

**Table 7.1.** Timeline and number of force-velocity assessments and competitions across the training year.

| Date | Phase | Type | Athlete 1 | Athlete 2 |
|---|---|---|---|---|
| June-21 | PREP | FV | 1 | 1 |
| July-21 | PREP | FV | 2 | 2 |
| Aug-21 | PREP | FV | 2 | 2 |
| Oct-21 | PREP | 100m/200m | - | 3 |
| Nov-21 | PREP | FV | 1 | 1 |
| Nov-21 | PREP | 100m/200m | - | 1 |
| Dec-21 | PREP | 100m/200m | - | 1 |
| Dec-21 | PREP | FV | 1 | 1 |
| Jan-22 | COMP | FV | 1 | 1 |
| Jan-22 | COMP | 100m/200m | 4 | 3 |
| Feb-22 | COMP | FV | 1 | 1 |
| Feb-22 | COMP | 100m/200m | 2 | 4 |
| Mar-22 | COMP | FV | 2 | 2 |
| Mar-22 | COMP | 100m/200m | 2 | 3 |
| Apr-22 | COMP | FV | 1 | - |
| Apr-22 | COMP | 100m/200m | 2 | 2 |

*PREP = preparation phase, COMP = competition phase, FV = force-velocity profile, 100m/200m = competition performance

Training components including acceleration, speed, speed endurance and strength endurance, were periodised across the year to ensure the development and retention of specific physiological and neuromuscular adaptations (184, 364). The structure of training was defined by the two track and field coaching staff working with Athlete 1 and Athlete 2 and included running based sessions on grass fields, hills and synthetic tracks, plyometrics, along with gym-based resistance training sessions focussed on developing aspects of the F-v continuum (150). Typical training cycles and periodisation of training components for the season are outlined in Table 7.2. During the preparation (PREP) phase, a 3:1 summated step loading model of periodisation, Figure 7.1: A, was implemented which allows for progressive overload of training modalities across three microcycles (~21 days), which is then followed by one microcycle (~7 days) of unloading, i.e. reduced training load

(31, 33, 263). The unloading period provides time for athlete regeneration and physiological adaptations to occur, while limiting the potential for overtraining (263). Furthermore, the step-loading model of periodisation also adds an aspect of inter-mesocycle contrast which may increase and stimulate adaptation(s) across the season (263). The competition (COMP) phase was characterized with an undulating periodisation model (also referred to as non-linear periodisation), Figure 7.1: B, across the mesocycle (~4 weeks) (271). Undulating periodisation provides more frequent changes to stimuli (i.e., volume, intensity) which have been reported to be more conducive to optimize gains in strength (271). During the COMP phase, this approach to periodisation has been implemented to provide a micro-dosing effect to training prior to reducing the training load ahead of a competition (80).

***Methodology***

Sprint F-v assessments occurred outdoors on synthetic running tracks during training sessions with Athlete 1 and Athlete 2 completing 12 and 11 assessments respectively. No wind measurements were obtained. Bodymass and environmental conditions (i.e., ambient temperature, barometric pressure) were collected on the day of each sprint F-v assessment due to its effect on F-v profile calculation. The biomechanical model to establish the F-v profile has previously been reported (286) and validated (246) when compared with direct measurement of ground reaction forces (GRF) from in-ground force plates and has been used in previous interventional studies (195). Position-time data from the electronic timing games were used in a custom-made Microsoft Excel spreadsheet (244) to derive and model all F-v variables using the equations developed by Samozino et al. (286). Recent explanations on the procedures used to determine sprint F-v characteristics are provided by Morin et al. (246).

Prior to the sprint F-v assessment, a standardized 45-minute warm-up consisting of light jogging, dynamic running-based drills and movements, and 4-8 linear accelerations, over 10-40m, progressing from sub-maximal to maximal was undertaken by each participant. Individually, participants then performed 30-metre maximal sprint efforts from either a four-point start or from starting blocks, wearing track spiked shoes. For each F-v assessment, the average splits times (i.e., 0-10m, 0-20m, 0-30m) across three trials was used for reliability purposes and to determine the minimal detectable change in performance, in line with previous research [27,28]. Timing of sprint efforts were collected with electronic timing gates (Freelap Timing System, Fleurier – Switzerland). The Freelap Timing System is an electronic timing system which records the position-time data via a radio frequency connection between an antenna located in the FxChip on the athlete, and the transmitter on the track (Tx Junior Pro). The radio frequency transmission field is suggested to be 0.80m by the manufacturer. Timing of the athlete began when the athlete moved their hand off the touch pad resting on the ground (Tx Touch Pro), with split times recorded at each 10-meter interval once the athlete passed the timing gate (Tx Junior Pro Transmitter).

**Table 7.2.** Typical training microcycles across preparation phases during the training year.

**Preparation Phase (General: Jun-Sept)**

| **DAY** | **SUNDAY** | **MONDAY** | **TUESDAY** | **WEDNESDAY** | **THURSDAY** | **FRIDAY** | **SATURDAY** |
|---|---|---|---|---|---|---|---|
| **INTENSITY** | MODERATE | MODERATE | MODERATE | MODERATE-HARD | MODERATE | EASY | MODERATE-HARD |
| **LOCATION** | GRASS INCLINE | GRASS FIELD | WEIGHTROOM | TRACK | WEIGHTROOM | POOL/BEACH | TRACK |
| **MAIN SESSION** | AM<br>Hill runs | PM<br>Speed Endurance | PM<br>Accumulation-Strength-Speed (UB) | PM<br>Special Endurance | PM<br>Accumulation- Speed-Strength (LB) | Regeneration | AM<br>Acceleration / Speed<br>Weightroom (TB)<br>Maximal effort |

**Preparation Phase (Specific: Oct-Dec)**

| **DAY** | **SUNDAY** | **MONDAY** | **TUESDAY** | **WEDNESDAY** | **THURSDAY** | **FRIDAY** | **SATURDAY** |
|---|---|---|---|---|---|---|---|
| **INTENSITY** | MODERATE | EASY-MODERATE | MODERATE-HARD | MODERATE | HARD | EASY | MODERATE-HARD |
| **LOCATION** | WEIGHTROOM | GRASS FIELD | TRACK | WEIGHTROOM | TRACK | POOL/BEACH | TRACK |
| **MAIN SESSION** | AM<br>Intensification - Strength-Speed (LB) | PM<br>Varied-paced runs | PM<br>Acceleration / Special Endurance | PM<br>Intensification -Speed-Strength (UB) | PM<br>Maximal Velocity + Tempo | Regeneration | AM<br>Acceleration / Speed Endurance |

**Competitive Phase (Jan-Mar)**

| DAY | **SUNDAY** | **MONDAY** | **TUESDAY** | **WEDNESDAY** | **THURSDAY** | **FRIDAY** | **SATURDAY** |
|---|---|---|---|---|---|---|---|
| INTENSITY | EASY | EASY-MODERATE | MODERATE-HARD | MODERATE | MODERATE | EASY | MODERATE |
| LOCATION | WEIGHTROOM | GRASS FIELD | TRACK | WEIGHTROOM | TRACK | POOL/BEACH | TRACK |
| MAIN SESSION | PM<br>Strength Circuits (TB) | PM<br>Varied-paced runs | PM<br>Acceleration / Speed | PM<br>Power (TB) | PM<br>Maximal velocity + Tempo | Regeneration | PM<br>Competition |

*(UB = Upper body, LB = Lower body, TB = Total body)

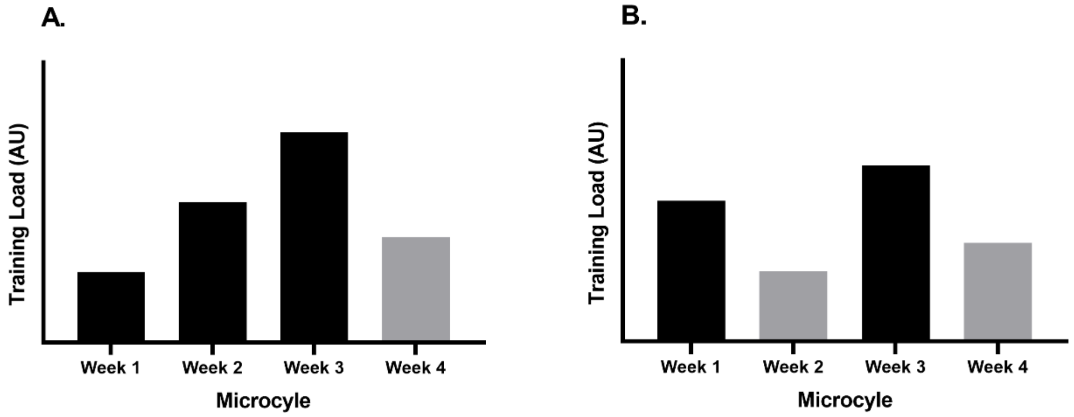


**Figure 7.1.** Periodisation models used across the training year. A: represents the summated step-loading periodisation model for the preparation phase; B: represents the undulating periodisation model during the competition phase.

The FxChip was positioned on the athletes at the midline of the waistbelt, adjacent to the anterior superior iliac crest (ASIS). Specifications for setting up the touch pad and timing gates are detailed in Figure 7.2. The reported benefits of using a 'touch-pad' approach to start the timing system is a possible reduction in the body swing and momentum gathered prior to the sprint start which may occur in a standing start (96). Previous research using a 'touch pad' reported strong between-test reliability, Intraclass correlation coefficient (ICC) =0.92, and a typical error of 0.03s over a 10-meter sprint distance, yet the authors noted the lack of familiarization of the starting technique with junior rugby players (96). At the conclusion of each sprint effort, electronic timing gate data was sent via Bluetooth to an application (MyFreelap) on a smartphone device. Reaction time is not included in the total sprint time, which at world class level is typically 0.17-0.18 ± 0.03 sec (331). Timing gate data was also provided as feedback to athletes at the conclusion of each sprint effort. Between each sprint effort there was 5-minute passive recovery period to ensure readiness before the next sprint and to limit fatigue.

The training year was periodised into two categories for statistical analysis: PREP (i.e., general and specific preparation phases – a focus on preparing the athletes for competition) and COMP (i.e., competitive phase – the focus is on achieving performance outcomes leading into state and national championships)(31, 33). The PREP phase was a 6-month period from June to December, while the COMP phase was a 3-month period from January to March. Split times were collected across the season (PREP and COMP) using timing gate data, along with bodymass, standing stature and environmental conditions (i.e. barometric pressure, temperature), which were then imported into a custom made Microsoft Excel spreadsheet (244) to determine the sprint mechanical parameters. Step kinematics were analysed according to the methodology by Salo et al. (278) and independently verified by authors (DH and RVT) using video analysis software (Kinovea v0.9.5) (264) to determine average step length and step frequency across all 100-meter performances accessible on video across the season (Athlete 1, n=6, Athlete 2, n=8).

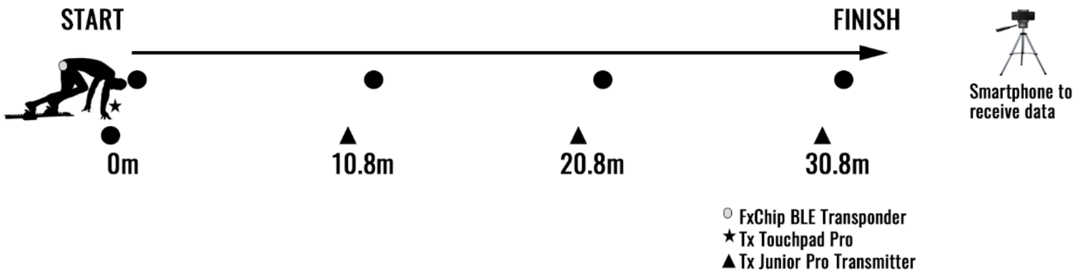


**Figure 7.2.** Electronic timing gate (Freelap) setup to record split times (10-meter intervals) from 0-30 meters.

***Statistical Analyses***

Statistical analyses were determined from input into Microsoft Excel spreadsheets (154) plus coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages. All descriptive data are presented as mean ± standard deviation (SD) for F-v and spatio-temporal variables and were assessed for normality and variance using the Shapiro-Wilks and Levene's test respectively. Intraclass correlation coefficient (ICC) with 95% confidence limits, using a two-way random effect model (absolute agreement) and coefficient of variation (CV) were used to assess relative and absolute reliability of F-v, spatio-temporal variables across the PREP phase only (152). Thresholds for evaluation of intraclass correlation coefficients were quantified using the following scale: 0.20-0.49 low, 0.50-0.74 moderate, 0.75-0.89 high, 0.90-0.98 very high and ≥ 0.99 extremely high (155). Previous biomechanical studies reported variables with a CV within the range of 10% as reliable (153), therefore acceptable reliability was determined with a CV ≤10% (69) and ICC >0.70 (7, 59, 348). To account for typical fluctuations in sprint performance across each phase of training (PREP and COMP), the minimal detectable change (MDC), using 90% confidence intervals, was used to determine the minimum level of change necessary to represent a 'true' performance change, rather than random measurement error. MDC was calculated as 1.645 x Standard error of measurement (SEM) x $\sqrt{2}$ (116, 135), from the average of sprint F-v profile variables collected during the PREP phase. The MDC% was defined as (MDC/$\bar{x}$ ) x 100 (115). Pearson's product-moment correlation coefficient (Pearson's *r*) was used to determine relationships between F-v variables and split times. The criteria to interpret the strength of the *r* coefficients were as follows: trivial (<0.1), small (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), or practically perfect (>0.9) (155). A one-way ANOVA with repeated measures was conducted to identify within-athlete changes between training phases. Within-athlete effect sizes (Cohen's d) between training phases were determined with 95% confidence limits. Magnitudes of effect size changes were interpreted using the following values: trivial (< 0.20), small (0.20 ≤ 0.60), moderate (0.60 ≤ 1.20), large (1.20 ≤ 2.00) and extremely large (> 2.00) (52). Linear regression analysis was also used to determine the relationship between 100-meter competition performance and step length (SL) and step frequency (SF). An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

**Results**

Shapiro-Wilks and Levene's test confirmed normality and homogeneity of variance for all F-v and spatio-temporal variables. Absolute and relative reliability, minimal detectable change (MDC) and standard error of measurement (SEM) data for F-v and spatio-temporal (split-times) variables for both athletes are presented in Table 7.3. Based on the F-v and spatio-temporal results from the PREP phase, intraclass correlation coefficients (ICC) and coefficient of variation (CV%) were almost all within acceptable limits (ICC: 0.73-0.98, CV%: 0.3-4.6) suggesting a high-level of reliability for both athletes when analyzing three sprint trials. The minimal detectable change (%) across F-v variables ranged from 1.3-10.0% while spatio-temporal variables were much lower, 0.94-1.48%, with Athlete 1 showing a higher 'true change' in performance across the season compared to Athlete 2.

Descriptive data for F-v and spatio-temporal (split-times) variables for both athletes are presented as mean ± standard deviation (SD) in Table 7.4. Changes to F-v and P-v relationships between phases are highlighted in Figure 7.3. Athlete 1 showed significantly large within-athlete effects between phases for relative $P_{MAX}$, $v_0$, $RF_{MAX}$, $V_{MAX}$, and split time from 0-20m and 0-30m ($-1.70 \leq ES \geq 1.92$, $p \leq 0.05$), which coincided with new personal best performances over both sprint distances during the COMP phase (100-meter: 10.47sec, 1050pts) (Table 7.4, Figure 7.4: A1). Athlete 2 reported significant differences with large effect for relative $F_0$ only (ES: $\leq$ -1.32, $p \leq 0.01$), which also led to new performance bests over 100-meter (10.81sec, 943 points) during the COMP phase (Table 7.4, Figure 7.4: A2). Both athletes also reported statistically significant increases in maximum ratio of forces ($RF_{MAX}$) (ES: $\leq$ -1.28, $p \leq 0.05$). No significant changes to bodymass were noted between phases ($p \geq 0.05$).

During the PREP phase, both athletes showed high negative correlations with relative $F_0$ and $P_{MAX}$ and split time from 0-10 meters ($r = -0.83$, $p \leq 0.02$), while during the COMP phase both athletes reported a higher correlation with $v_0$ and 0-30 meters which coincided with sprint performance outcomes during competition (Figure 7.5, Supplemantal files. The relationship between $S_{FV}$, $D_{RF}$, Tau and 0-30m was also stronger during the COMP phase (Figure 7.5). An analysis of 100-meter performance and step kinematics highlights the reliance Athlete 1 (Figure 7.6: A1, A2) has on step length to achieve faster sprint times ($r = -0.95$, $p = 0.01$), whereas Athlete 2 showed similar relationships between both step length ($r = -0.72$, $p=0.04$) and step frequency ($r = -0.70$, $p=0.06$) and 100-meter performance, however only step length achieved significance (Figure 7.6: B1, B2). Non-significant changes were evident for $S_{FV}$ and $D_{RF}$ across the training year.

## Discussion

The aim of this case study was to explore the mechanical changes to the sprint F-v profile and sprint outcomes across a track and field season in two 100-meter athletes who qualified for the national championships. To the authors knowledge, this is the first study to use longitudinal training data to investigate the relationship between F-v variables and sprint performance outcomes across a 10-month period. We believe the information presented including typical training microcycles, F-v and spatio-temporal variables, along with step kinematic, provide a holistic and transparent view of the changes which occur in response to periodised sprint training.

Our key findings are as follows: a), when comparing the PREP and COMP phases, Athlete 1 showed an enhanced F-v profile due to significant changes to relative $P_{MAX}$, $v_0$ and improved $F_0$, whereas Athlete 2 reported significant changes to $F_0$ and improved $P_{MAX}$ thereby demonstrating a more 'force-oriented' F-v profile, b) positive mechanical changes and improved sprint performance observed during the early COMP phase was significantly correlated with increased step length and favourable step frequency, and c) inter-athlete differences were observed for correlations between $F_0$ and $P_{MAX}$ and 0-10 meters in the PREP phase, and $v_0$ and 0-30 meters during COMP phase.

**Table 7.3.** Reliability measures and minimal detectable change for force-velocity and spatio-temporal variables across the training year.

| Variable | Relative $F_0$ (N.kg$^{-1}$) | $v_0$ (m.s$^{-1}$) | Relative $P_{MAX}$ (W.kg$^{-1}$) | Relative $S_{FV}$ (N.s.m$^{-1}$.kg$_{-1}$) | $RF_{MAX}$ (%) | $D_{RF}$ (%.m.s$^{-1}$) | $V_{MAX}$ (m.s$^{-1}$) | Tau | Split time 0-10m (s) | Split time 0-20m (s) | Split time 0-30m (s) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Athlete 1** | | | | | | | | | | | |
| ICC | 0.94 (0.89, 0.96) | 0.73 (0.51, 0.88) | 0.94 (0.85, 0.98) | 0.87 (0.73, 0.95) | 0.96 (0.91, 0.98) | 0.85 (0.70, 0.94) | 0.82 (0.62, 0.94) | 0.87 (0.73, .95) | 0.89 (0.77, 0.96) | 0.98 (0.94 0.99) | 0.91 (0.81, 0.97) |
| CV (%) | 1.83 | 1.69 | 0.99 | 3.36 | 0.55 | 3.44 | 1.40 | 3.06 | 0.57 | 0.31 | 0.30 |
| SEM | 0.11 | 0.18 | 0.31 | 0.01 | 0.002 | 0.002 | 0.12 | 0.04 | 0.01 | 0.01 | 0.02 |
| MDC | 0.32 | 0.51 | 0.86 | 0.05 | 0.008 | 0.005 | 0.32 | 0.10 | 0.03 | 0.03 | 0.06 |
| MDC% | 4.24 | 4.56 | 4.08 | 7.46 | 1.66 | 8.33 | 3.06 | 7.35 | 1.48 | 0.95 | 1.43 |
| **Athlete 2** | | | | | | | | | | | |
| ICC | 0.89 (0.76, 0.96) | 0.86 (0.70, 0.95) | 0.96 (0.87, 0.98) | 0.80 (0.26, 0.94) | 0.96 (0.91, 0.98) | 0.82 (0.36, 0.94) | 0.88 (0.72, 0.96) | 0.81 (0.61, 0.93) | 0.93 (0.81, 0.98 | 0.97 (0.95, 0.98) | 0.97 (0.95,0.98) |
| CV (%) | 2.31 | 2.23 | 0.68 | 4.50 | 0.64 | 4.61 | 1.88 | 3.94 | 0.49 | 0.30 | 0.28 |
| SEM | 0.09 | 0.22 | 0.28 | 0.02 | 0.003 | 0.002 | 0.17 | 0.03 | 0.01 | 0.01 | 0.01 |
| MDC | 0.26 | 0.65 | 0.79 | 0.06 | 0.006 | 0.006 | 0.48 | 0.09 | 0.03 | 0.03 | 0.05 |
| MDC% | 3.65 | 5.78 | 3.95 | 9.37 | 1.30 | 10.00 | 4.61 | 6.29 | 1.44 | 0.94 | 1.17 |

*ICC = intraclass correlation coefficient; CV = coefficient of variation; MDC = minimal detectable change, ICC are expressed with 95% confidence intervals.

**Table 7.4.** Descriptive statistics for force-velocity and spatio-temporal variables across the training year.

| Variable | Participant | PREP Mean ± SD | COMP Mean ± SD | Mean difference, %Δ | Within-athlete ES (+95% CL) (PRE-COMP) | p value |
|---|---|---|---|---|---|---|
| **Relative $F_0$ ($N.kg^{-1}$)** | Athlete 1 | 7.53 ± 0.50 | 7.96 ± 0.56 | 0.43, 5.77 | - 0.81 (-2.55, 0.92) | 0.19 |
| | Athlete 2 | 7.12 ± 0.27 | 7.60 ± 0.35 | 0.48, 6.33 | -1.56 (-3.17, 0.03) | 0.03* |
| **$v_0$ ($m.s^{-1}$)** | Athlete 1 | 11.18 ± 0.31 | 11.62 ± 0.35 | 0.44, 3.81 | -1.32 (-3.44. 0.79) | 0.04* |
| | Athlete 2 | 11.23 ± 0.59 | 11.27 ± 0.72 | 0.04, 0.29 | -0.05 (-1.46, 1.36) | 0.94 |
| **Relative $P_{MAX}$ ($W.kg^{-1}$)** | Athlete 1 | 21.03 ± 1.32 | 23.10 ± 1.09 | 2.07, 8.99 | -1.70 (-3.79. 0.37) | 0.01** |
| | Athlete 2 | 20.00 ± 1.48 | 21.36 ± 0.49 | 1.36, 6.34 | -1.08 (-2.59, 0.42) | 0.12 |
| **Relative $S_{FV}$ ($N.s.m^{-1}.kg^{-1}$)** | Athlete 1 | -0.67 ± 0.05 | -0.69 ± 0.06 | -0.02, 1.80 | 0.20 (-2.40, 1.80) | 0.73 |
| | Athlete 2 | -0.64 ± 0.03 | -0.68 ± 0.07 | -0.04, 6.42 | 0.80 (-0.66, 2.27) | 0.23 |
| **$RF_{MAX}$ (Maximum ratio of forces)** | Athlete 1 | 0.48 ± 0.01 | 0.49 ± 0.01 | 0.01, 3.71 | -1.28 (-3.21, 0.63) | 0.05* |
| | Athlete 2 | 0.46 ± 0.01 | 0.48 ± 0.002 | 0.02, 3.24 | -1.46 (-3.04, 0.11) | 0.04* |
| **$D_{RF}$ (Decrement in ratio of forces)** | Athlete 1 | -0.060 ± 0.00 | -0.061 ± 0.00 | 0.001, 0.88 | 0.10 (-1.50, 1.70) | 0.87 |
| | Athlete 2 | -0.057 ± 0.00 | -0.061 ± 0.01 | 0.003, 5.97 | 0.70 (-0.75, 2.16) | 0.29 |
| **$V_{MAX}$ (Maximal horizontal velocity)** | Athlete 1 | 10.43 ± 0.24 | 10.84 ± 0.26 | 0.41, 3.83 | -1.63 (-3.93, 0.65) | 0.01** |
| | Athlete 2 | 10.41 ± 0.49 | 10.48 ± 0.57 | 0.07, 5.69 | -0.13 (-1.55, 1.28) | 0.84 |
| **Tau (Relative acceleration)** | Athlete 1 | 1.36 ± 0.10 | 1.34 ± 0.11 | -0.02, 1.64 | 0.20 (-1.38, 1.78) | 0.74 |
| | Athlete 2 | 1.43 ± 0.07 | 1.36 ± 0.12 | -0.07, 2.20 | 0.81 (-1.55, 2.28) | 0.22 |
| **Split time 0-10m (s)** | Athlete 1 | 2.02 ± 0.04 | 1.96 ± 0.04 | -0.06, 2.72 | 1.20 (-0.61, 3.01) | 0.06 |
| | Athlete 2 | 2.07 ± 0.04 | 2.02 ± 0.01 | -0.05, 2.15 | 1.10 (-0.40, 2.62) | 0.11 |
| **Split time 0-20m (s)** | Athlete 1 | 3.14 ± 0.07 | 3.04 ± 0.05 | -0.10, 3.38 | 1.57 (-0.55, 3.70) | 0.02* |
| | Athlete 2 | 3.19 ± 0.07 | 3.11 ± 0.03 | -0.08, 2.45 | 1.23 (-0.30, 2.76) | 0.08 |
| **Split time 0-30m (s)** | Athlete 1 | 4.18 ± 0.07 | 4.05 ± 0.05 | -0.13, 3.11 | 1.92 (-0.18, 4.03) | 0.007* |
| | Athlete 2 | 4.25 ± 0.11 | 4.17 ± 0.06 | -0.07, 2.03 | 0.83 (-0.63, 2.30) | 0.22 |

*PREP= preparation phase (general and specific), COMP=competitive phase. ES = effect size, CL = confidence limits.

In reference to our hypothesis, the longitudinal nature of this study primarily identifies the influence specific sprint training stimuli and periodisation models have on sprint F-v characteristics, thereby highlighting the F-v profile adheres to the SAID principle (Specific Adaptations to Imposed Demands)(143). Once the periodisation model changed between the PREP and COMP phase, sprint mechanical characteristics were enhanced in both athletes. This confirmed our hypothesis. With respect to the F-v profile with the highest force value for each athlete, relative $F_0$ (8.13-8.92 N.kg-1), $V_{MAX}$ (9.67-10.49 m.s-1) and $P_{MAX}$ (21.11-24.78 W.kg-1) were maximized during the COMP phase within a 35-day period between January and March with changes evident in F-v profiles between phases. For Athlete 1, when relative $P_{MAX}$ increased during the COMP phase it resulted in a season's best 100-meter performance (10.47sec), whereas Athlete 2 had similar performance outcomes (10.84sec) in response to an increase in relative $F_0$ (Figure 7.4: B1 and B2). Samozino et al. (285) have recently showed sprint acceleration performance, irrespective of distance, is directly related to the average external power output produced over the entire targeted distance, therefore from a mechanical perspective, the 100-meter performance differences and changes in pre-post F-v profiles between athletes may be expected due to Athlete 1 demonstrating superior $P_{MAX}$, and significant changes to $v_0$ in the COMP phase. Furthermore, previous studies focussing on longer sprint accelerations (i.e., 40-100-meter) identified both $P_{MAX}$ and $v_0$ as key determinants of performance (235, 236, 266, 308).

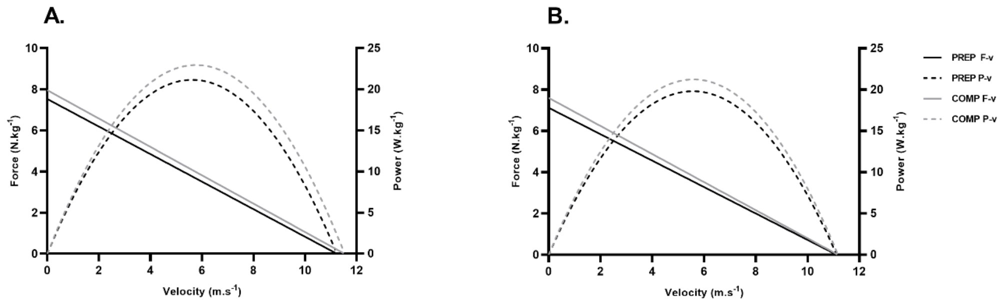


**Figure 7.3.** Sprint force-velocity (F-v) and power-velocity (P-v) relationships between the PREP and COMP phase. A: Athlete 1, B: Athlete 2.

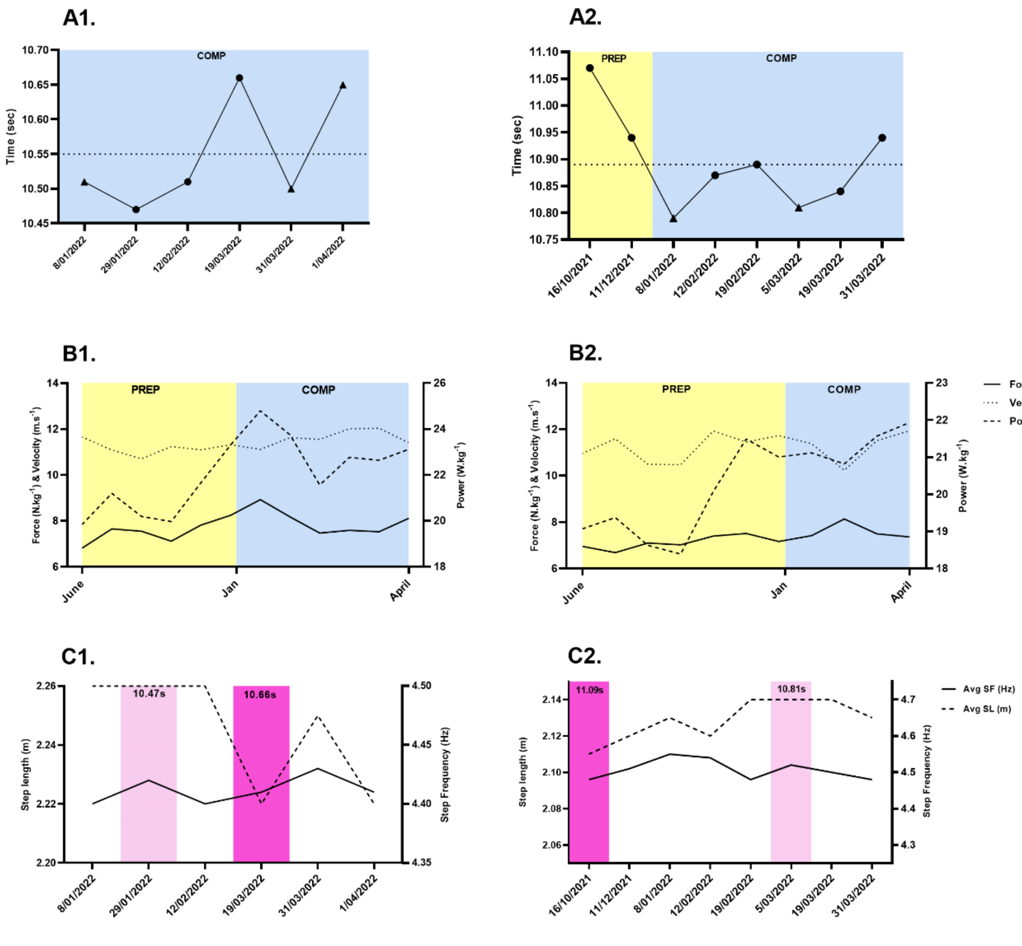


**Figure 7.4.** Sprint performance, F-v variables, and step kinematics across the training year. A1: Athlete 1 100-meter performances, A2: Athlete 2 100-meter performances (PREP = preparation phase, COMP = competition phase. Dotted line: average of performances. Circle: legal performance, triangle: wind-aided performance (>+2.0m.s-1)); B1: Athlete 1 force, velocity, and power changes across the training year, B2: Athlete 2 force, velocity, and power changes across the training year; C1: Athlete 1 step kinematics during 100-meter competitions; C2: Athlete 2 step kinematics during 100-meter competitions. (Dark shade column = slowest performance of season, Light shade column = Season's best).

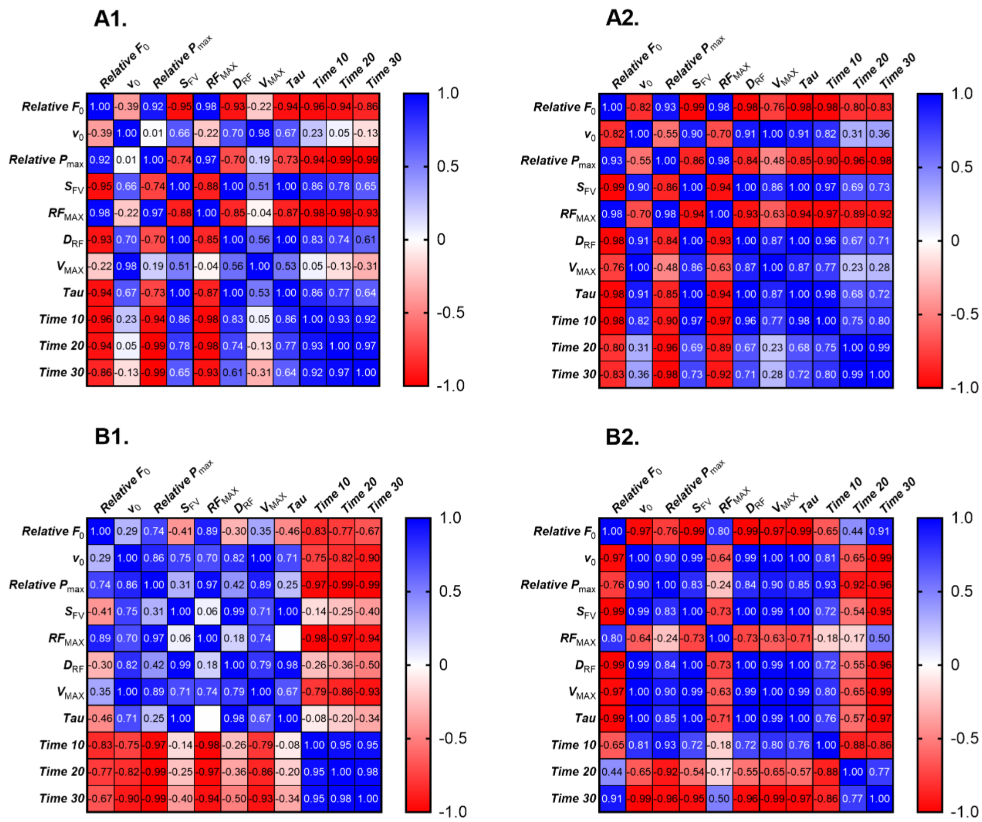


**Figure 7.5.** Correlation matrix between F-v variables and spatio-temporal variables. A1: Athlete 1 PREP, A2: Athlete 1 COMP; B1: Athlete 2 PREP, B2: Athlete 2 COMP.

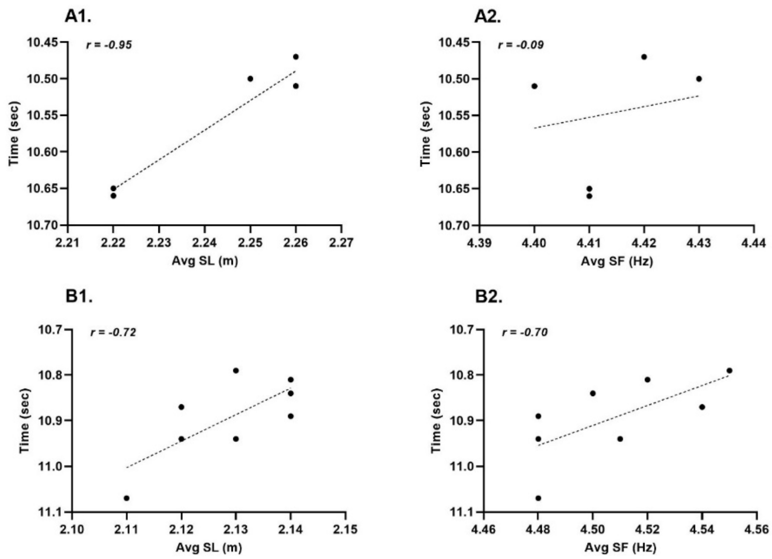


**Figure 7.6.** Individual 100-meter competition times as a function of step length (SL) and step frequency (SF). Athlete 1: A1, A2; Athlete 2: B1, B2. Note that the y-axes have been inverted because faster times highlight improved performance. Due to inverted y-axes, the direction of *r* values do not match the visual impression.

Significant mechanical changes also appear to coincide with a change in periodisation models. A step-loading periodisation model in the PREP phase had a focus on speed endurance (i.e., high intensity efforts for 7-15 seconds in duration), strength endurance (i.e., hill work, moderate to high intensity efforts for 15-45 seconds in duration) and a greater number of strength and conditioning sessions, whereas during the COMP phase an undulating model placed a greater focus on acceleration and speed work (i.e., maximum intensity and velocity efforts ≤ 7 seconds in duration), plyometrics, less strength and conditioning sessions, with an overall higher intensity and lower volume (metres) (Table 7.2). When comparing both athletes, during the transition period from PREP to the COMP phase, although greater for Athlete 1, it could be surmised the upward trend in $P_{MAX}$ reflects a reduction in training density, less mechanical load, greater recovery time and an emphasis on neuromuscular development via velocity specific training modalities (Figure 7.4: B1). This change in periodisation model from training quantity (i.e., volume) to training quality (i.e., speed-specific intensity), although relatively typical during sprint training programmes (143), appears to have been also led to personal best performances during 100-meter competitions.

Both athletes in this study showed a significant relationship between step length and 100-meter performance ($r \geq -0.72$, $p \leq 0.01$), highlighting their reliance on this component to achieve faster velocities, however Athlete 2 did also demonstrate a moderate non-significant correlation with step frequency ($r \geq -0.70$). Associations between step length (2.46-2.60m) and sprint performance have previously been reported in elite level male sprinters (10.18-10.52sec), highlighting key differences in finishing position based on step length (119). Other research has acknowledged a significant relationship between step length and sprint velocity (r=0.73), and a negative interaction effect between step length and step frequency (r=-0.78) based on individual biomechanical and kinematic characteristics (119, 156). Contradictions to these findings have also been presented (21) identifying a clear association between step frequency (group mean: 4.85Hz) and 100-meter performance (10.16 ± 0.16sec), with lower step frequency noted in specific training blocks (4.34Hz). It has previously been suggested step length is more related to increased force production, whereas step frequency is associated with higher rates of force production during ground contact and leg turnover requiring greater neural adaptations (275, 278), which may also be a reflection of training load and training content during the COMP phase. It could therefore be concluded, that by limiting the volume of speed endurance and strength endurance leading into important competitions has maximized mechanical characteristics and step kinematics necessary to drive 100-meter performance outcomes. Moreover, when attempting to plan training for the successive training year, placing a greater emphasis on acceleration and speed work during these periods at the expense of other training modalities, may enhance $P_{MAX}$ as these training modalities would encourage higher $V_{MAX}$ and therefore potentially further optimize step kinematics and the F-v profile and provide greater improvements in sprint performance. Despite differences in previous studies regarding step kinematics, this may be accounted for due to subject population and performance level of the athlete (i.e., faster athletes).

Correlations between F-v and spatio-temporal variables across the training year identify how the training phase affects F-v characteristics of each athlete differently. Both athletes demonstrated similar correlations between $F_0$ and $P_{MAX}$ from PREP to COMP phase however stronger correlations between spatio-temporal variables and $v_0$ exist once the periodisation structure moved into the COMP phase (Figure 7.5). This is likely a result of the change in training focus, but more importantly the frequent demand for maximal velocity efforts during competitions. The decrement in ratio of forces ($D_{RF}$) or mechanical effectiveness (286) of both athletes, also showed stronger correlations in the COMP phase compared to the PREP phase, potentially due to neuromuscular adaptation and the ability to continue producing a high level of horizontally directed force across the sprint effort at higher running velocities. Adaptations for $D_{RF}$ have been observed in sprint athletes with similar 100-meter performance levels of those in this case study (314).

It is interesting to note, for both athletes, a downward trend in bodymass (Athlete 1: -2.6%, Athlete 2: -1.9%) from the beginning of the PREP phase until the early COMP phase also coincided with positive mechanical changes and performance outcomes (Supplemental files). Bodymass is a key consideration for sprint performance due to fundamental Newtonian laws of motion and the energy cost of accelerating a higher mass. Uth (335) has previously identified elite male sprinters having bodymass values of 77 ± 7kg, however it is the change and improvement in relative mechanical values and the ability to apply mass specific force (i.e., force and power per kilogram of bodymass) which is of greater importance during maximal velocity sprinting (352).

A novel aspect of this case study is to explore the variability and minimal detectable change (MDC) in respect to sprint F-v variables across the training year. Based on the average of F-v variables across the PREP phase, Athlete 1 and Athlete 2 exceeded the MDC in 82% and 55% of sprint F-v and spatio-temporal variables respectively, suggesting a true change in performance occurred beyond the measurement error (Table 7.4). Previous research using MDC to detect changes in F-v characteristics and sprint performance in junior Australian football players suggests this is an appropriate measure to determine improvements are a result of the training interventions rather than error (100). The MDC for the same variables are much lower in magnitude in this case study compared to previous research, however this is likely accounted for in difference in sprint performance between the two population groups.

Interestingly, Athlete 1 tested positive to COVID-19 on 18/FEB/2022, therefore beginning a 10-day isolation period in his home, as per local government regulations. During this time, the athlete was quite ill and only limited training could be done including basic bodyweight resistance training and stationary bike intervals. Upon resuming training, an obvious level of fatigue was evident resulting in slower running times. This appears to be reflected in a decline in relative $F_0$ (-9.51%), $v_0$ (-0.06%) and $P_{MAX}$ (-9.22%) between the F-v profiles collected before and after the illness (Figure 7.4: B1), along with recording the slowest 100-meter performance of their season, 10.66 (19/MAR/22)(Figure 7.4: A1). Analysis of step kinematics identifies a reduction in step length during this performance period, which is likely a result of a reduction in force production while sprinting (Figure 7.4: C1). Commentary on the impacts of COVID-19 and sport performance has centred on physical and mental health, with authors suggesting the reduced training frequency, potential loss in muscle function and emotional health from isolation to have a negative impact on performance outcomes once returning to training and competition (159, 295, 350).

Due to the exploratory nature of this case study, the authors' identified several limitations. Firstly, the small sample size of athletes (n=2) provides a narrow cross-section of sprint F-v and performance data in which to analyse. Post-hoc analysis using the following test details: 'ANOVA: Repeated measures, within factors, with an effect size of 0.5, alpha of 0.05, provides a power level of only 0.29, which highlights differences between the means will only be detected 29% of the time. To achieve 0.8 power, we would require 6 participants in this study. This may limit the conclusions outlined below as the case study is underpowered. Secondly, the part-time status of the athletes and the availability of training hours on synthetic tracks, made it necessary to conduct F-v assessments at different hours of the day (i.e., morning and late evening) across the training year, reflecting the dynamic considerations of the practitioners. Also, despite several F-v assessments occurring as part of a designated testing session, most assessments were collected as part of a typical training session within the mesocycle. Thirdly, recent research (338) has suggested a time correction (+0.21) is necessary for calculating accurate F-v profiles when comparing electronic timing gate data with more precise technology such as an optical laser gun. Despite the difference in methodology and data collection in this study, this should be taken into consideration. Finally, future research should investigate sprint athletes involved in national finals or international competition to monitor the change in mechanical, spatio-temporal and sprint kinematic variables leading into a major competition.

## Conclusions

This is the first longitudinal study to investigate how a periodised sprint training programme influenced F-v characteristics, step kinematics and 100m sprint performance in national level sprint athletes. For both athletes, once the periodisation model changed between training phases sprint mechanical characteristics were enhanced and increases in step length showed greater correlations with 100m sprint performance. The findings of this study may provide practitioners with greater insight into training programme design and periodisation structure for athletes of similar performance levels, plus identify the underpinning mechanical characteristics and step kinematics affecting sprint outcomes leading into national championships. Practitioners may also use the results of this study to anticipate changes to sprint performance at different phases of the training year, while also identifying which periodisation models and sprint mechanical characteristics lead to improved performance outcomes for their athletes.

## PRELUDE

The purpose of Chapter 8 and chapter 9 is to collate the learnings of the thesis into two evidence-based approaches as to how best to utilize F-v profiling methodology to inform training interventions and improve physical performance. This chapter (and Chapter 9) acts as the practical application sections of the thesis. Chapter 8 provide practitioners with a system to categorize and individualize training prescription from sprint F-v profiles to enhance performance in team and individual sport athletes. Despite F-v variables presenting key information about the underpinning mechanisms contributing to sprint performance, the overall data interpretation may be limited for the practitioner to implement training interventions when compared to the researcher. Therefore, using mechanical characteristics of sprint performance, this article provides coaches with a conceptual framework to determine an appropriate training prescription based on individual biomechanical and technical characteristics contributing to performance.

# CHAPTER 8

# Individualization of training based on sprint force-velocity characteristics: A conceptual framework for biomechanical and technical training recommendations

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**Abstract**

The purpose of this article is to provide practitioners with a system to categorize and individualize training prescription from sprint F-v profiles to enhance performance in team and individual sport athletes. Despite F-v variables presenting key information about the underpinning mechanisms contributing to sprint performance, the overall data interpretation may be limited for the practitioner to implement applied training interventions when compared to the researcher. Therefore, this article provides a conceptual framework to determine appropriate training prescriptions based on individual biomechanical and technical characteristics contributing to sprint performance.

## Introduction

Acceleration ability is one of the key components to success in athletic sprint events yet also an essential skill in many team-based field and court sports. Faster team sport players can often reposition themselves on the field more quickly during decisive moments of the game such as challenges for the ball and during goal scoring opportunities (108, 272), therefore identifying the mechanical characteristics underpinning acceleration and sprint performance is desirable. Key performance indicators during the acceleration phase of a sprint action include: propulsive impulse (142, 157), thereby producing and applying a high level of antero-posterior (horizontal direction) force (236) under time constraints; increased magnitude of maximal external power (285); plus the continued ability to orient the force vector horizontally as running velocity increases (166, 236, 266). To quantify the mechanical determinants contributing to sprint performance a field method known as F-v profiling has been proposed (286).

Sprint F-v profiling is a diagnostic tool used to determine the maximal mechanical capabilities of the neuromuscular system (286) and describes the linear F-v relationship. Sprint F-v profiling has gained greater interest in sports performance literature more recently due to simple field method approaches (266, 286) providing performance characteristics which can be used to individualize training interventions (194, 195), plus identify potential risk of injury (98, 223). A sprint F-v profile is typically determined by performing maximal unloaded sprint efforts across 20-40m with various split times (e.g. 0-10m, 10-20m, 20-30m etc.) collected by timing games/photocells (145), velocity-time or position-time data collected using a radar gun (195, 302) or other technology types including high-speed camera, optical laser (303), a portable resistance training device (146) or global positioning system (GPS) units (192). From the velocity-time or position-time data, this can then be input in a custom made Microsoft excel spreadsheet (244) to determine athletes' step-averaged kinetics and kinematics in the sagittal plane of motion and used to generate mechanical relationships based on the field method previously outlined (286). The linear F-vand polynomial power-velocity (P-v) relationships obtained from sprint accelerations, provide a macroscopic and integrative view of the overall F-v-power profile of an athlete in sprint specific actions (286). This method has been shown to be valid and reliable compared to the gold standard; in-ground force plates (246).

The key variables obtained from sprint F-v profiling include theoretical maximal force ($F_0$), theoretical maximal movement velocity ($v_0$) and external theoretical maximal power ($P_{MAX}$) (i.e. not power at the joint(s)), and often referred to as determinants of performance based on the fundamental laws of motion (286) (Figure 8.1). Both $F_0$ and $v_0$ have been shown to be independent of each other and representative of different biomechanical and technical abilities via a complex integration of physiological and neural mechanisms (95, 162). Other associated variables collected during profiling assessments include the F-v slope ($S_{FV}$), maximum ratio of forces ($RF_{MAX}$) (236) and decrement in ratio of forces ($D_{RF}$) (286), which in turn have been used to distinguish between sports, age, gender, playing position  and level of performance (74, 85, 86, 139, 351). $RF_{MAX}$ is computed as the ratio of the step-averaged horizontal component of the ground reaction force (i.e., mechanical effectiveness) to the corresponding resultant force (236). A higher percentage ratio of force represents a greater proportion of total force production directed in the forwards direction in the initial stages of the sprint acceleration. The $D_{RF}$ represents an index of force application and describes the athlete's capability to limit the loss in mechanical effectiveness with increasing running velocity (236). Across a range of sports, the relationship (Pearson's *r*) between F-v sprint variables and 10-meter sprint performance have previously been reported to show mostly strong correlations (i.e., $F_0$: -0.89, $v_0$: -0.87,

$P_{MAX}$: -1.00, $RF_{MAX}$:-1.00), however the $S_{FV}$ and $D_{RF}$ demonstrated greater associations with 40-meter sprint time (139). At an elite level, a comparison of the F-v profiles of male and female world class sprinters showed significant negative linear relationships between $P_{MAX}$ (r = -0.87), $RF_{MAX}$, (r = -0.81), $v_0$ (r = -0.78), and $F_0$, (r = -0.66) and 100-meter sprint times, highlighting the utility of mechanical characteristics to explain variance in elite sprint performance (315). External maximal power in the horizontal direction ($P_{MAX}$) is of particular interest to coaches, not only due to strong correlations with sprint performance (73, 235, 266, 308), but since it is the product of force and velocity expressed horizontally, it provides coaches with greater insight into which input(s) should be the focus during training to improve overall maximal power output. The F-v slope ($S_{FV}$) established via the axis intercepts of each variable, highlights the linear F-v relationship between both variables. These have been identified as indicators to whether a greater focus on high velocity actions or force-based strength training should be a key focus during preparation periods (242). Furthermore, by analyzing all F-v characteristics and comparing sprint profiles between athletes, it may identify potential imbalances or deficits in mechanical characteristics (175), which when targeted with individualized gym-based or sprint-specific training (150, 195) could maximize overall sprint capabilities, reduce sprint time and therefore enhance athletic performance.

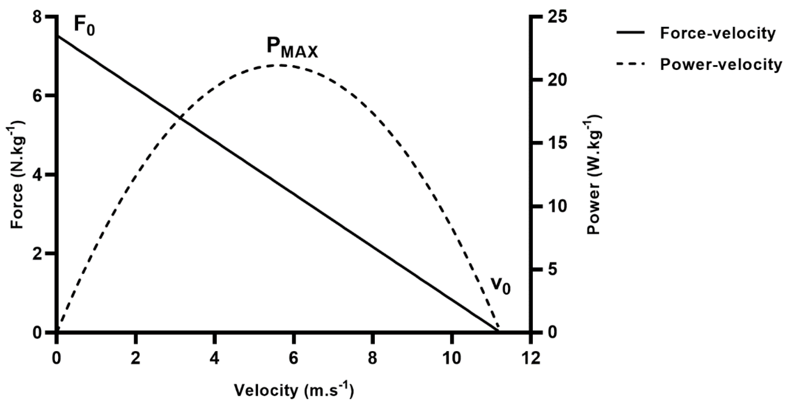


**Figure 8.1.** Visual representation and key variables obtained from the simple field method of sprint force-velocity profiling. ($F_0$ = theoretical maximal force, $P_{MAX}$ = theoretical maximal external power, $v_0$ = theoretical maximal velocity).

For practitioners, individualizing training prescription is key to optimizing athlete performance (75, 285), however before coaching staff can begin to improve capabilities, they must first understand the mechanical components which underpin sprint performance and determine if this combination is optimal for the athlete based on individual characteristics and sport/event demands. Despite the F-v slope providing the key data to determine whether an athlete has a force or velocity-oriented profile, or a balanced profile (equal reliance on both force and velocity), comparisons to peers in the same team or event may be difficult when analyzing the slope of several athletes (Figure 8.2: A), plus may be challenging to rapidly categorize athletes compared to group normative values. Therefore, another approach which may provide practitioners with an alternate visualization of the relationship between force and velocity and their associated variables is by grouping athlete data into quadrants or categories (Figure 8.2: B). A quadrant or category-based system attempts to improve the readability of the data for the practitioner by providing insight to potential 'windows of opportunity' and identifying biomechanical and technical strengths or weaknesses and creating more *coach friendly* language and visualizations.

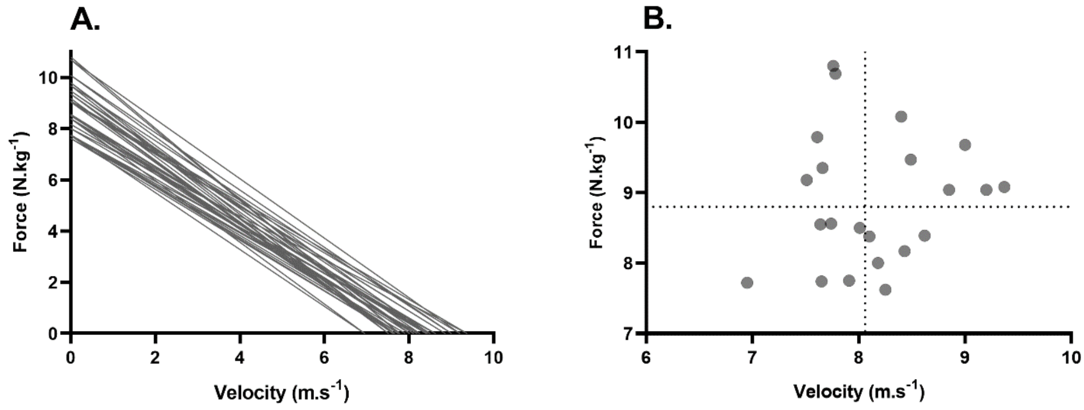


**Figure 8.2.** Force-velocity ($F_0$-$v_0$) data presented as the F-v slope (A) compared to a scatter plot divided into quadrants (B). The same data in represented in both plots.

Sprint acceleration is a result of applying a large forces ($F_0$) in the horizontal direction, in a short amount of time (propulsive impulse) to achieve a high level of power and attain the highest velocity possible, which are related to *biomechanical* factors (236). However, *technical* factors such as orienting the body's center of mass in a more horizontal direction in reference to the point of force transmission (i.e., the foot) (25) also influences acceleration performance. Specifically, the maximum ratio of forces ($RF_{MAX}$) applied in the first few steps, along with how the ground reaction force vector changes as velocity increases across the sprint effort, i.e., mechanical effectiveness (236). The combination of biomechanical and technical F-v variables provides a more well-rounded analysis to explain the overall sprint performance. Moreover, with greater information about an athlete's current capabilities, the coach can design a training intervention from both a biomechanical (neuromuscular) and technical (coaching cues) perspective to further enhance sprint outcomes.

It is the authors' opinion that although many coaches understand the concept of the F-v relationship during sprinting and the benefit of profiling their athletic population, many are limited with applying this information to their training programme design to improve performance. Therefore, the primary aim of this article is to first, explore a conceptual framework to sprint F-v profiling by establishing quadrants and categories to describe the biomechanical and technical characteristics of sprint performance, and then secondly, based on these characteristics provide practitioners with physical preparation and sprint-specific training and coaching recommendations to enhance sprint performance. Practitioners are encouraged to use this framework to enhance overall sprint performance with their athletes however to also be mindful the biomechanical and technical suggestions may not always be appropriate for athletes within each quadrant an/or category due to inter-athlete differences and may represent stereotypical characteristics of athletes who have clear mechanical strengths and weaknesses.

**Biomechanical analysis**

In a strength and conditioning setting, sprint performance is often based upon improving acceleration capabilities (150). During a sprint effort, acceleration is inversely proportional to bodymass and therefore the ability to express a high level of force relative to bodymass (e.g., a =F/m) is essential. However, due to the nature of the task, horizontally directed relative force ($N.kg^{-1}$) must be produced at changing velocities ($m.s^{-1}$) and time intervals (contact time; ms). In a 100-meter sprint setting, when beginning the sprint effort i.e., initial steps, the velocity is lower (5-7 $m.s^{-1}$) and longer ground contact times (>100 milliseconds [ms]) are necessary, whereas once the athlete approaches maximal velocity (>10 $m.s^{-1}$), high velocities and shorter ground contact times (< 100ms) become prominent (228). In team sports, depending on positional demands, some athletes may produce an efficient sprint effort by producing force in the horizontal direction at low velocities, i.e., Offensive lineman, whereas other athletes will express force in the horizontal direction at higher velocities i.e., wide receiver (85), and yet also be effective in their sport or position.

By analyzing the biomechanical variables underpinning the sprint effort (i.e., $F_0$-$v_0$) and creating a coordinate plane using a scatter plot, i.e., the intersection of the x-axis (velocity [m.s-1]) and y-axis (force [$N.kg^{-1}$]), and in this example, using the median data point ($50^{th}$ percentile) from a team sport population dataset, we can establish four quadrants with different biomechanical and sprint performance characteristics. Figure 8.3 and Table 8.1, identify the F-v characteristics of National Football League (NFL) draft picks (85) across all positions and then separated into three broad position groups. Despite the homogeneous population at each position, there remains considerable biomechanical differences contributing to sprint performance within each quadrant thereby highlighting potential limitations to performance. Many practitioners understand the importance of individualizing training prescription; however, the NFL dataset reveals distinct between-position and within-position differences, suggesting distinct training strategies are potentially required to address biomechanical strengths and weaknesses specific to sprint performance. Although overall sprint time (i.e., 40-yard) is not identified in this analysis, recent research (285) suggests sprint performance is optimized when power expression in the horizontal direction increases. This suggests datapoints located in quadrants 2-4 have biomechanical limitations which if addressed via strength and conditioning interventions could potentially improve sprint outcomes. The suggested biomechanical characteristics of each quadrant are explained below and detailed in Figure 8.

**Table 8.1.** Sprint force-velocity profile data across National Football League draft positional groups divided into quadrants based on the within-position median value of force and velocity datapoints (85).

| | **Quadrant 1** | | **Quadrant 2** | | **Quadrant 3** | | **Quadrant 4** | |
|---|---|---|---|---|---|---|---|---|
| | **Force ($N.kg^{-1}$)** | **Velocity ($m.s^{-1}$)** | **Force ($N.kg^{-1}$)** | **Velocity ($m.s^{-1}$)** | **Force ($N.kg^{-1}$)** | **Velocity ($m.s^{-1}$)** | **Force ($N.kg^{-1}$)** | **Velocity ($m.s^{-1}$)** |
| **All Positions** | > 9.88 | > 9.77 | > 9.88 | < 9.77 | < 9.88 | < 9.77 | < 9.88 | > 9.77 |
| **Skill (RB, WR, DB)** | > 10.53 | > 10.22 | > 10.53 | < 10.22 | < 10.53 | < 10.22 | < 10.53 | > 10.22 |
| **Big Skill (QB, LB, TE)** | > 9.97 | > 9.61 | > 9.97 | < 9.61 | < 9.97 | < 9.61 | < 9.97 | > 9.61 |
| **Linemen (OL, DL)** | > 8.88 | > 8.89 | > 8.88 | < 8.89 | < 8.88 | < 8.89 | < 8.88 | > 8.89 |

*RB=running back, WR=wide receiver, DB=defensive back, QB=quarter-back, LB=linebacker, TE=tight end, OL=offensive linemen, DL=defensive linemen

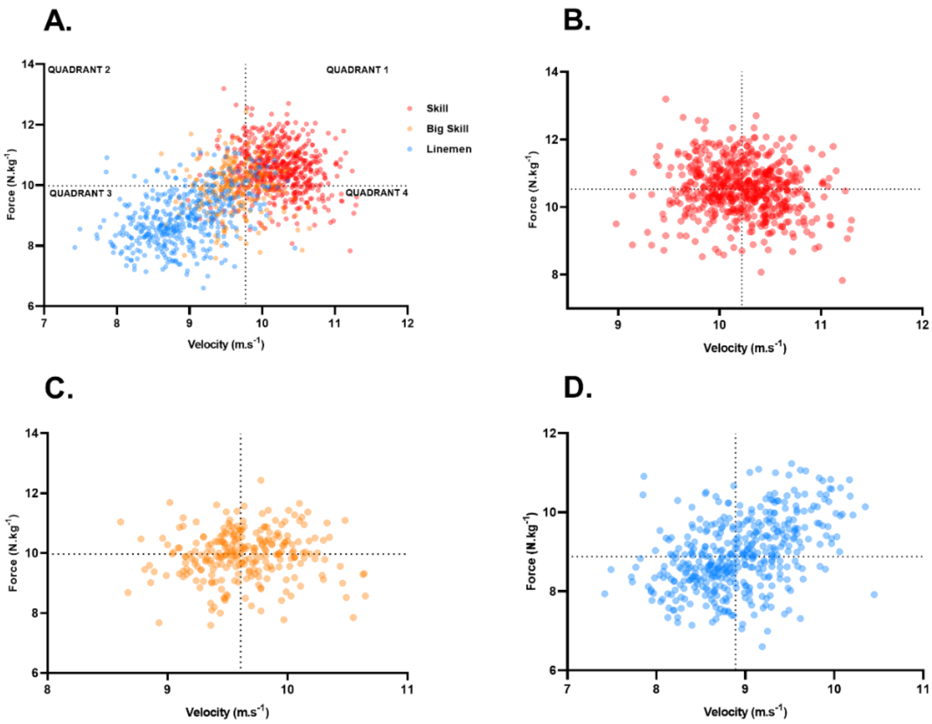


**Figure 8.3**. A quadrant-based approach to force-velocity variables using a National Football League dataset (85). Median value from each variable in the cohort creates the coordinate plane. A: Combined positional groups [n=400]; B: Skill [Running back, Wide Receiver, Defensive Back] n=197; C: Big Skill [Tight end, linebacker, quarterback] n=84; D: Linemen [Offensive linemen, defensive linemen] n=119).

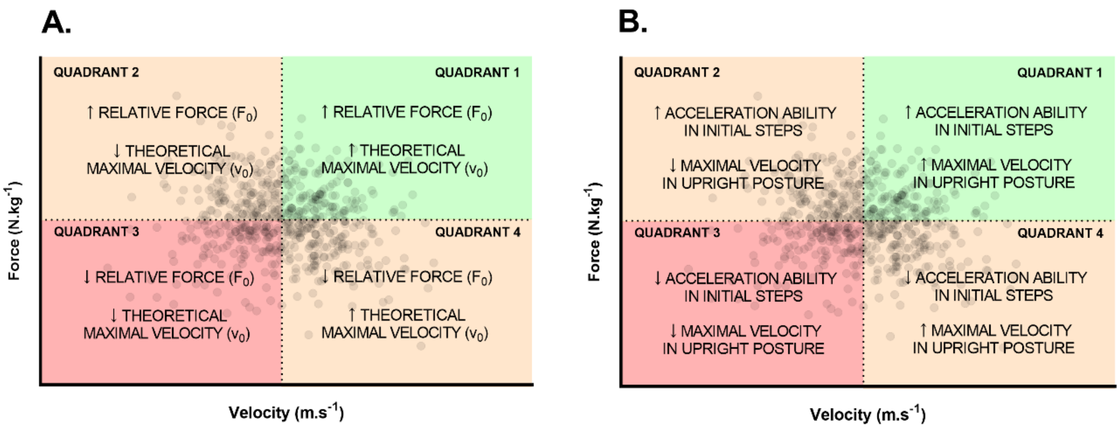


**Figure 8.4.** Biomechanical characteristics from sprint force-velocity data (A) and suggested effect on sprint performance (B).

### Quadrant 1 (High $F_0$-High $v_0$)

Athletes in quadrant 1 demonstrate higher levels of relative force ($N.kg^{-1}$) and velocity across the sprint effort. The biomechanical characteristics of athletes in quadrant 1 would include a high rate of force production in the horizontal direction while also achieving a high maximum velocity. Quadrant 1 displays mechanical characteristics most desirable to optimize sprint performance, as relative to sprint distance, external maximal power is maximized via high values of both force and velocity.

### Quadrant 2 (High $F_0$-Low $v_0$)

Athletes in quadrant 2 demonstrate higher levels of relative force ($N.kg^{-1}$) but fail to reach a high maximal velocity across the sprint effort. The biomechanical characteristics of athletes in quadrant 2 would include a high rate of force production in the horizontal direction yet a relatively limited maximum velocity. Quadrant 2 displays mechanical characteristics where force is the dominant variable contributing to external maximal power expression.

### Quadrant 3 (Low $F_0$-Low $v_0$)

Athletes in quadrant 3 demonstrate lower levels of relative force ($N.kg^{-1}$) and maximal velocity across the sprint effort. The biomechanical characteristics of athletes in quadrant 3 would include a slower rate of force production in the horizontal direction and a limited maximum velocity. Quadrant 3 displays mechanical characteristics least desirable to optimize sprint performance, as relative to sprint distance, external maximal power expression is limited via low values of both force and velocity.

### Quadrant 4 (Low $F_0$-High $v_0$)

Athletes in quadrant 4 demonstrate lower levels of relative force ($N.kg^{-1}$) but a higher respective maximal velocity across the sprint effort. The biomechanical characteristics of athletes in quadrant 4 would include a slower rate of force production in the horizontal direction yet achieve a relatively high maximum velocity. Quadrant 4 displays mechanical characteristics where velocity is the dominant variable contributing to external maximal power expression.

Interestingly, since external maximal power is the product of force and velocity, athletes may achieve the same level of power yet with different combinations of both mechanical variables i.e., quadrant 2 and 4, therefore identifying a particular deficit or imbalance which could be addressed to improve performance and reduce sprint time (285). Data in the quadrant is specific to the individual, age, sex and sport/event/position and should serve to provide context to a homogenous sporting population. Within each sport i.e., NFL, experienced practitioners should aim to develop a priori, or a set of normative values for desirable F-v targets (Table 8.1), yet also determine and understand the biomechanical strengths or weaknesses of the athlete.

### Technical analysis

Data from sprint F-v profiling can also indirectly describe how the athlete is moving in space and time during the sprint effort, therefore providing the practitioner with technical insights about the orientation and application force into the ground. The relationship between the $RF_{MAX}$ during early acceleration and horizontal velocity ($v_H$), describes the orientation of force in the initial steps of the sprint (i.e., mechanical effectiveness) (185) which is a technical component of sprint running. This is achieved at approximately 0.3-0.5sec into the sprint effort (280). Elite level sprint athletes and American Football players have shown $RF_{MAX}$ values of approximately 46-54% (85, 235), whereas lower level team sport and youth athletes demonstrate $RF_{MAX}$ values between 40-48% (104, 170). This identifies how this F-v variable differentiates between performance level and the technical aspects of sprinting. The slope of the linear decrease in net force production in the horizontal direction for each meter as running velocity increases ($D_{RF}$), further characterizes and athletes ability (or inability) to maintain force application in the horizontal direction as running velocity increases across the sprint effort (280). Morin et al. (235, 236) has previously reported strong correlations between $D_{RF}$ and key 100-meter performance parameters, with high level sprinters demonstrating 'good' $D_{RF}$ values between -6 to -4%, whereas those with 'poor' $D_{RF}$ values displaying lower values of -7.05 to -11.65%, typically evident in team sport and youth populations (9, 104, 365). As an athlete's $D_{RF}$ becomes more negative i.e., steeper $RF_{MAX}$-$v_H$ slope, the less net force directed horizontally is being produced during the sprint acceleration; effectively limiting sprint performance (236), and vice-versa with a 'flatter' $RF_{MAX}$-$v_H$ slope. Effectiveness of ground force application values for $RF_{MAX}$ and $D_{RF}$ are highlighted in Table 8.2 and provide context to performances across a range of sports and ability levels.

Therefore, by analyzing sprint F-v data from a technical perspective, athletes can be placed into four categories based on their orientation of force in the horizontal direction (i.e., $RF_{MAX}$), mechanical effectiveness (i.e., $D_{RF}$ slope) and sprint characteristics which are detailed below and in Figure 8.5.

**Table 8.2.** Effectiveness of ground force application values of sprint performance derived from force-velocity profiles across team and individual sport populations.

| | $RF_{MAX}$ (%) | $D_{RF}$ |
|---|---|---|
| **Elite male sprinters (9.92-10.20sec)** | 53-58.4 | -4.2 to -8.0 |
| **Running back (American Football)** | 53 | -9.3 |
| **Sub-elite sprinters (10.49 ± 0.24sec)** | 49 | -7.33 |
| **Male Futsal players (1st division)** | 49 | -7.60 |
| **Recreational sprinters (11.77 ± 0.22sec).** | 45.9 | -7.5 |
| **Female hurdlers (14.06 ± 0.3 s)** | 42.8 | -7.32 |
| **Soccer players (youth)** | 43 | -9.0 |
| **Australian Football players (youth)** | 42 | -8.55 |

*$RF_{MAX}$ = maximum ratio of forces; $D_{RF}$ = index of force application (17, 85, 104, 112, 170, 235, 314, 316).

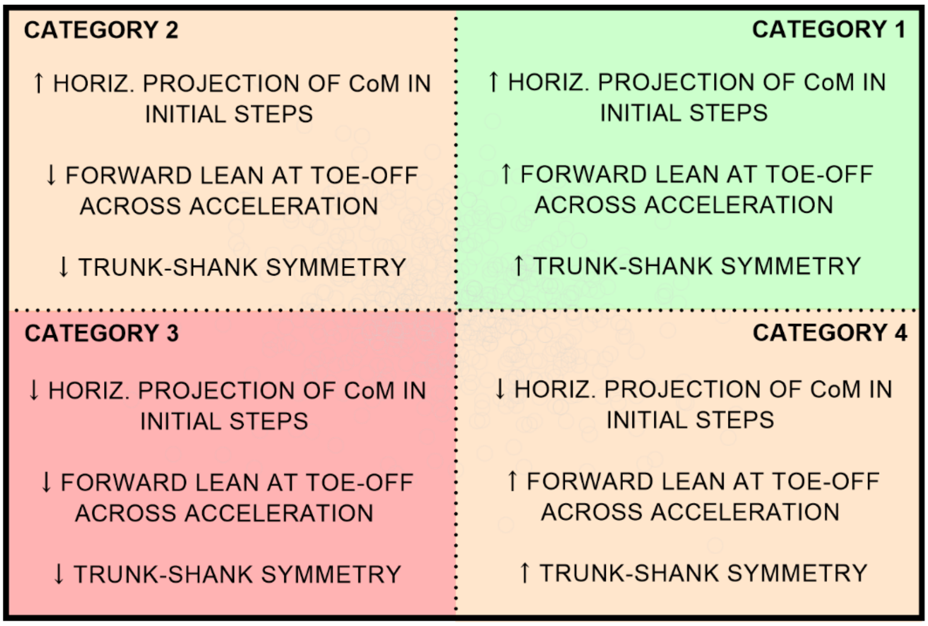


**Figure 8.5.** A category-based approach to force-velocity variables describing the technical characteristics (A) and suggested effect on sprint performance (B). Horiz. = horizontal, $F_H$ = horizontal force production, $D_{RF}$ = index of force application, CoM = centre of mass.

### Category 1 (High $RF_{MAX}$-High mechanical effectiveness)

Athletes in category 1 demonstrate strong qualities to orient their force in a horizontal direction at the beginning of the sprint effort yet demonstrate a more gradual decrease in force production directed horizontally as velocity increase across the sprint effort. The technical characteristics of athletes in category 1 would likely include a strong ability to project their center of mass forwards in the initial steps of acceleration potentially due to an effective shin roll (4), while also maintaining mechanical effectiveness as velocity increases. This would see the athlete move from a more horizontal to upright posture relatively late in the sprint effort due to demonstrating greater forward lean at toe-off (191) and greater trunk-shank symmetry (92, 93, 349). Category 1 displays technical characteristics most desirable to optimize overall sprint acceleration performance.

### Category 2 (High $RF_{MAX}$-Low mechanical effectiveness)

Athletes in category 2 demonstrate strong qualities to orient their force in a horizontal direction at the beginning of the sprint effort but demonstrate a rapid decrease in force production directed horizontally as velocity increases across the sprint. The technical characteristics of athletes in category 2 would likely include a strong ability to project their center of mass forwards in the initial steps of the acceleration, potentially due to an effective shin roll (4), yet the inability to maintain mechanical effectiveness as velocity increases. This would see the athlete move from a more horizontal to upright posture relatively early in the sprint effort due to demonstrating less forward lean at toe-off (191) and less trunk-shank symmetry (92, 93, 349).

### Category 3 (Low $RF_{MAX}$- Low mechanical effectiveness)

Athletes in category 3 are limited in their ability to orient their force in a horizontal direction at the beginning of the sprint, along with showing a rapid decrease in force production directed horizontally as velocity increases across the sprint effort. The technical characteristics of athletes in category 3 would likely include a limited ability to project their center of mass forwards in the initial steps of acceleration, potentially due to an ineffective shin roll (4), along with limited ability to maintain mechanical effectiveness as velocity increases. This would see the athlete move from a more horizontal to upright posture relatively early in the sprint effort due to demonstrating less forward lean at toe-off (191) and less trunk-shank symmetry (92, 93, 349).

**Category 4 (Low $RF_{MAX}$- High mechanical effectiveness)**

Athletes in category 4 are limited in their ability to orient their force in a horizontal direction at the beginning of the sprint effort but demonstrate a gradual decrease in horizontal force production as velocity increases across the sprint effort. The technical characteristics of athletes in category 4 would likely include a limited ability to project their center of mass forwards in the initial steps of acceleration, potentially due to an ineffective shin roll (4), yet a relative ability to maintain mechanical effectiveness as velocity increases, despite the $D_{RF}$ slope being more negative than Category 1 athletes. This would see the athlete move from a more horizontal to upright posture slower than athletes in category 2 and category 3, due to a greater ability to maintain their forward lean at toe-off (191) and greater trunk-shank symmetry in reference to the ground (92, 93, 349).

Furthermore, using video analysis of athletes across their sprint acceleration to create a sequence of images, similar to a kinogram (240), to analyse in conjunction with the F-v data can provide greater insight about potential coaching or cueing strategies which could be implemented to improve acceleration abilities (Figure 8.6).

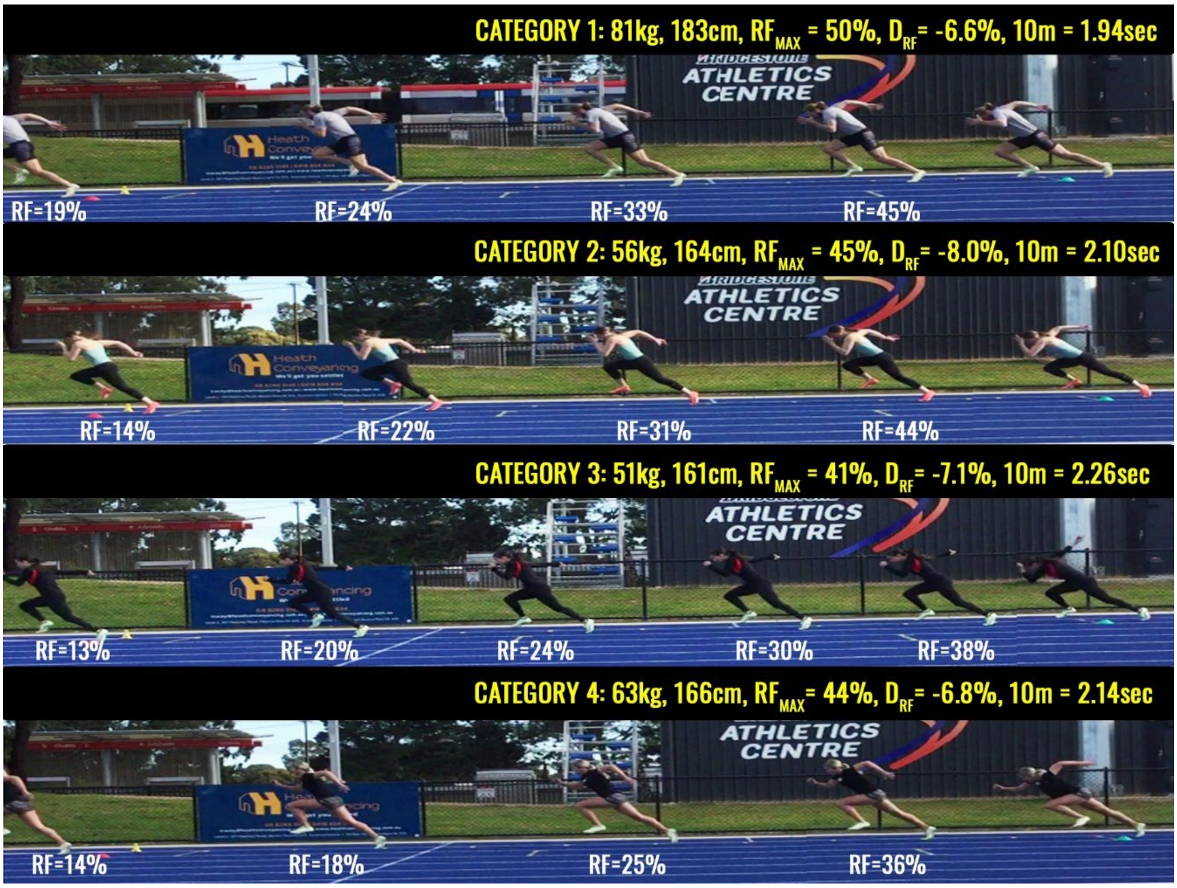


**Figure 8.6.** A video analysis sequence across a 10m sprint acceleration identifying the ‘toe-off’ position which is strongly correlated with the orientation of force in the horizontal direction (191). Ratio of force (RF%) is identified at toe-off at step 2, 4, 6, 8 (and 10) for each athlete (244). 10-meter time recorded using Freelap Timing System (excluding reaction time.

### Practical applications and guidelines

After analysis of the biomechanical and technical characteristics from the sprint F-v profile, the practitioner must then determine any potential ‘*windows of opportunity’* to improve overall sprint performance. Sprint F-v literature (242) suggests all athletes should be aiming to improve biomechanical characteristics by increasing overall $P_{MAX}$ expression in the horizontal direction, i.e., pushing their data point *‘up and to the right’*, whereas technical characteristics should be enhanced to improve the orientation and application of force across the total duration of the sprint effort. Proposed characteristics of movement, physical preparation, and sprint-specific training and coaching recommendations to improve biomechanical and technical characteristics of sprint performance are identified in Table 8.3 and Table 8.4.

As opposed to solely using traditional gym-based exercises (i.e., power clean, back squat), biomechanical and technical imbalances or deficiencies during sprinting will likely be improved by targeting the neuromuscular system through sprint-specific (37, 41-43, 142, 143, 150, 233) or velocity-specific exercises (190), plus using attentional focus to improve motor learning adaptations (19). For example, it is suggested that if an athlete displays F-v characteristics in quadrant 2 (i.e., higher force, lower velocity), they will likely produce a rapid acceleration through a relatively high step frequency, which may be advantageous in some sports with a high number of short sprint efforts i.e., basketball (9). However, these characteristics of the performance may limit the overall sprint outcome if further sprint distances are required in the sport or event (285). Although technical factors must always be considered, to improve the biomechanical characteristics of athlete's located in quadrant 3 (i.e., lower force, higher velocity), it is suggested athletes focus on exercises which span the F-v continuum and explore multiple loads (329) to improve $P_{MAX}$ such as resisted sprint training (241) and speed bounding (306). The predicted visual description of sprint movement based on the technical characteristics from the sprint F-v profile suggests various coaching cues may be useful to improve or reduce the technical errors the athlete is making during their sprint performance (Table 8.4). For example, it is suggested that if an athlete displays technical characteristics in category 3, they have a limited ability to overcome inertia and project their center of mass forwards in the initial steps, plus they limit force production in the horizontal direction as their center of mass resides closer (above) to the point of force transmission (191), thereby emphasizing a greater vertical component to the ground reaction force earlier in the sprint effort. Also, a more perpendicular lower limb shank angle during touchdown has been identified to reduce acceleration performance and differentiate between elite and sub-elite sprinters (92, 349). To improve the technical characteristics of athlete's located in category 3, it is suggested the coach provides technical cues which focus on providing a more conducive start position to push greater force horizontally, improve their shin roll, focus on pushing down and back, improve trunk-shank symmetry (92) and slowly raise the torso with each successive step. Recently, Alt et al. (4) emphasized the importance the shin segment's orientation to produce a mechanically efficient acceleration, which appears to support previous studies highlighting orientation of the body center of mass and subsequent propulsive impulse (191). Practitioners should also critically analyse the inter-athlete biomechanical and technical variability during the sprint action despite athletes residing in the same quadrant or category. It is feasible some athletes may not fit the stereotype within each suggested group and may require other training components to enhance sprint performance.

**Table 8.3.** Characteristics of movement and training recommendations to improve or maintain biomechanical characteristics of sprint performance (37, 142, 143, 150, 233).

| Quadrant | Characteristics | Visual description of movement | Training modality to improve or maintain force-velocity qualities |
|---|---|---|---|
| Quadrant 1 | Faster acceleration, higher velocity | • higher force producing capabilities at low velocity<br>• patient acceleration<br>• good mix of step rate and step length<br>• maximizes acceleration distance<br>• repositions lower limbs optimally<br>• ground contact time is lower at max velocity | • acceleration/speed work (<7 seconds)<br>• resisted sprint training (25-50% velocity decrement, ~10-20m)<br>• flying sprints<br>• assisted sprint training<br>• speed bounding<br>• improved isometric hamstring strength |
| Quadrant 2 | Faster acceleration, lower velocity | • higher force producing capabilities at low velocity<br>• rushed acceleration<br>• high step rate<br>• achieves maximal velocity rapidly<br>• repositions lower limbs rapidly<br>• ground contact time is higher at max velocity | • acceleration/speed work (<7 seconds)<br>• resisted sprint training (25-50% velocity decrement, ~10-20m)<br>• flying sprints<br>• assisted sprint training<br>• improved stretch shortening cycle<br>• improved reactive strength<br>• improved connective tissue strength |
| Quadrant 3 | Slower acceleration, lower velocity | • lower force producing capabilities at low velocity<br>• limited acceleration distance<br>• inability to create a good step rate and step length<br>• repositions lower limbs slowly | • acceleration/speed work (<7 seconds)<br>• resisted sprint training (50-75% velocity decrement, ~10m)<br>• flying sprints<br>• improved stretch shortening cycle<br>• improved strength of hip extensors<br>• improved strength of soleus and gastrocnemius |

| | | | |
|---|---|---|---|
| | | • ground contact time is higher at max velocity | • improved absolute/relative force qualities<br>• improved reactive strength<br>• improved rate of force development |
| Quadrant 4 | Slower acceleration, higher velocity | • lower force producing capabilities at low velocity<br>• limited acceleration distance<br>• has the ability to create a good step rate and step length<br>• repositions lower limbs rapidly<br>• ground contact time is lower at max velocity | • acceleration/speed work (<7 seconds)<br>• resisted sprint training (50-75% velocity decrement, ~10m)<br>• improved strength of hip extensors<br>• improved absolute force/relative qualities<br>• improved rate of force development<br>• improved connective tissue strength |

**Table 8.4.** Characteristics of movement and training recommendations to improve or maintain technical characteristics of sprint performance *CoM = centre of mass (4, 19, 25, 40, 45-47, 93, 150, 191, 233, 236, 255, 353).

| **Category** | **Characteristics** | **Visual description of movement** | **Technical cues to improve or maintain efficiency of movement** |
|---|---|---|---|
| Category 1 | Strong orientation of force in initial steps, and good mechanical effectiveness of force at increasing speeds | • effective push and projection of the CoM in initial steps<br>• torso has a forward lean, leading to shank creating more horizontal force through the acceleration (i.e., effective shin roll)<br>• effective heel lock, shin block, shin drop and horizontal ankle rocker<br>• effective 'scissor like action' between the limbs<br>• due to slower transition of the CoM from in front of point of force application (i.e., the foot) to above the point of force application, horizontal force production (i.e., resultant ground reaction force) is extended across the acceleration | • Maintain good hip extension through each successive step<br>• Keep pushing down and back i.e., *like you are pushing a car*<br>• Maintain a more horizontal rather than vertical torso position<br>• Slowly raise your CoM position with each successive step<br>• Maintain a stiff ankle joint upon ground contact<br>• Further increase thigh angular velocity i.e., *whip from the hip* |
| Category 2 | Strong orientation of force in initial steps, but limited mechanical effectiveness of force at increasing speeds | • effective push and projection of the CoM in initial steps<br>• torso becomes vertical rapidly, leading to shank producing less horizontal force through the acceleration (i.e., limited shin roll)<br>• moderate level of heel lock, shin block, shin drop and horizontal ankle rocker | • Keep your eyes focused on the track (i.e., therefore not raising torso too soon)<br>• After initial steps, push for longer and extend through the hip, rather than creating flexion at the knee<br>• Land on the forefoot of your shoe<br>• Don't let your heel drop to the track |

| | | | |
|---|---|---|---|
| | | • moderate level of 'scissor like action' between the limbs<br>• due to rapid transition of the CoM from in front of point of force application (i.e., the foot) to above the point of force application, horizontal force production (i.e., resultant ground reaction force) is limited | • Keep your hip in front of the point of force application/transmission (i.e., the foot)<br>• Keep pushing down and back *like you are pushing a car*<br>• Patiently move your torso from more horizontal to vertical *like a plane taking off*<br>• Increase thigh angular velocity i.e., *whip from the hip*<br>• Reduce horizontal braking forces at max velocity |
| Category 3 | Limited orientation of force in initial steps, and limited mechanical effectiveness of force at increasing speeds | • limited push and projection of the CoM in initial steps<br>• torso becomes vertical rapidly, leading to shank producing less horizontal force through the acceleration (i.e., limited shin roll)<br>• limited heel lock, shin block, shin drop and horizontal ankle rocker<br>• ineffective 'scissor like action' between the limbs<br>• due to rapid transition of the CoM from in front of point of force application (i.e., the foot) to above the point of force application, horizontal force production (i.e., resultant ground reaction force) is limited | • Ensure the lead foot is behind the hip when applying force off the start line (i.e., improve horizontal orientation of force)<br>• Create good hip extension through each successive step and limit knee flexion (i.e., whip from the hip)<br>• Keep pushing down and back *like you are pushing a car*<br>• Maintain a more horizontal rather than vertical torso position<br>• Slowly raise your CoM position with each successive step<br>• Land on the forefoot of your shoe<br>• Don't let your heel drop to the track<br>• Increase thigh angular velocity i.e., *whip from the hip*<br>• Reduce horizontal braking forces at max velocity |
| Category 4 | Limited orientation of force in initial steps, but good mechanical effectiveness of force at increasing speeds | • limited push and projection of the CoM in initial steps | • Ensure the lead foot is behind the hip when applying force off the start line (i.e., improve horizontal orientation of force)<br>• Keep pushing down and back *like you are pushing a car* |

| | | | |
|---|---|---|---|
| | | • torso has a forward lean, leading to shank creating more horizontal force through the acceleration (i.e., effective shin roll)<br>• limited heel lock, shin block, shin drop and horizontal ankle rocker<br>• ineffective 'scissor like action' between the limbs<br>• due to slower transition of the CoM from in front of point of force application (i.e., the foot) to above the point of force application, horizontal force production (i.e., resultant ground reaction force) is extended across the acceleration | • Maintain a more horizontal rather than vertical torso position<br>• Slowly raise your CoM position with each successive step<br>• Maintain a stiff ankle joint upon ground contact<br>• Further increase thigh angular velocity i.e., *whip from the hip*<br>• Reduce horizontal braking forces in initial steps of acceleration |

From a biomechanical and technical perspective, strength and conditioning interventions could be established using primary, secondary and tertiary foci based on key priorities of the training cycle of the sport (Figure 8.7). These foci are suggestions for coaches of where to place their focus first and potentially areas which may provide the best *bang for their buck* when selecting training interventions. The primary focus of all athletes aiming to improve sprint performance should be to increase the ratio of force (%) oriented horizontally across the initial steps of the sprint effort (22, 185). Across various athletic populations, $RF_{MAX}$ has almost perfect correlations with 10-meter (-1.00 ± 0.01) and 40-meter (-0.96 ± 0.01) split times, with sprint athletes typically demonstrating the highest values (>50%) (139, 266). According to Newton's second law, an increased ability to produce, orient and apply force in the antero-posterior direction will directly result in improved acceleration capabilities of the athlete center of mass, and therefore must be the priority (236). Improving these qualities may be achieved by increasing the absolute and relative force qualities of the athlete via targeted training interventions (150), along with focusing on the athlete's orientation and transmission of force through the foot. A secondary focus should be placed on analyzing and potentially addressing the deficit(s) or imbalance(s) identified via a quadrant/category approach and maintaining qualities if necessary (Table 8.3 and Table 8.4). To improve overall sprint performance from a biomechanical and technical perspective, it may be necessary to implement a training intervention(s) to improve the ability to produce $P_{MAX}$, orient and transmit force in a more horizontal direction and maintain mechanical effectiveness across the sprint effort. For example, biomechanical imbalances (quadrant 2-4) may improve by including training modalities such as moderate or heavy resisted sprint training using a sled (37, 194) plus also assist in placing the athlete in a more desirable posture to apply force during acceleration. Conversely, athletes located in quadrant 1 may need to improve $P_{MAX}$ by focusing on exercises at the velocity end of the F-v continuum such as assisted sprint training (337), thereby attempting to improve motor learning, electromyography activity and coordination at supramaximal velocities (225). Furthermore, analyzing the athlete's kinematics and shapes (Figure 8.5) (240) to determine whether this is a limiting factor to sprint performance should also be a consideration. A tertiary focus should be placed on the time during the season when assessing F-v profiles. The duration of the preparation phase (251) and overall periodisation of training or competition will influence whether imbalances identified within the quadrants should be addressed with specific interventions at a particular time of the season.

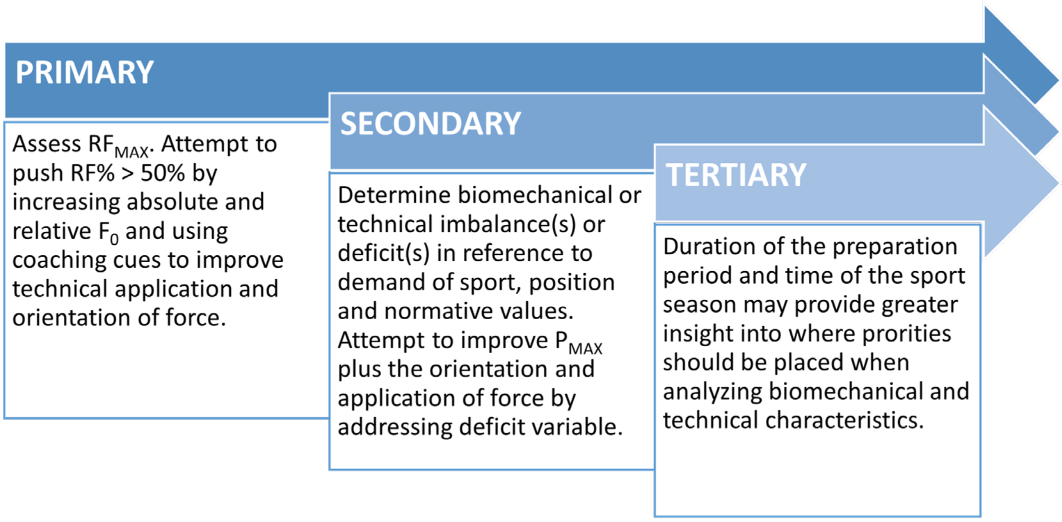


**Figure 8.7.** A flow chart of priorities based on general force-velocity profile characteristics, mechanical imbalances, and preparation periods.

### Optimizing the sprint F-v profile

Recently, the theoretical and conceptual basis for an optimal sprint F-v profile has been presented to demonstrate sprint acceleration performance is largely determined by maximizing external power capabilities along with the optimization of the mechanical F-v profile of sprint propulsion in reference to sprint distance (285). Optimization of the F-v profile has previously been reported for vertical jump actions (242, 288). Regardless of the $S_{FV}$, an inverse relationship was identified between $P_{MAX}$ and sprint times, highlighting the necessity to understand the best balance of force and velocity to maximize this variable across the sprint effort for a set distance. From a practical perspective, due to the dynamic nature and demands of team sports, attempting to optimize an athlete's F-v profile is challenging, however an analysis of the demands of the sport and position within the sport may provide a more desirable profile based on frequency of sprint distance and individual F-v characteristics (285). For example, due to the biomechanical, technical, and tactical demands of the position, one athlete with a balanced F-v profile, may need to maximize external power over varying sprint distances during training due to positional requirements (i.e., midfielder in soccer). Whereas the optimal F-v profile for another player (i.e., running back, defensive back, wide receiver; American Football) may require maximal power to be achieved via a more force-oriented profile due to the focus and requirement of initial acceleration to 'break-through' or 'break-away' during decisive plays during the game. Therefore, the categorization of groups of athletes (i.e. positions, sports) via quadrants also has strong utility towards attempting to optimize the F-v profile, as it may provide greater insight into which type of training programme (e.g., force-oriented, velocity-oriented, optimal load)(150) may induce the best adaptation to improve $P_{MAX}$ and reduce sprint time.

## Limitations

Although sprint F-v profiles may present some similar characteristics amongst athletes within the same sport, previous research has suggested profiles to be more individual than sport specific (139). In a practical setting, this would highlight the importance of using a quadrant or category-based system to analyse and compare athletes with their peers, interpret the information, then categorize individuals presenting similar characteristics and prescribe training accordingly. Furthermore, athletes within the same sport or position may present a similar F-v profile, however individual data should form the basis for training prescription (139, 285).

Sprint performance of the overall athlete population group can present limitations when utilizing quadrants or categories to prescribe training interventions. Since the intersection of perpendicular lines of the quadrant may be based on the median value of the group, if a greater number of athletes in the group record poor performances, or the overall performance in the group is low (e.g., novice, adolescent athletes), it can artificially place athletes into sections of the quadrant not warranted when compared against cohorts in the same competition yet performing at a higher level. Therefore, developing a set of priori or normative values for each variable (and athlete population) will enhance the interpretation of results and provide greater context when assessing or targeting group variables. Finally, despite this framework providing biomechanical and technical consideration for performance coaches, the sprint performance outcome, i.e., the time to cover the set distance, should remain one of the key performance indicators.

## Further considerations

Upon analysis of sprint F-v data, the time required to elicit both biomechanical and neuromuscular adaptations, along with technical changes should be a consideration of the sports performance coach. Resistance training literature suggests neural adaptations can occur relatively quickly after briefs bouts of intensive exercise (134). However, it is suggested due to the complex nature and segmental dynamics of sprinting, biomechanical changes may occur over a longer period of time (275). Previous research has shown that velocity of movement, as controlled by the load, is one of the key factors in improving high-velocity performance (218) and therefore at specific periods of the season, specificity of the task may need to inform training direction (190). In the case of sprint performance improvement, coaches may only have 6-10 weeks to work with an athlete during their off-season, e.g. American football off-season preparation (251), which may require the coach to consider the time investment to improve the athlete. Coaches must assess whether there is sufficient time to develop neuromuscular adaptations through physical training or technical changes (e.g. improved step length, step frequency, force orientation) and improved skill acquisition via sprint specific training (21). Therefore, an analysis should be undertaken to which type of training intervention will have the greatest effect or return on investment on sprint performance in the training time provided.

A sprint F-v profile categorization system may also identify potential injury risk factors in athletic populations. Athletes characterized with low force production in the horizontal direction may provide an initial *red flag* for practitioners due to the association with hamstring injuries in team sport athletes (98). In a prospective cohort study of 284 football players (soccer), lower $F_0$ values, specifically at low velocities e.g., initial steps of the sprint effort, during in-season sprint testing was significant ($p<0.001$) in higher occurrences of new hamstring injuries. The relationship between $F_0$ and risk factors to high-speed running has also been reported in case studies using rugby players (223).

Although there are some valid concerns to various aspects of sprint F-v profiling, specifically, the mechanical misconceptions of the biomechanical model, plus the reliability and utility of variables (114, 142), we believe in conjunction with quality coaching pedagogy and practitioners using their *coach's eye* and video analysis tools, sprint F-v profiling provides a macroscopic, holistic view to not only assess sprint performance but to also quantitatively guide the coach to individualize the training programme. Therefore, the utility of using quadrants or categories to group athletes, then apply interventions based on the biomechanical and technical recommendations included in this article, seems useful from a pedagogical view. Finally, an individualized approach to optimize and enhance sprint performance should be utilized once more common approaches to sprint training and physical preparation have been exhausted. Athletes with a low training and chronological age, will likely find greater benefit from a traditional progressive overload approach to sprint and resistance training (41-43, 143).

**Summary**

A quadrant or category-based analysis of F-v characteristics during sprinting provides a novel approach to categorize and prescribe individualized training interventions aimed at enhancing sprint performance based on the biomechanical and technical characteristics of the athlete and demands of the sport. Although sprint F-v profiling is not necessary for an effective sprint training programme, the ability to establish quadrants or categories provides a quantitative approach to sprint analysis, plus provides a more *coach-friendly* visualization of F-v profile data to guide coaching practice. Practitioners are encouraged to use this approach to F-v profiling and target physical preparation and explicit sprint training (i.e., coaching) to improve biomechanical, neuromuscular, and motor learning adaptations specific to sprint performance.

## PRELUDE

Like Chapter 8, this chapter provides further practical applications from all results gathered from studies in this thesis. Chapter 9 provides practical training recommendations and guidelines to improve program design based on mechanical characteristics. Therefore, the purpose of chapter 9 was to extend on the data-driven conceptual framework provided in chapter 8 which categorized athletes based on their biomechanical and technical strengths and weaknesses and provided suggested training recommendations to improve sprint performance. However, this application paper provides coaches with recommendations for practical training methods and programme design (i.e., sprint-specific and gym-based strength and conditioning) to address individual F-v characteristics therefore optimizing acceleration and sprint performance. Therefore chapter 9, along with chapter 8, demonstrate how the learning established across cross-sectional, interventional and case studies can be practically implemented within an individual and team sport setting.

# CHAPTER 9

## Improving mechanical effectiveness during sprint acceleration: practical recommendations and guidelines

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**Abstract**

Sport scientists and strength and conditioning coaches are showing growing interest in the magnitude, orientation and application of ground reaction force during acceleration actions in sport, as it can identify the key mechanical determinants of performance. Horizontal F-v profiling, or sprint profiling, helps practitioners understand the capacity of the mechanical force production during the acceleration phase of a sprint. This review examines the methods used in the field for determining horizontal F-v (sprint) profiles. It also includes recommendations for practical training methods to address individual F-v characteristics, mechanical effectiveness, thereby optimizing acceleration performance.

## Introduction

Strength and conditioning coaches are interested in understanding the limitations in mechanical performance during activities involving linear and multidirectional speed. High speed running (sprinting) is the fundamental component of many team sports and involves two key phases: acceleration and maximal velocity (25). The ability to accelerate and reach the highest velocity possible in the shortest period of time is underpinned by the mechanical components of the neuromuscular system, force, velocity and power and specifically the F-v profile (279). Within strength and conditioning literature, methods to identify these mechanical components during acceleration has been limited, making it unclear the most appropriate training prescription which should be utilized to improve these qualities. Therefore, if a resistance training program is designed to enhance sprint acceleration, should strength and conditioning coaches select exercises which focus on force, velocity and power, or prioritize one variable over the other?

During the stance phase of a sprint action, a ground reaction force (GRF) is produced which includes both horizontal and vertical components of the GRF (referred to as horizontal and vertical forces for simplicity), along with the resultant GRF. The stance or contact phase can be divided into braking and propulsive phases in the antero-posterior direction, followed by a flight phase when the limbs are repositioned in the air before contacting the ground again (231). This ongoing exchange of kinematic positions defines sprinting as a ballistic action (231). In comparison with various track and field events where only linear speed is required, in team sports like Australian rules football and rugby, jumping actions followed by a sprint acceleration in multiple directions is common. These constant changes in velocity, require athletes to accelerate or decelerate their body mass (72, 269) and can include rapid changes in direction to chase down or evade an opponent. Although achieving maximal velocity is important in many team sports (108, 144), the ability to accelerate (and decelerate) can be of far greater assistance to an athlete's on-field performance (11, 77), therefore coaches must place a large emphasis on improving this quality.

To accelerate in the horizontal direction in the shortest period of time, the athlete has to develop the highest net horizontal force possible, averaged across each step during the sprint effort. An individual's ability to perform this task are characteristics of both the mechanical and neuromuscular systems (175), however also influenced by the athlete's technical ability to apply the force and the propulsive impulse (force x time) produced by the athlete. The constraints of applying force over increasingly shorter periods of ground contact as the athlete moves through the sprint acceleration identifies how impulse can affect performance. Acceleration performance will be limited if the impulse is high due to force production occurring over a longer ground contact time. Therefore, the ability to achieve a high net external force applied in the opposite direction to the centre of mass displacement, as the running velocity increases, and ground contact decreases is of primary concern. In many team sports, rapidly changing one's velocity and momentum to evade opponents is crucial (131), however applying force in a more horizontal direction, is a major factor in differentiating between rates of acceleration (53, 157, 235, 236, 253).

During the acceleration phase, the ability to apply horizontally oriented force has been shown to be one of the key determining factors to performance (236). This is in contrast to maximal velocity running where Weyand et al. (352) showed that the magnitude of ground reaction force production, oriented vertically over the contact phase, was the limiting factor to performance. Effectively applying lower limb force in a horizontal direction as velocity increases has been referred to as *mechanical effectiveness*

(286). This mechanical description is underpinned by the force applied by the athlete across the acceleration effort and describes the ratio of the net horizontal component and resultant GRF across the acceleration (236). One ‘simple’ macroscopic method used to determine mechanical effectiveness across a sprint acceleration is horizontal F-v profiling, also known as sprint profiling. Across a sprint acceleration effort, sprint profiling models the step averaged mechanical outputs (force, velocity, power) in the horizontal direction. This innovative method provides a detailed ‘roadmap’ for understanding the mechanical components underpinning acceleration. As a means of accurately assessing the horizontal force produced by an athlete, sprint profiling assists coaches to calculate the degree of horizontally directed force applied over any distance or velocity across the sprint effort (242). It also identifies the athlete's mechanical strengths and weaknesses when accelerating, specifically their ability to apply horizontal force and accelerate towards maximal velocity.

Sprint profiling helps coaches and athletes understand the F-v and power-velocity (P-v) relationships, along with how horizontal force production capacity changes across the acceleration, plus provides a global view of the likely morphological and neuromuscular properties involved (66). Furthermore, when attempting to understand the mechanical variables which contribute to acceleration performance it raises the question of whether the conventional approach of manually or electronically timing a 40-yard sprint should be used in conjunction with the more in-depth sprint profiling? Moreover, can this information be effectively used to individualize a resistance training program to target the mechanical strengths and weakness of the athlete, thereby improving performance? Additional detail provided by mechanical sprint profiling including power and force orientation provides practitioners with superior means to objectively evaluate, effect, and monitor sprint qualities.

Although sprinting is the most specific and highest velocity training method used to improve an athlete's linear speed, strength and conditioning coaches will often look to other resistance training methods to compliment speed training. These methods are used to further elicit adaptations to F-v characteristics and to address various mechanical qualities contributing to performance. The selection of exercises to improve physical performance in a sport should be based on factors which demonstrate the highest transfer to that sport. Since horizontal and vertical components of the GRF are produced while accelerating, yet in different magnitudes, there is often conjecture on where the focus should be placed from an exercise selection perspective when producing force; in the horizontal or vertical direction? Two concepts which will be discussed in this review regarding exercise selection are dynamic correspondence (345) and the force-vector theory. These concepts describe that the biomechanics, force production and orientation, plus velocity of training movements should be similar to those used in the athlete's sport. Both concepts provide a framework for exercise selection. Yet, when selecting resistance training exercises to improve acceleration performance, should strength and conditioning coaches select exercises based on specificity to the sprint action or maintain a broad approach when attempting to change F-v characteristics?

This review aims to provide background information on the F-v relationship, determinants and biomechanics of acceleration performance, sprint profiling, as well as discussing exercise selection and training programs for improving athletes' mechanical effectiveness during acceleration. The practical recommendations in this review could be used to address F-v characteristics and horizontal force application, plus devise individualized training programs for teams and individual sport athletes.

### Determinants of force and velocity

Mechanical variables such as force and velocity play a vital role in ballistic activities such as sprinting and determine overall neuromuscular performance (286). However, these variables are in a sense limiting given that the force produced and the shortening velocity of skeletal muscle are constrained by morphological factors such as fibre type, fascicle length, pennation angle and neural mechanisms such as motor unit recruitment and intramuscular coordination (66). Each of these variables has a direct effect on the ability of skeletal muscle to exert maximal power; ($P_{MAX}$). High power outputs are considered critical performance characteristics for success and will often differentiate between ability levels in sport (318). Practitioners have long argued that athletes should be training at loads which maximize power (63, 182, 309, 355), however other investigators have suggested loads which are above and below optimal load develop $P_{MAX}$ to a greater degree (138, 218) warranting further exploration to determine whether an "optimal load" exists and leads to comparatively greater training-induced improvements. It has been shown that ballistic activities are determined by the $P_{MAX}$ of the lower limbs and impulse but are also strongly influenced by the individual's F-v capabilities which is also known as the F-v profile (288). Training status and relative strength also influence force expression and therefore evaluations of F-v profiles should be highly standardized to maximize reliability of data (145, 174). Understanding an athlete's strengths and weaknesses in terms of their mechanical output, assists a strength and conditioning coach to devise an appropriate training program based on the specific needs of the athlete's F-v profile.

### Biomechanical determinants of sprint acceleration

Newtonian laws show that sprint acceleration in a forward direction is determined by the horizontal and vertical components of the resultant GRF, the horizontal and vertical impulse, and the displacement of the center of mass (CoM) (247). Force and impulse are vector quantities which include direction and magnitude, and depend on the phase of the sprint action, along with the position of the athlete's body. These vectors are oriented either horizontally (mainly antero-posterior) or vertically. When starting from zero velocity, the impulse will be a combination of force applied over longer ground contacts and as velocity increases, the time in which force can be applied reduces, therefore making quality force application at ground contact critical. Although net horizontal force determines the rate of acceleration (266, 286), the impulse-momentum relationship governs the time in which force is applied; it has been shown that this factor accounts for slow or fast rates of acceleration, where shorter contact times beget the need for increased force expression. Hunter et al. (157) identified in a series of 25m sprints, the greatest variance (61%) occurred with the horizontal impulse measured at the 16-m mark. Morin et al. (247) supported this view and the argument that the fastest sprinters were able to produce greater net horizontal impulse compared to their sub-elite counterparts. Also, of importance, it was shown that the faster sprinters maintained this impulse across the duration of the sprint acceleration as velocity was increasing and ground contact was decreasing. This was critical to performance.

The way in which a GRF is oriented is key to the acceleration performance or maximal velocity achieved in sprinting (23). Emphasis must be placed on maximizing and orienting horizontal (antero-posterior) force application during acceleration, since the speed runners ultimately attain specifically correlates with the magnitude of the propulsive force (and time over which it is applied) at the start of the effort, along with the successive strides during acceleration (49, 296, 362). It has been shown that elite sprinters produce higher net horizontal force and impulse with each step at any given velocity, which allows them to attain higher velocities than their sub-elite counterparts

(235, 266). Although the orientation of force is superior in elite sprinters, their training history and kinematics mean they are also more effective at transferring force into the ground. Such technical skills are also derived from specific neuromuscular properties including the structural integrity of muscle and tendon (235, 266).

The position of the athlete's body when sprinting, whether accelerating or at maximal velocity influences application and orientation of force (191). Positioning the overall body (not only the trunk-head segments) in an inclined position in relation to the ground makes it possible to achieve a more propulsive resultant GRF (39, 49, 191). Whereas, when an athlete is sprinting at maximal velocity in an upright position, a greater reliance is placed on achieving high GRF with a vertical orientation to limit time spent on the ground, thereby reducing deceleration (48, 352). Directing the resultant GRF in a more forward or horizontally oriented direction is more important during the acceleration phase of a sprint, compared to the overall magnitude of force applied to the ground and therefore this component is critical to focus on during training (53, 235, 236, 266). Colyer et al. (53) showed that sprinters, when compared with soccer players, exhibit more horizontally directed force during the late braking phase and early propulsive phase, allowing them to accelerate to higher velocities; this was a key difference between athlete groups. Orientation of force is also affected by the touchdown or ground contact distance in reference to the body CoM upon ground contact (25). During this contact in early stance phase, maintaining a stiff ankle increases the resultant GRF and momentum due to the impulse and subsequent horizontal velocity achieved (40). Therefore, assessing and diagnosing the way in which athletes apply horizontal force during acceleration, has important ramifications for attaining the best possible sporting performance.

**Horizontal force-velocity profiling**

Horizontal F-v profiling (sprint profiling) is an assessment and diagnostic tool that examines the key characteristics of F-v and P-v relationships in sprint actions; its main focus is on the acceleration phase (76, 242). These relationships define the changes in propulsive force and horizontal power when running velocity increases, see Figure 9.1 (242). Using a series of timing gates or a radar device, as well as biomechanical modeling derived from speed-time data (286), it is possible to calculate horizontal force, velocity and power as the athlete accelerates. This information describes the current mechanical output from the athlete, along with the mechanical limits of the neuromuscular system while accelerating. Limits include theoretical maximal horizontal force at null velocity ($F_0$), theoretical maximal horizontal velocity until which force can be produced ($v_0$) and the maximal power produced in a horizontal direction ($P_{MAX}$), see Figure 9.2 (286). Over the duration of a sprint acceleration, Morin et al. (236) use the term ratio of forces (RF) - which describes the horizontal (antero-posterior) component of the GRF ($F_H$) vector as a percentage of the total GRF ($F_{TOT}$) vector, see Figure 9.3. This ratio identifies the technical ability an athlete may or may not possess to orient force horizontally while accelerating. Since orientation of the force is more important than its magnitude, understanding the force ratio is critical. From this data, the mechanical effectiveness of applying force ($RF\% = F_H/F_{TOT}$) at each step can be determined. The higher the RF%, the more horizontal orientation of the GRF has been achieved. Mechanical effectiveness is important for determining the athlete's ratio of decreases in force ($D_{RF}$) with increasing velocity (242), which describes how force orientation changes from more horizontal to vertical. Morin et al. (236) states that even if $F_{TOT}$ is similar in two athletes, the RF% can identify mechanical differences including weaknesses, which can then be targeted with training interventions. Quantifying individuals' mechanical effectiveness during sprint acceleration means it is possible to determine differences between performers but also to establish a biomechanical link between profile and sprint performance (280).

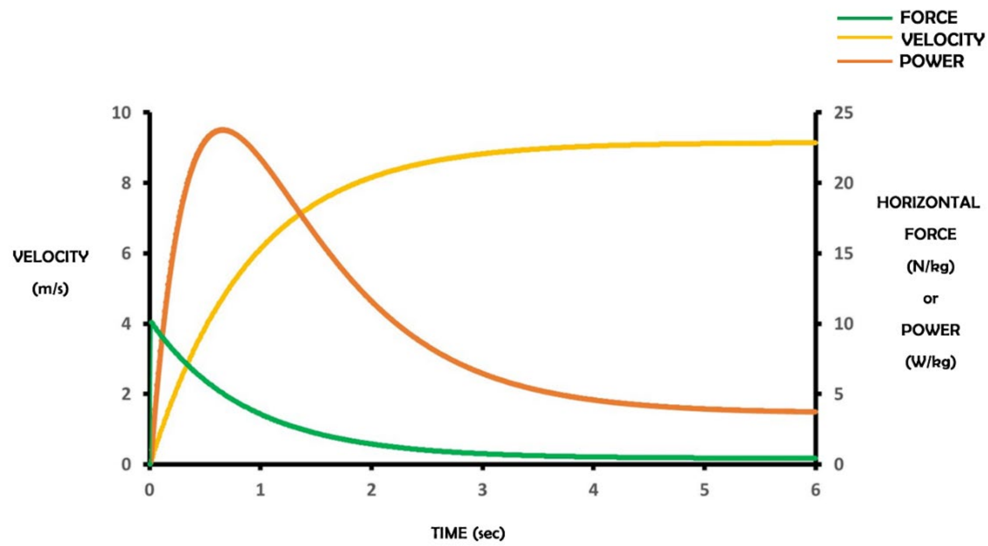



**Figure 9.1** Changes in horizontal force and power as running velocity increases.

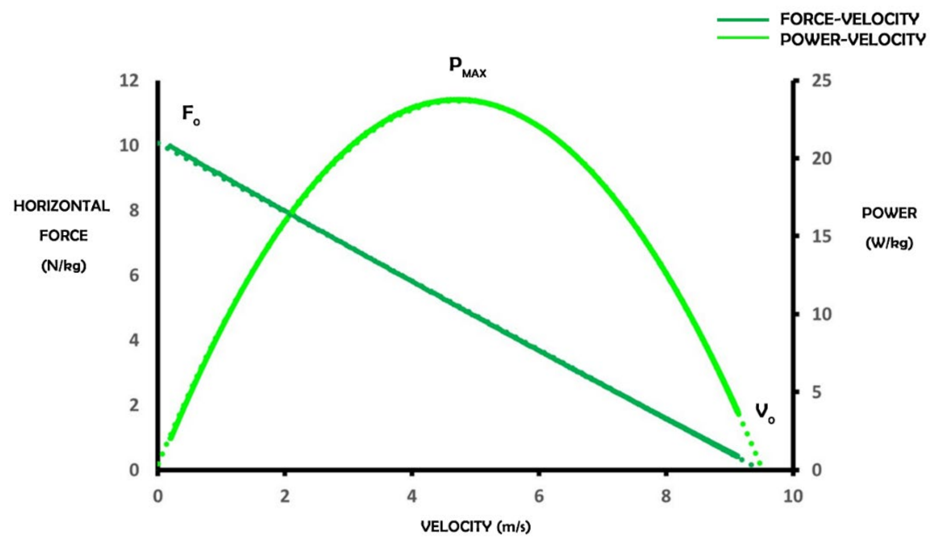



**Figure 9.2** Changes in mechanical output across an acceleration effort. These variables identify the current performance output of the athlete, plus the mechanical limits of the neuromuscular system: theoretical maximal force ($F_0$), theoretical maximal velocity ($v_0$) and maximal power ($P_{MAX}$) in the horizontal direction.

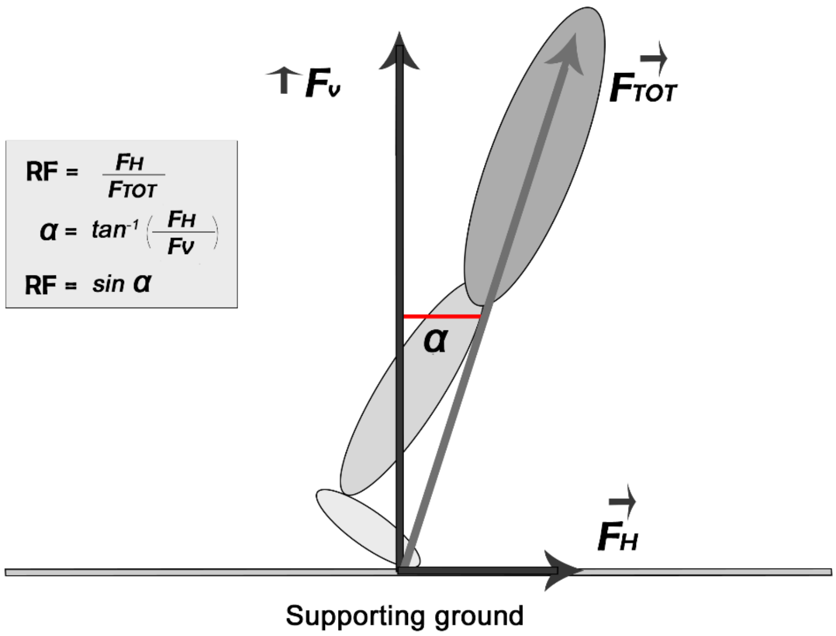



**Figure 9.3** A representation of lower limb ratio of forces, net positive horizontal ($F_H$) divided by total force ($F_{TOT}$, which includes the vertical component). The forward orientation of the total GRF vector is represented by the angle α.

Field-based sprint profiling (246, 266) using inverse dynamics, a computation method of calculating forces from kinematics of a body, is a highly reliable process that has been evaluated against gold standard laboratory-based (252, 254, 286) tests using inbuilt force plate systems. Field-based methods of profiling, referred to by Samozino et al. (286) as a *simple method*, is a practical process needing limited technology and equipment to determine an individual's mechanical profile and assess the $P_{MAX}$ the neuromuscular system is able to achieve during the acceleration phase. Sprint profiling assists coaches to identify the specific interventions required to improve acceleration and determine whether training should be directed at increasing $P_{MAX}$ by improving the horizontal force produced at low velocity, (force quality), horizontal force at high velocity (velocity quality) or by training at optimal load (maximal power). Sprint profiling can provide some unique findings given it is able to distinguish between athletes independently of $P_{MAX}$ values or sprint times. Although time is the critical factor in sprint acceleration, two athletes may achieve similar acceleration times and $P_{MAX}$ values over a given distance yet with very different slopes and mechanical characteristics to their F-v profiles, see Figure 9.4. This is connected to an athlete's ability to have different a combination (described as balance or imbalance by Morin and Samozino (242) between force and velocity (force-dominant or velocity-dominant), which is also related to their mechanical effectiveness for the duration of sprint acceleration (242). In comparison to generic training programs where the focus is on improving absolute force and sprint times, sprint profiling provides a specific guide for identifying and targeting the athlete's strengths or weaknesses in order to improve their acceleration performance. This approach has been explored with elite female athletes in Rugby sevens (298) and team handball players (268), where individual speed training programs based on data from sprint profiles showed varying levels of effectiveness depending on how the sprint profiles were interpreted and how training loads were implemented. Morin et al. (242) provided a written explanation about the process of optimizing F-v profiles but information about practical sprint and resistance training interventions that may have assisted coaches was limited.

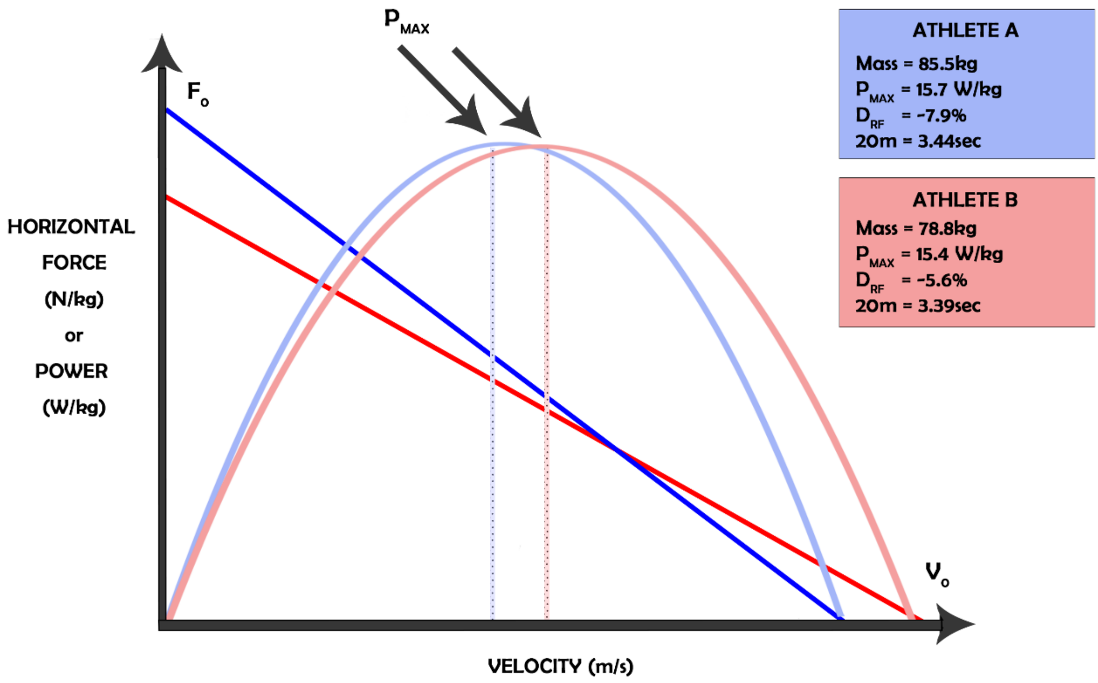



**Figure 9.4.** Horizontal force-velocity profiles for two athletes. Both athletes display similar maximal horizontal power outputs and sprint times, yet different theoretical maximal force and velocity values (see slope).

### Practical applications and guidelines

The mechanical determinants and variables seen in profiles such as force, velocity and power are susceptible to the demands imposed on the body and key neuromuscular adaptations can occur as a result of prescribing specific exercises (323). This provides scope for a strength and conditioning coach to improve acceleration performance by selecting exercises and loads which mostly target specific areas on the theoretical F-v spectrum and practical load-velocity spectrum; force, velocity or power, see Figure 9.5. The resistance training exercises used in most sports are traditionally prescribed off characteristics across the F-v spectrum and the load-velocity (and thus force) context they induce within the movement. Examples of exercises which span this spectrum are detailed in Figure 9.6. Resistance such as an athlete's bodyweight against gravity or external loads, are a way to set the velocity at which the maximum effort will occur and indicate the production of force that is possible. Studies which have used resistance training (including vertically and horizontally oriented exercises) to improve sprint performance have included high force/low velocity exercises; force dominant (8, 138, 183), low force/high velocity exercises; velocity dominant (8, 14, 44, 68, 183, 218), and optimal load exercises; power dominant (77, 138), suggesting the load, orientation and mechanical focus may elicit different adaptations to the performance.

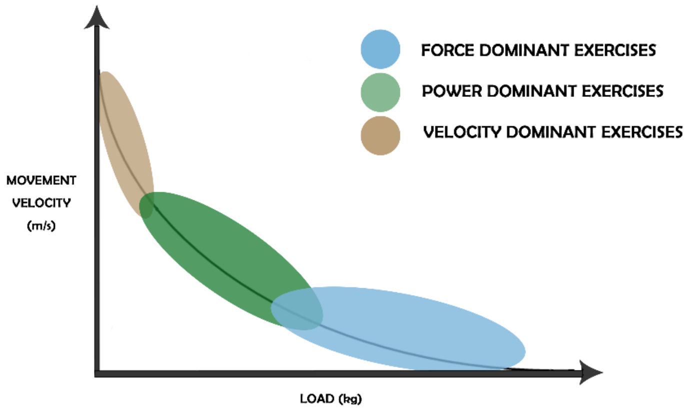



**Figure 9.5.** Resistance training categories across the force-velocity (load-velocity) spectrum used to modify the mechanical variables or individualize the F-v profile.

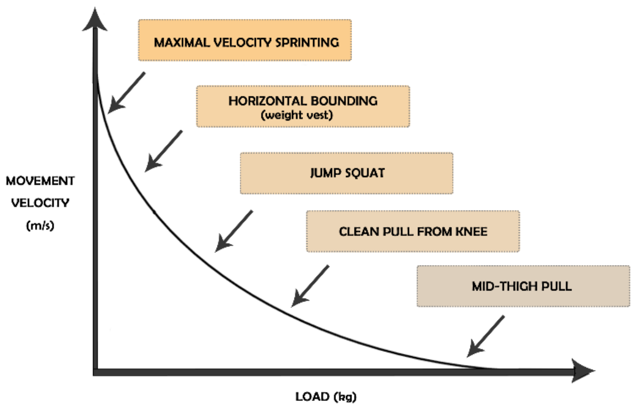



**Figure 9.6.** A selection of exercises across the force-velocity (load-velocity) spectrum will be prescribed to each athlete depending on their level of mechanical effectiveness across the acceleration phase.

Categorization of resistance training exercises is useful to understand how adaptations to the profile will affect physical performance. Force dominant exercises are aimed at improving the force applied at very low velocities. In regard to sprinting, these exercises focus on the athlete's ability to overcome inertia at the start of the sprint acceleration and effectively apply force in a backwards direction, be it by improving the capacity of the lower limb force produced or peak mechanical effectiveness. Velocity dominant exercises are aimed at improving the application of force at high velocities to enhance the athlete's ability to maintain force application as velocity increases. This can be achieved by improving the lower limb force production at high velocities and/or by improving the orientation of force and maintaining the highest possible mechanical effectiveness despite the increase in velocity. Power dominant exercises aim to improve the force applied at moderate velocities that is, at close to half of the theoretical maximal velocity (75). These exercises stimulate the athlete's ability to produce greater $P_{MAX}$ output during the sprint acceleration, and when prioritized as interventions within a training program and periodised appropriately, can be effective in enhancing performance. The aim of selecting exercises across the F-v spectrum is to target the variable contributing to the current level of F-v imbalance, thereby improving the athlete's overall mechanical effectiveness across the sprint acceleration.

It is advisable when selecting resistance training exercises, that they demonstrate transfer to movement task and enhance various characteristics which contribute to sprint acceleration. Sprinting is performed on a horizontal training axis (sagittal plane), therefore it may seem intuitive to focus on exercises which develop force in the same direction (269, 367); known as the "force-vector theory" (58). Using exercises which allow athletes to apply force in the same direction (vector – magnitude and force) as that which occurs in the sport task, may suggest a greater transference effect (361) or dynamic correspondence (345), due to similar overall biomechanical characteristics. Using these concepts as an example, volleyball or basketball players often express movements vertically, and therefore should address the F-v spectrum by prioritizing exercises which have a vertical force orientation. In comparison, American football players, rugby players and sprinters, who predominantly express movement through linear locomotion, would be recommended to prioritize horizontally oriented exercises (204, 361). Although conjecture surrounds the application of the force-vector theory (114) (see Limitations section), a thorough understanding of the kinetics and kinematics of the movement task, is essential when designing a resistance training programs.

When designing and programming training sessions to improve an athlete's horizontal profile, strength and conditioning coaches need to appropriately periodize resistance training focused sessions into the weekly sport training program. The structure of a training week in a team sport must primarily focus on the tactical and technical elements of the sport, then prioritize other modalities such as injury prevention, recovery modalities and resistance training, see Figure 9.7. For optimal F-v adaptations, resistance training should occur over the course of several mesocycles (87) or until the F-v profile has been re-assessed and adaptations which contribute to improved $P_{MAX}$ and/or a reduction in F-v imbalance are evident. Continual assessments of the vertical profile (jumping) to determine if F-v adaptions had occurred were regarded as critically important within a recent study (175). Depending on the level of F-v imbalance revealed in the profile, some or all of the exercises identified in the following sections could be integrated into a the weekly microcyle, ensuring a minimum 48 hour recovery period between high-intensity days. This is necessary to limit the level of residual fatigue before the athlete embarks on the next training session. Understanding the training phase and how this may affect the general or specific nature of exercise intensity and selection is also a critical factor in team sports (87). Schuster et al. (297) explored these concepts in their recommendations for physical preparation with Rugby 7 athletes, where a weekly combination of high (2 sessions), medium (2 sessions) and low (2 sessions) intensity sessions including strength and conditioning, rugby specific training and recovery sessions were cycled across a week to optimize performance during the preparation block leading into competition.

| Team sport weekly microcycle | | | | | | |
|---|---|---|---|---|---|---|
| MESOCYCLE | Preparation Phase | MICROCYCLE | 5 | CLUB / SPORT | U21 WOMEN'S | SOCCER |
| SUNDAY | MONDAY | TUESDAY | WEDNESDAY | THURSDAY | FRIDAY | SATURDAY |
| 19-May-19 | 20-May-19 | 21-May-19 | 22-May-19 | 23-May-19 | 24-May-19 | 25-May-19 |
| Rest Day | Pitch C | Pitch B | Pool | Pitch B | Pitch A | Home Stadium |
| Recovery | Technical + Tactical | Acceleration + S&C | Aerobic Capacity | Tech/Tact. + S&C | Positional / Individual | Accel, MxV + SSG |
| INTENSITY | INTENSITY | INTENSITY | INTENSITY | INTENSITY | INTENSITY | INTENSITY |
| LOW | MEDIUM | HARD | LOW | MEDIUM | MEDIUM | HARD |
| Predicted sRPE - 1 | Predicted sRPE - 6 | Predicted sRPE - 8 | Predicted sRPE - 3 | Predicted sRPE - 7 | Predicted sRPE - 5 | Predicted sRPE - 8 |
| ANCILLARY | ANCILLARY | ANCILLARY | ANCILLARY | ANCILLARY | ANCILLARY | ANCILLARY |
| NIL | MOBILITY & ACTIVATION | MOBILITY & ACTIVATION | NIL | MOBILITY & ACTIVATION | SOFT TISSUE WORK | MOBILITY & ACTIVATION |
| TRAINING | TRAINING | TRAINING | TRAINING | TRAINING | TRAINING | TRAINING |
| Players day off | Attackers, defenders and neutral support on section of 1/2 pitch. Focus on movement off ball and manipulation of defenders. Neutral players cycle in on direction of coach. | Linear > Static: 2 x 10, 15, 20. Rolling: 2 x 10, 15, 20. Curved > Rolling: 2 x 10, 15, 20 | Dynamic warmup in pool in shallows. 2 x Session A in 25m pool using fins. 1 x Session B performing DWR + power series against pool wall. | Formation A & B played against reserve grade. 20min blocks. 5min period between blocks. | Attackers, defenders split and matched up with reserves. Finishing drills for attackers. 2 v 1, 3 v 1, 3 v 2 for defenders. GKs Pitch C. | Linear > Static: 4 x 10, Rolling: 4 x 10, Curved > Rolling: 4 x 10, Max velocity wicket runs 4 x 20 |
| | Attackers focus. Final third attacking principles + set piece design and implementation. | Clean Pull (4 x 2 x 82.5%), Back Squat (4 x 2 x 87.5%), Mid-Thigh Pull (3 x 5 x 110%) | | Resisted sprinting (2 x 4 x 20, load to reduce mxv 30%), Prowler March (2 x 20, 30, 40m @ 120% BW), Hip Thrusts (5 x 5 x 82.5%) | Conditioning block for RTP, reserves and optional Top-up for players recently back from injury. | Tactical Small-Sided Games (1/2 Pitch). Full-sized goals. 6 v 6 incl. GK. 2-touch play max. Rolling team on 7mins. |
| POST WORKOUT | POST WORKOUT | POST WORKOUT | POST WORKOUT | POST WORKOUT | POST WORKOUT | POST WORKOUT |
| | CORE-SERIES | CWI | STRETCH SERIES | CORE-SERIES | STRETCH SERIES | CWI |
| NOTES | NOTES | NOTES | NOTES | NOTES | NOTES | NOTES |
| Send wellness details to coaching staff. | Bring field and track footwear for tomorrow's session. | Meet at pool in morning (bathers, fins, goggles) | Bring field and track footwear for tomorrow's session. | Optional physio/chiro appt. | Bring field and track footwear for tomorrow's session. | |

**Figure 9.7.** A weekly microcycle for a team sport detailing the integration of the technical and tactical sport focus, injury prevention, recovery and resistance training program.

Recommendations about addressing the F-v imbalance and mechanical effectiveness in sprint acceleration through targeted resistance training programs directed across the F-v spectrum are detailed in the following sections.

### Improving force production at low velocities

Athletes with physiological, and perhaps technical qualities that limit their ability to apply a high amount of horizontal force at low velocities are at a disadvantage in many on-field competitive situations. This will be evident early on during the sprint effort with their inability to apply enough horizontal force, thereby reducing their horizontal impulse. In turn, this will compromise the overall velocity which is achieved as this is determined by the athlete's ability to accelerate to this speed. To improve the force produced at low velocities, the prescribed sprint and resistance training needs to include movements that focus on the right hand-side of the F-v spectrum, where force is applied against a heavy external resistance, >85% 1RM (322) and targets maximal strength qualities, see Table 9.1.

**Table 9.1.** Exercises to improve the production of maximal force.

| EXERCISE | % 1RM / LOAD |
|---|---|
| Back Squat | > 85% |
| Kettlebell Swing | > 85% |
| Romanian Deadlift | > 85% |
| Trapbar Deadlift | > 85% |
| Hip Thrust | > 85% |
| Mid-Thigh Pull | > 100% clean |
| Clean Pull from Knee | > 100% clean |
| Rack Pull | > 100% deadlift |
| Prowler March | up to 150% BW |
| Resisted Sprinting | up to 100% BW |

Exercises that target maximal or absolute strength and specifically improve the force applied in a horizontal direction include heavy sled pulls, resisted sprinting, see Figure 9.8, and prowler marches, see Figure 9.9. Horizontally oriented exercises at these loads will encourage force application in the same direction as what occurs during the acceleration phase of a sprint. Although maximal strength exercises may only be specific to early acceleration, several studies (10, 322, 323) that focused on the right hand side of the F-v spectrum, noted the crucial role strength plays in in providing the foundation to improving maximal power, highlighting its importance for potentially improving other aspects of the F-v spectrum. Table 9.2 identifies two resistance training sessions which could be performed across one week, including both horizontal and vertically oriented exercises. These exercises and the associated sets, repetitions and loads are programmed to improve the maximal force produced at low velocities.

**Figure 9.8.** Resisted sprint training using a sled at 85% bodyweight.

**Figure 9.9**. Resisted sprint training using a prowler sled to march at 140% bodyweight.

**Table 9.2.** Force production at low velocity.

| DAY 1 - HORIZONTAL ORIENTATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Resisted Sprinting | 2 x 4 x 10m | Load which restricts to <30% of max velocity | 2 x 4 x 20m | Load which restricts to <30% of max velocity | 2 x 5 x 20 | Load which restricts to <30% of max velocity | 2 x 3 x 20 | Load which restricts to <30% of max velocity |
| Prowler March | 2 x 20, 30, 40m | 120% of BW | 3 x 20, 30, 40m | 130% of BW | 4 x 20, 30, 40 | 140% of BW | 3 x 20, 30, 40m | 120% of BW |
| Hip Thrusts | 5 x 5 | 82.5% | 5 x 5 | 87.5% | 5 x 5 | 92.5% | 5 x 5 | 85% |
| **DAY 2 - VERTICAL ORIENTATION** | | | | | | | | |
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Clean Pull | 4 x 2 | 82.5% | 6 x 2 | 87.5% | 12 x 1 | 92.5% | 4 x 2 | 85% |
| Back Squat | 3 x 5 | 87.5% | 3 x 3 | 90% | 3 x 3 | 92.5% | 3 x 5 | 85% |
| Mid-Thigh Pull (% based off clean) | 3 x 5 | 110% | 3 x 3 | 120% | 3 x 3 | 130% | 3 x 5 | 110% |

*** BW = bodyweight, % based off 1 repetition maximum in exercise**

Some athletes are capable of high levels of force at low velocities but cannot sustain it as their acceleration increases. This often leads to a rapid decrease in the ratio of forces ($D_{RF}$) as the athlete approaches top speed. Analysis of the profile shows it is likely that during acceleration the athlete will be losing their ability to apply and orient horizontal force too early, which during acceleration corresponds to early changes in body position from approximately more horizontal to vertical. Although the production of high (mostly vertically oriented) force is vital at maximal velocity (48, 49, 352), the speed attained will be limited due to a rapid decrease in ratio of forces. This has a direct impact in sporting activities like rugby when players try to outrun their opponents when making for the try line. Sprinters face the same problem when they need to maintain acceleration for a longer duration and reach higher velocities in a 100m sprint. Improving sprint acceleration performance over longer distances and maintaining a high ratio of horizontal-to-resultant force at increasing velocities, require exercises that focus on characteristics from the left-hand side of the F-v spectrum, along with improved inter and intra-muscular coordination properties. Exercises demanding high velocity are generally those which require high rates of force, see Table 9.3.

The F-v spectrum suggests the smallest load the human body can work against is the force of gravity on body mass such as when performing a vertical jump. However, research suggests even this load may be too great to affect the velocity portion of the F-v spectrum (214). Assisted vertical jumps, see Figure 9.10, using elastic bands is one method which has been used to de-load or negatively load an athlete's body mass, by reducing the effects of gravity on the body (214). Markovic and Jaric (214) found that countermovement jumps with zero-load maximized mean power and jump height, yet the velocity (peak) of the centre of mass at take-off increased by de-loading bodyweight by 30% (214). Horizontally oriented exercises including a novel exercise known as an assisted horizontal squat jump, see Figure 9.11, has been shown to be beneficial to improving movement velocity due the extremely high velocity reached by pushing against almost zero gravity (172, 289). This exercise, part of a longitudinal training intervention aimed at improving F-v balance in individual profiles (175), was shown to produce extremely large changes in the velocity component of the F-v profile, as well as effecting increased jump heights.

**Table 9.3.** Exercises to improve the maximum velocity of movement**.**

| **EXERCISE** | **% 1RM / LOAD** |
|---|---|
| Countermovement Jump | BW |
| Assisted Jumps | Assisting force to deload BW by 30% |
| Horizontal Squat Jump | <BW |
| Assisted Horizontal Squat Jump | Assisting force 95-110N |
| Squat jumps | BW - 10% BW |
| Assisted sprinting | 100-106% maximal velocity |
| Reactive jumps | BW |
| Box jump (bilateral and unilateral) | BW |
| Jump Shrug | BW + 20-40kg |
| Hang High Pull | BW + 20-40kg |


**Figure 9.10.** Assisted vertical jumps to deload athlete bodyweight by 30% a using an elastic band.


**Figure 9.11.** Assisted horizontal squat jump using a roller-board and elastic band to push against reduced gravity.

Assisted sprinting may provide another unique approach for overloading the neuromuscular system at higher than the maximal voluntary velocities. Using a horizontal towing mechanism such as the DynaSpeed (MuscleLab™), see Figure 9.12, or the 1080Sprint™, acute horizontal running velocities increased, along with lower limb electromyography activity, which suggested that higher neural activity took place with possible transfer to unassisted maximal sprinting (224, 226-228). However, given that maximal running velocity is by definition the far-left side of the F-v spectrum, research should aim to verify whether training over an individual's maximal voluntary running speed (i.e overspeed training) benefits unassisted performances. Plyometric activities such as bounding, drop jumps and reactive jumps are also recommended for athletes who want to improve force produced at high velocity, due to the reliance on the stretch shortening cycle (91). Table 9.4 identifies two resistance training sessions which could be performed across one week, which includes both horizontal and vertically oriented exercises. These exercises and the associated sets, repetitions and loads are programmed to improve the maximal movement velocity of the athlete.


**Figure 9.12.** Assisted sprinting using the DynaSpeed (MuscleLab™) to allow athletes sprint at supramaximal speed.

**Table 9.4.** Force production at high velocity.

| DAY 1 - HORIZONTAL ORIENTATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Assisted Sprinting (DynaSpeed) | 1 x 20, 30, 40m (flying run) | 101% of training max velocity (flying run) | 2 x 20, 30, 40m | 102% of training max velocity (flying run) | 3 x 20, 30, 40m | 103% of training max velocity (flying run) | 2 x 20, 30, 40m | 101% of training max (flying run) |
| Maximal Sprinting | 3 x 40m (20m accel + 20m fly) | BW | 3 x 50m (20m accel + 30m fly) | BW | 3 x 60m (30m accel + 30m fly) | BW | 2 x 40m (20m accel + 20m fly) | BW |
| Horizontal Bounding (8 contacts/set) | 3 x 8cts | BW | 4 x 8cts | BW | 5 x 8cts | BW | 3 x 8cts | BW |
| **DAY 2 - VERTICAL ORIENTATION** | | | | | | | | |
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Reactive Hurdle Hops (5 contacts/set) | 3 x 5cts | BW | 4 x 5cts | BW | 5 x 5cts | BW | 3 x 5cts | BW |
| Band-Assisted Vertical Jumps | 2 x 5 | deload BW 30% | 3 x 5 | deload BW 30% | 4 x 5 | deload BW 30% | 2 x 5 | deload BW 30% |
| Double Leg Depth Jump to box | 3 x 6 | BW | 4 x 6 | BW | 5 x 6 | BW | 4 x 6 | BW |

* BW = bodyweight

### Improving maximal power (optimal loading conditions) for sprinting

Training at a load that is associated with movement velocity at which maximal mechanical power occurs has been shown to be the most effective method for increasing overall maximal power (133, 182). Haff and Nimphius (133) define optimal load as that which maximizes mechanical power for a specific exercise. Within strength and conditioning literature, the assessment of power is broad, with technology including force plates, linear position transducers (LPT) and accelerometers, deriving power metrics which are used to determine optimal load. Therefore, the context of the variable must be understood and interpreted correctly when implementing into the training program (see Limitations section). During resistance training, the optimal load for developing $P_{MAX}$ in a jump squat has been shown to range from 0% of 1RM (63-65), to 30-45% of bench press 1RM in the bench press throw (256, 301) and 70-80% of IRM when performing weightlifting exercises such as the snatch and/or clean (63, 67, 182). This approach to training has also been used in cycling via torque-velocity tests to determine the optimal pedalling conditions (frequency) over a set distance (95). The discrepancy power assessment and 1RM percentages across a range of exercises demonstrates a lack of clarity and inconsistency to determine the load to achieve $P_{MAX}$.

However, improving maximal horizontal power for sprinting requires focusing on the factors that contribute to this variable; horizontal force and horizontal velocity. Depending on the training phase and needs of the athlete, exercise prescription should be directed to all parts of the F-v spectrum to ensure a strong level of mechanical effectiveness is maintained and to achieve the highest ratio of horizontal force during acceleration. In regard to sprinting, this may entail using specific exercises for producing maximum power by training at an optimal load, see Cross et al. (77). Optimal load training has previously been shown to be more effective for improving dynamic athletic performance when compared with other loading conditions (256, 355). However, combining different resistance training loads to improve power and ballistic performance has also been shown to be effective in many studies (62, 138, 181, 218, 329, 330). With this in mind, across the F-v spectrum, exercises to improve maximal power could include resisted sprinting, sprinting at maximum speed, jump squats (Trapbar), see Figure 9.13, plyometrics (horizontal bounding) and assisted sprinting, see Figure 9.12. Highlighting exercises from all aspects of the F-v spectrum, should result in athletes maintaining or raising their mechanical effectiveness with limited decline in either contributing variable. Although all loads across the F-v spectrum contribute to $P_{MAX}$, Table 9.5 identifies two resistance training sessions which could be performed across one week, which include both horizontal and vertically oriented exercises. These exercises and the associated sets, repetitions and loads are programmed to focus on maximizing power.

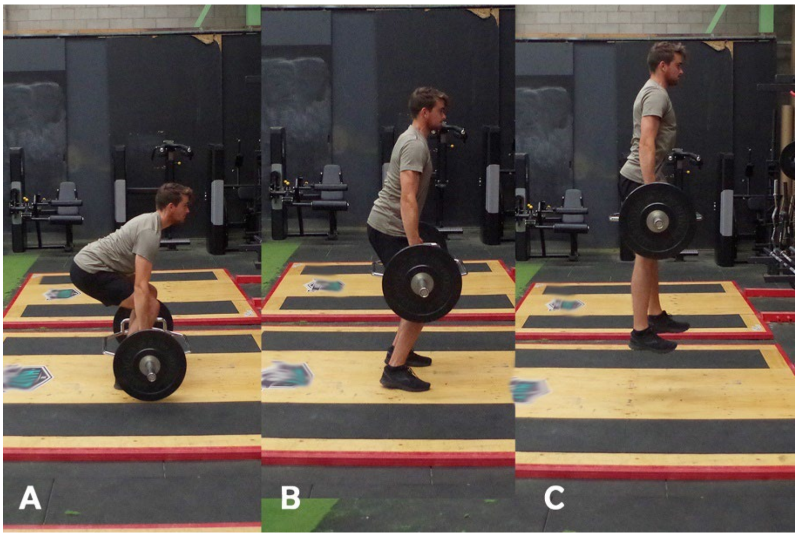



**Figure 9.13**. Jump squat with Trapbar at optimal load (approx. 40% BW).

**Table 9.5.** Force production at maximal power (optimal load).

| DAY 1 - HORIZONTAL ORIENTATION | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Resisted Sprinting (DynaSpeed) | 3 x 10, 20, 30m | Individual $P_{MAX}$ | 4 x 10, 20, 30m | Individual $P_{MAX}$ | 5 x 10, 20, 30m | Individual $P_{MAX}$ | 3 x 10, 20, 30m | Individual $P_{MAX}$ |
| Maximal Sprinting | 3 x 30m (20m accel + Flying 10m) | BW | 4 x 30m (20m accel + Flying 10m) | BW | 3 x 40m (20m accel + Flying 20m) | BW | 2 x 40m (20m accel + Flying 20m) | BW |
| Hip Thrust | 3 x 5 | Individual $P_{MAX}$ | 3 x 5 | Individual $P_{MAX}$ | 4 x 5 | Individual $P_{MAX}$ | 3 x 5 | Individual $P_{MAX}$ |
| **DAY 2 - VERTICAL ORIENTATION** | | | | | | | | |
| Exercise | Week 1 | | Week 2 | | Week 3 | | Week 4 | |
| | Volume | Load | Volume | Load | Volume | Load | Volume | Load |
| Jump Squat (Trapbar) | 5 x 3 | 20-50% | 5 x 3 | 20-50% | 5 x 2 | 20-50% | 5 x 2 | 20-50% |
| Power Clean | 4 x 5 | 70-80% | 4 x 3 | 70-80% | 5 x 5 | 70-80% | 5 x 3 | 70-80% |
| Power Snatch | 5 x 3 | 30-50% | 5 x 3 | 30-50% | 5 x 2 | 30-50% | 5 x 2 | 30-50% |

*** BW = bodyweight, % based off 1 repetition maximum in exercise**

## Limitations

Coaches need to carefully consider the implications of the training interventions they select to address characteristics of the F-v profile. Potential weaknesses should be addressed but not at the expense of building upon athlete strengths. It follows that strength and conditioning coaches need to keep sight of their primary training goals and use sprint profiling as a monitoring and diagnostic tool, similar to testing hamstring strength or force plate analysis of vertical jump actions to assess benchmarks. Detraining qualities is a risk if too much time is being expended on weaknesses. For example, an athlete who produces maximal power with lower force values will result in decreases in velocity values if training focusses on those particular movements for an extended period. This may impact on an athlete's ability to produce power in situations where force is required at different magnitudes and velocity (133).

Recent research suggests the selection of exercises based solely on dynamic correspondence and the force-vector theory (114) contain certain limitations. A thorough understanding of dynamic correspondence often means the selection of specific exercises is narrow and pre-determined. Contreras et al. (58) and more recently Loturco et al. (202) suggest the force-vector theory should be the primary focus when selecting exercises to improve sprint acceleration and maximal velocity. The theory states that the force-vector which comes into play when sprinting, occurs in the antero-posterior direction relative to the body, and therefore the exercises selected must focus on producing horizontal force, provide necessary time for skill acquisition, which in turn should improve transfer to the performance to a greater degree than vertically oriented exercises (58). Currently, the majority of resistance exercises are vertically oriented (269), for example the back squat, deadlift or weightlifting derivatives, therefore emphasizing vertical force production (269). However, this serves to negate horizontally oriented force and opposes dynamic correspondence and the force-vector theory. Notwithstanding, Loturco et al. (202) found strong correlations with sprint performance when performing hip extension focused exercises, e.g. hip thrust, with the initial phase of the sprint acceleration, whereas those exercises loaded vertically, e.g. jump squat, showed greater transfer to the maximal velocity phase. Both of these findings however, are in direct contrast to the findings of Seitz et al. (299) who found positive acceleration changes, 0-30m, from studies primarily concerned with the back squat, and Jarvis et al. (165) who found no sprint performance transfer from an 8-week study using the hip thrust exercise. This suggests conjecture remains in regard to the training-axis which should be utilized to enhance sprint acceleration performance.

While the force-vector theory is intuitive in many respects, Fitzpatrick et al. (114) proposed that applying the force-vector theory to training was a basic misunderstanding of simple mechanics. Primarily, the issue lies in understanding the difference between the direction of force relative to the global frame, as against the direction of force determined by the orientation of the athlete (131). This is evident in sprinting when the athlete adopts a triple flexion (front-side mechanics) position during acceleration and when reaching maximal velocity; the orientation of the body is at approximately 45˚ while accelerating and at approximately 90˚ when at maximal velocity. Kugler and Janshen (191) noted the strong relationship between body lean and direction of GRF, as leaning forward during acceleration places the athlete in an advantageous position for applying propulsive force. However, while orientation of force needs to be understood, from a practical standpoint, a combination of both vertical and horizontally loaded resistance training exercises appears to be the ideal approach when attempting to improve sprint performance (58, 202, 269, 367).

Maximal power is a major performance indicator and thus frequently a priority when selecting exercises to improve dynamic, ballistic performance (61, 63, 64, 66, 67, 73, 301, 319, 323), yet conjecture and difficulties exist when determining load for actions involving multiple joints. Maximal power and optimal load is influenced not only by the technology which derives the variable but also whether it is specific to 'system power' (external – whole body), joint power (internal – at a specific joint), or perhaps more applicable to the weight room, 'bar power' (using an LPT). Previously, Cormie et al. (60) have recommended using a combination of a force plate and a linear position transducer(s) to best determine power in lower body exercises. In a resistance training context, the discrepancies in how optimal load is reported therefore presents a high level of ambiguity in reference to the load-power relationship and presents issues with how practitioners can make sense of how to apply exercise prescription to not only improve maximal power but how optimal load is established (60). The use of a range of methodologies to determine power has led to a broad range of approximate 1-repetition maximum (1RM) percentages for which maximal power is developed in various exercises such as the power clean, squat and jump squat. Considerations for effectively understanding and interpreting "optimal load" must also include the specific movement pattern(s) used, training history/status of the athlete and whether the exercise uses single or multiple joints (67).

Cross et al. (75) noted that during un-resisted sprint acceleration, maximal power was achieved within the first two seconds of the movement, and therefore, the remainder of the sprint occurred at a sub-optimal load. In order to re-create and extend the conditions in which athletes move at an optimal load, resisted sprint training was introduced using a loaded sled that corresponded to approximately 96 percent of the athlete's body mass; or the equivalent to a velocity decrement of ~50% of maximal velocity. This allowed athletes to sprint at optimal loads throughout the acceleration phase. In a later study, further changes to sprint acceleration were not evident when athletes performed a resisted sprinting protocol at optimal load, when compared to groups which used lighter or heavier loads (75). However, the authors acknowledged that the current state of the individual F-v profile and the random group assignment may well have affected greater adaptations to sprint acceleration and greater research is required.

One limitation recently noted on sprint profiling methodology using the 'simple method' (246), is that the power variable only represents step-averaged external power produced in the horizontal direction to accelerate the body centre of mass, neglecting the internal 'joint' power ($P_{int}$) required to move the limbs around the centre of mass (260). Pavei et al. (260) suggests other mechanical components aside from horizontal power are needed to accelerate in a sprint such as the body centre of mass and internal power ($P_{int}$). Although the 'simple method' provides valuable insight into power in the horizontal direction across the sprint acceleration, there must be the understanding that no internal power variables are measured and therefore the overall power output computed via the 'simple method' will be an underestimation of the total power developed by muscles but will rather characterize the power capabilities of overall sprint propulsion. Notwithstanding, the practical application to coaches using $P_{int}$ is limited considering the exhaustive technology necessary to obtain the data and therefore the 'simple method' may be a more appropriate measure in the field. In addition, it is not known whether $P_{int}$ is a performance indicator, thus a key variable of interest in training.

Therefore, when using optimal load as a training strategy to improve maximal power, it is prudent to understand the context of power you are measuring, along with incorporating a variety of loads across the F-v spectrum to ensure a balanced approach for force and velocity adaptations (73, 329, 330).

### Further considerations

The majority of the literature on sprint profiling discusses factors which contribute to the overall mechanical output across the performance, however there has been a growing level of interest in understanding the application of sprint profiling in the rehabilitation field and return to play (RTP) protocols from hamstring injuries (223). Although not the primary focus of this review, the application of using mechanical variables of pre-injury performance and utilizing these in the return to play protocols with sports medicine staff may provide further comparative data to ensure a safe return to performance. Mendiguchia et al. (223) identified that sprint profiling highlights the capability to produce horizontal force at low speed is a limiting factor to performance when returning from a hamstring injury, therefore, the application of sprint profiling as a monitoring tool to assess how force production changes across a competitive season or in response to an injury could be useful individual information to sports medicine staff.

### Summary

Sprint profiling using the field methods briefly outlined in this review, offers an innovative and alternative approach to understand the mechanical determinants of sprint acceleration. Although further research and experimental evidence is needed, together with applied longitudinal exercise interventions, the field method is a practical and valid approach that allows strength and conditioning coaches to access kinetic data on sprint acceleration, which previously was only attainable in a laboratory. This data allows coaches to design individualized training programs.

The resistance training program used to address mechanical effectiveness should consist of exercises which focus on both horizontal and vertical force production, acknowledging the limitations to the force-vector theory, however a priority could be placed on one orientation over the other depending on the phase of the training cycle or the needs of the athlete. Sprint profiling can be utilized for athletes involved in sports where sprint acceleration is crucial, and for identifying and changing the variables contributing to performance. It may allow coaches to devise individualized training programs to a greater degree compared with traditional methods, as a means of enhancing sprint acceleration and improving the effectiveness of force application.

Guidelines for implementing a training and/or rehabilitation program which addresses the mechanical variables of horizontal F-v and power-velocity include:

- Assess the capabilities of producing horizontal force and the mechanical effectiveness of force application during sprint acceleration (sprint profile)
- Identify any existing F-v imbalance across sprint acceleration.
- Prescribe appropriate training programs to address the needs of the athlete and the slope of the profile.
- Re-assess the athlete after an appropriate period of time to determine adaptations to mechanical effectiveness and changes to sprint acceleration.

# CHAPTER 10

## Summary, Future research directions and practical applications

### Chapter Overview

The main aim of this PhD research was to provide a comprehensive understanding of jump and sprint F-v profiling in team and individual sport populations with the aim of improving physical performance. This was achieved by a narrative review, five studies using cross-sectional, interventional, and case study research designs. In addition, two application chapters to conclude the program of research provide practical recommendations to sports performance coaches to implement the findings in their context. This general discussion chapter will provide an overall summary, plus theoretical, biomechanical and practical considerations with reference to each chapter. Strengths and limitations of the program of research, and recommedations for future research will also be presented.

### Summary of Findings

The overarching aim of this research was addressed by a series of studies. Study 1 (Chapter 2), a narrative review, evaluated the existing literature on vertical and horizontal F-v profiling with a specific focus on 'field' methods, which provided mechanical characteristics of performance without the use of expensive laboratory-based technology. The findings indicated inconsistencies when using the field method (i.e., Samozino's method) to model jump-based mechanical characteristics with various studies citing reliability and validity concerns. Despite this, studies which showed strong reliability and validity demonstrated various diagnostic applications for mechanical profiling to identify mechanical strengths, weakness and imbalances although these were largely found in cross-sectional studies with limited practical transfer to coaches. At the time of completing the initial review, it was concluded that mechanical characteristics needed to be explored in interventional studies to determine changes in response to physical preparation strategies. Furthermore, although many research studies identified potential training goals in response to individual mechanical characteristics, limited 'taking the laboratory to the field' research existed to demonstrate to practitioners how to make actionable decisions from F-v data and enhance performance through gym-based or sprint-specific training recommendations, guidelines and programmes.

### *Chapter 2: Mechanical profiling in team and individual sports*

The aim of this chapter was to review and compare literature related to vertical and horizontal F-v profiling using a macroscopic inverse dynamics approach. To achieve this objective, a narrative review of literature was completed focussing on the following four sections: (a) exploring the biomechanical models for determining jumping and sprinting F-v profiles using inverse dynamics, (b) analyzing the reliability and validity of jump and sprint profiling methodology, (c) exploring the concept of individualizing and optimizing the F-v profile, and (d) investigating the utility of using profiling to inform training interventions to enhance sport performance.

**The key findings of this Chapter were:**

1. Between studies, it is evident there is limited standardization across F-v profiling protocols regarding methodological practice. Greater research is needed on the

reliability and validity of methods, and their comparison with gold-standard, laboratory-based methods.

2. There exists limited research on the use of F-v profiling across a range of team and individual sports.
3. While F-v profiling is widely used in adult sport populations (and aging general population groups)(2, 3), there is limited research on the application of the methodology in young athletes, which may have implications in reference to maturation status such as peak heigh velocity (188, 211), musculoskeletal development and performance.
4. More research studies focussed on changes to mechanical characteristics in response to specific training interventions over longer periods, potentially addressing mechanical strengths and weaknesses are necessary.
5. Studies focussed on the use of F-v profiling to monitor changes to mechanical characteristics over the course of a competitive sport season is under researched.
6. There is a paucity of conceptual frameworks, training recommendations and guidelines specific to enhancing vertical and horizontal mechanical characteristics and greater links must be made for practitioners by linking the data to programme design.

### *Chapter 3: Reliability and Validity*

The aim of this chapter was to determine the reliability and validity of Samozino's (SAM) field-based method using 'simple inputs' to quantify vertical F-v characteristics in free-weight countermovement jump actions (i.e., barbell, hexbar) when compared to in-ground force plates. Laboratory grade force plates are typically regarded as 'gold standard' technology and measure vertical ground reaction forces (Fz) at high sampling frequency (1000Hz). In Samozino's seminal study, the field-method was validated against force plates using a smith machine (i.e., constrained vertical jump action) which provides increased reliability due to kinematic redundancy (129), yet may be regarded as less ecologically valid compared to free-weight unconstrained vertical jump actions. Vertical F-v profiles were assessed with a barbell and hexbar against four incremental loads (bodymass [BM], BM+15kg, BM+30kg, BM+45kg), with F-v variables established from force plate data and the SAM method.

**The key findings of this Chapter were:**

1. Samozino's method provided acceptable levels of reliability for mean force, velocity, and power (ICC > 0.90, CV% < 5.5) across both loading conditions.
2. Limits of agreement analysis showed the mean bias was 2.7%, 15.4%, 7.2% and 1.8%, 12.4%, 5.0% for mean force, velocity, and power during barbell and hexbar countermovement jumps respectively.
3. Based upon these findings, Samozino's method is reliable when measuring mean force, velocity and power during loaded and unloaded barbell and hexbar countermovement jumps, but also identifies limitations regarding concurrent validity compared to the gold standard.
4. Across loading conditions, Samozino's method overestimated mean force (0.5-4.5%) and underestimated mean velocity (11.81-16.78%) and mean power (2.26%-7.85%) compared to the force plates.
5. Due to fixed and proportional bias between criterion and predictor, the results do not support the use of Samozino's method to measure mean force, velocity, and power and therefore, it is not recommended for practitioners to use the field

method to estimate mechanical variables during loaded and unloaded countermovement jump actions using a barbell and hexbar.

### *Chapter 4 and Chapter 5: Cross-sectional studies (team sport)*

The aim of these chapters were to investigate the utility of using mechanical profiling to distinguish between sex and positional demands in team sport, plus analyse mechanical transfer to inform physical preparation strategies. The first cross-sectional study (Chapter 4) investigated whether jump-based mechanical profiling could differentiate between sex and positional groups in club-level field hockey athletes. The key objective of this study was to identify if positional demands in field hockey (i.e., attacker or defender) are sex-specific or whether they display similar mechanical characteristics (i.e., force or velocity-oriented profile). Due to the findings of Chapter 3, portable force-plates were used to measure vertical ground reaction force in this study, rather than using the SAM method. Vertical F-v profiles were assessed using hexbar using three incremental loads (bodymass [BM], BM+25% external added mass relative to BM, BM+50% external added mass relative to BM).

**The key findings of Chapter 4 were:**

1. When comparing athletes by sex, male athletes reported significant mean differences in all F-v variables (12.81-40.58%, $p \leq 0.001$, ES = 1.10-3.19), and a more enhanced F-v profile (i.e., greater theoretical maximal force, velocity, and power values).

2. Stronger correlations were evident for male athletes between relative maximal power ($P_{MAX}$) and jump height ($r = 0.67$, $p \leq 0.06$) when compared to female athletes ($-0.71 \leq r \geq 0.60$, $p = 0.08$).
3. Male attackers demonstrated a more 'velocity-oriented' F-v profile compared to defenders due to significant mean differences in theoretical maximal velocity ($v_0$) (6.64%, $p \leq 0.05$, ES: 1.11), however differences in absolute and relative force ($F_0$) (15.43%, $p \leq 0.01$, ES = 1.39) led to female attackers displaying a more 'force-oriented' profile in comparison to defenders.
4. These findings highlight power expression between sexes relies on opposing mechanical qualities suggesting physical preparation strategies to develop power should be sex specific.
5. Overall, this study identified sex and position specific F-v strengths, weaknesses and imbalances could be targeted with physical preparation strategies to enhance neuromuscular performance.

The second cross-sectional study (Chapter 5) aimed to extend on the previous findings by analyzing the level of mechanical transfer between vertical and horizontal F-v profiles. The key objective was to investigate the transfer of mechanical characteristics in different force-vectors and determine the correlations between vertical and horizontal F-v profiles and performance outcomes in field hockey athletes. Mechanical characteristics were also explored as potential predictive variables for jump and sprint performance. Vertical F-v profiles were assessed using a hexbar at three incremental loads (bodymass [BM], BM+25% external added mass relative to BM, BM+50% external added mass relative to BM). Horizontal F-v profiles were assessed using a commercially available Radar device (Stalker ATS I, 36.6Hz) which provides instantaneous velocity-time data of the athletes' centre of mass.

**The key findings of Chapter 5 were:**

1. When comparing matched mechanical variables between F-v profiles in each force orientation, small to moderate significant correlations ($r = 0.37$-$0.62$, $p \leq 0.03$) were observed for relative theoretical maximal force ($F_0$), power ($P_{MAX}$) and theoretical maximal velocity ($v_0$).
2. The performance outcomes (i.e., jump height, sprint time) of both F-v profiles highlighted a large, significant negative correlation ($r = -0.86$, $p = 0.001$) between variables.
3. Multiple linear regression analysis of F-v profiles identified $F_0$ and $v_0$ accounted for 74% and 94% of the variability in jump height and sprint time respectively, however $v_0$ appeared to be a greater predictor of both performance outcomes.
4. Due to the significant relationships between variables, the results of this study suggest vertical and horizontal F-v profiling may explain the same key lower-limb mechanical characteristics, despite the orientation of the movement task.
5. Therefore, coaches could potentially use mechanical profiling methods interchangeably to prescribe physical preparation interventions, however for greater mechanical insight, it is likely worthwhile to assess neuromuscular function plus mechanical strengths and weaknesses by performing one F-v assessment in both force-vectors.

***Chapter 6 and Chapter 7: Experimental studies (team and individual sports)***

The aim of these chapters were to investigate the longitudinal changes to horizontal F-v characteristics and sprint performance in team and individual sport athletes. The key objective of this experimental study (Chapter 6) was to investigate the mechanical changes to junior Australian football players in response to a sprint-specific training programme across a 7-week period. Specifically, two groups were established based on 20-metre sprint performance, with participants pairwise matched into either: a combined sprint training (CST) group (performed both maximal velocity sprinting and assisted sprinting), or the maximal sprint training (MST) group (performed unassisted maximal velocity sprinting only). Pre and post intervention, horizontal F-v profiles were assessed using a commercially available Radar device (Stalker ATS I, 36.6Hz) which provides instantaneous velocity-time data of the athletes' centre of mass.

**The key findings of Chapter 6 were:**

1. Moderate to high relative reliability was achieved across all sprint variables (ICC=0.65-0.91), except for the F-v slope ($S_{FV}$) and decrement in ratio of forces ($D_{RF}$) which reported poor reliability (ICC=0.41-0.44).
2. The CST group exceeded the pre-post minimal detectable change (MDC) in most sprint variables suggesting a 'true change' in performance across the intervention.
3. Moderate to large pre-post within group effects ($-0.65 \leq ES \geq 0.82$. $p \leq 0.01$) in the CST group for relative theoretical maximal force ($F_0$) and power ($P_{MAX}$) were reflected in improved sprint performance from 0-20 meters, thereby creating a more force-oriented F-v profile.
4. The MST group displayed statistically significant pre-post differences in sprint performance between 10-20 meters only (ES = 0.18, p = 0.04).
5. Overall, it is concluded that implementing a short-term, combined sprint training intervention consisting of assisted and maximal sprint training methods may

enhance sprint mechanical characteristics and sprint performance to 20-meters in junior Australian football players.

The second experimental study (Chapter 7) aimed to extend on the previous findings in Chapter 6 by exploring changes to horizontal F-v characteristics across a training year in sprint athletes. The key objective of this case study was to analyse F-v characteristics, sprint kinematics and 100-meter performance in response to a periodised training program across a 45-week track and field season in two national level sprint athletes. Over a 10-month period, two athletes completed horizontal F-v assessments using electronic timing gates. Sprint mechanical characteristics were derived from 30-meter maximal sprint efforts using split times (i.e., 0–10 m, 0–20 m, 0–30 m) whereas step kinematics were established from 100-meter competition performance using video analysis.

**The key findings of Chapter 7 were:**

1. Between the preparation (PREP) and competition (COMP) phase, Athlete 1 showed significantly large within-athlete effects for relative maximal power ($P_{MAX}$), theoretical maximal velocity ($v_0$), maximum ratio of force ($RF_{MAX}$), maximal velocity ($V_{MAX}$), and split time from 0-20 m and 0-30 m ($-1.70 \leq ES \geq 1.92$, $p \leq 0.05$). Athlete 2 reported significant differences with large effects for relative maximal force ($F_0$) and $RF_{MAX}$ only (ES: $\leq -1.46$, $p \leq 0.04$).
2. In the PREP phase, both athletes reported almost perfect correlations between $F_0$, $P_{MAX}$ and 0–20 m ($r = -0.99$, $p \leq 0.01$), however in the COMP phase, the relationships between mechanical characteristics and split times were more individual.

3. Competition performance in the 100-meter sprint (10.64 ± 0.24 s) showed a greater reliance on step length ($r \geq -0.72, p \leq 0.001$) than step frequency to achieve faster performances.
4. The minimal detectable change (%) across mechanical variables ranged from 1.3 to 10.0% while spatio-temporal variables were much lower, from 0.94 to 1.48%, with Athlete 1 showing a higher 'true change' in performance across the season compared to Athlete 2.
5. The estimated sprint F-v data collected across a training year may provide insight to practitioners about the underpinning mechanical characteristics which affect sprint performance during specific phases of training, plus how a periodised training design may enhance sprint F-v characteristics and performance outcomes.

### *Chapter 8 and Chapter 9: Applied Practice*

The aim of these chapters were to 'bring the laboratory to the field', allowing coaches to better understand how to use mechanical data to inform physical preparation strategies and training programme design to enhance sprint performance.

**The key findings of these Chapters were:**

1. A quadrant-based approach can be used to 'bucket/group' athletes based on their biomechanical characteristics expressed while sprinting allowing coaches to rapidly individualize gym and field-based physical preparation strategies for team and individual sport athletes.

2. Mechanical data can be used in a category-based system to describe athletes by their technical characteristics while sprinting. This allow coaches to individualize their technical coaching cues to athletes exhibiting similar technical strengths or weaknesses.
3. Both approaches aimed to provide coaches with a conceptual framework for biomechanical and technical training recommendations plus attempted to provide a link between the data and technical sprint performance.
4. Strength and conditioning coaches can select exercises and loads which target specific areas on the theoretical F-v spectrum and practical load-velocity spectrum to improve athletes' mechanical effectiveness during acceleration based on horizontal F-v characteristics
5. The resistance training program used to address horizontal mechanical characteristics should consist of exercises which focus on both horizontal and vertical force production, acknowledging the limitations to the force-vector theory, however a priority could be placed on one orientation over the other depending on the phase of the training cycle or the needs of the athlete.
6. The recommendations and guidelines may allow coaches to devise individualized training programs to a greater degree compared with traditional methods, as a means of enhancing sprint mechanical performance.

## Theoretical and biomechanical field-method considerations

This PhD research has important theoretical considerations for practitioners to consider before implementing field-based mechanical profiling into their practice.

### *Chapter 2: Mechanical profiling in team and individual sports*

The narrative review explored in detail the macroscopic biomechanical model based on inverse dynamics of the centre of mass, which was first explained in the initial studies on the topic (283, 286). For each model (i.e., vertical and horizontal), anthropometric and environmental inputs must be measured accurately. Furthermore, there are various assumptions and simplifications made when using these models to provide reliable and valid kinetics and kinematics (i.e., force, velocity and power) about jumping and sprinting actions.

1. One simplification of the field method is only mean ground reaction forces used to project the body centre of mass vertically (i.e., Fz) or horizontally (i.e., antero-posterior) are considered in the mechanical profile, thereby disregarding other external forces. Similarly, velocity and power achieved in each profiling method are described as mean values. Maximum or peak mechanical values are ignored due to representing only a single time point rather than the entire action.
2. When considering horizontal sprint profiling, the model describes the step-averaged kinetics and kinematics contributing to the overall sprint performance, rather than force, external power or velocity upon each ground contact or step, or the power achieved at specific joints of the lower limbs (260).
3. Theoretical implications are related to the mechanical misconceptions potentially identified using field-based macroscopic modelling, some of which were identified

as limitations across this program of research. Due to the simplification and model assumptions identified above, various commentaries (50) have been made questioning the F-v relationship represented in Samozino's approach, suggesting it has misrepresented the impulse-momentum relationship in vertical actions. Practitioners are recommended to read the literature and commentaties regarding F-v profiling but also understand the field method 'attempts to bring the laboratory to the field'; it is not supposed the replicate laboratory conditions.

4. Furthermore, despite attempting to be specific in use of terminology across latter studies in this program of research, other researchers (142) have been critical of the use of mechanical terminology expressed in profiling research relating to orientation and scalar/vector quantities, for example horizontal force and horizontal power. This criticism is valid and therefore it is recommended to use mechanical terminology more appropriately such as '…force applied in the horizontal direction', or '…power at the centre of mass expressed in the horizontal direction.'
5. When using field-based methods to determine mechanical characteristics of jump and sprint performance, ensure the methodology has been validated via pilot studies (246). It is recommended pilot studies occur 4-8 weeks prior to initial testing to allow practitioners time to process and analyze the data and address any procedural concerns before the first round of data collection. Pilot testing may identify changes which may need to occur regarding standardisation of testing protocols, delivery of testing protocols, or the number of familiarization sessions required to ensure participants understand test requirements and perform to their best ability. Each of these factors will likely reduce measurement errors during active data collection.

6. Standardized testing protocols are necessary to ensure longitudinal reliability and validity of mechanical variables, while avoiding measurement error and creating 'noise' in the data.

***Chapter 3: Reliability and Validity***

7. For validation purposes, if self-processing force-time data from force plates using code (i.e., R Script), ensure the key phases of the countermovement jump are scripted accurately using previously validated calculations (222).
8. Removing a fixed bar path along with the effect of load positioning on jump strategy and kinematics (324, 325) will likely influence the validity of mechanical characteristics when compared to force plates.
9. Field-based validity concerns in Chapter 3 were related to variability in squat depth (i.e., affecting height of push-off [$h_{po}$]) and unconstrained jump actions, along with load selection across the F-v continuum. Similar concerns were raised by other researchers for between-day reliability when using variations of vertical field-based F-v variables (ICC: <0.70, CV >10% for all variables) (199, 336). These factors identified the necessity for stringent testing procedures which should include greater familiarization session (1-3 sessions), along with the use of a band or box to constrain the individual height of push-off for each athlete.
10. Post hoc analysis using 21 subjects provided a power level of 0.57, which identifies differences between the means will only be detected 57% of the time which may limit the conclusions of this study.

*Chapter 4 and Chapter 5: Cross-sectional studies (team sport)*

11. The resistance training experience and background in sport (i.e., club-level, novice) potentially impacted expression of mechanical characteristics in each force orientation and likely required greater familiarization sessions. Familiarization sessions should occur in the preceding 2-4 weeks before testing sessions, as was used for Study 2 and Study 3, and expose participants to the exercises included in the testing protocol at the specific external loads (and subsequent velocities) which will be assessed. By including these sessions, it should provide a level of comfort to the participants as they would have performed the exercises previously, but it should also provide participants with the confidence to safely perform the test with mximal intent and limited fear of injury.
12. The field-based model requires participants to perform maximal effort actions either directed vertically while jumping or horizontally while sprinting, to ensure the mechanical limits of the body are expressed at a specific external load, whether that be bodyweight or with added external mass. Many participants showed apprehension to jumping with external load. Failure to jump or sprint maximally directly affects the F-v linear regression model and the velocity-time mono-exponential function (i.e., maximal sprint) thereby reducing validity of results. This was a concern which was repeatedly addressed with participants within these studies using both external and internal verbal and visual cues (136).

*Chapter 6 and Chapter 7: Experimental studies (team and individual sports)*

13. The age of participants in the experimental study potentially impacted expression of mechanical characteristics in the horizontal direction due to maturation and peak

height velocity (211). An assessment of the athlete's peak height velocity pre and post intervention may provide greater insight into mechanical changes. These assessments were conducted for Study 4 however no significant changes ($p > 0.05$) were evident specific to mechanical or performance variables.

14. Changes to bodymass in participants across the experimental study was not significant ($p = 0.07$), however the variable suggests changes occurred in some participants which may have impacted F-v model characteristics during post-testing. According to the F-v model, changes to bodymass will influence absolute force and power values, however when normalised to current bodymass, pre and post data can still be used to determine significant changes across the intervention.
15. Specific to Chapter 6, post hoc analysis using 22 subjects provides a power level of 0.76, which identifies differences between the means will only be detected 76% of the time, which may limit the conclusions of this study.
16. The ecologically-dynamic approach of case studies makes it hard to monitor or control all environmental variables (i.e., pressure, temperature, wind) across a 10-month period when collecting mechanical data. Despite this, if the same measurement methodology is utilized (and implemented by the same practitioner), F-v variables should remain reliable within this field-based setting.

This research indicates that field-based mechanical profiling can play an important role identifying the underpinning mechanical characteristics of jump and sprint performance, however it relies on methodological rigor of the practitioner to standadise all testing procedures and practices, along with conducting pilot studies to validate new testing equipment. Concerns regarding the validity of unconstrained vertical F-v profiling were addressed in Chapter 3 with changes occurring in subsequent chapters due to these findings. Despite being unable to perform a validation study on horizontal F-v profiling due to the scarcity of in-ground force plates covering sprint distances, as located in Japan (the only one in the world) (253), across remaining studies (Chapters 5-7), the reliability of most sprint F-v profiling variables was deemed acceptable. In the present research, the macroscopic inverse dynamics approach to field-based, biomechanical modelling provides practitioners with a method to evaluate the mechanical limits of the neuromuscular system, to differentiate between athletes (i.e., sex, position, performance) and monitor the impact of training interventions (i.e., sprint-specific training) on mechanical strengths, weaknesses and imbalances in order to improve each individual's mechanical performance. Despite various mechanical assumptions and simplifications being made in the macroscopic model, the ability to quantify the contributing mechanical characteristics of the performance and explore the utility of this knowledge with new applications and populations suggests it warrants further research.

## Practical Considerations

This PhD research has many practical considerations for sports performance coaches in team and individual sports. Specifically, the key aim of this research was to investigate through validation, cross-sectional and experimental studies the utility of using field-based mechanical profiling methodology to gather greater insight about the underpinning mechanical characteristics of jump and sprint performance. The results of these studies were aimed at providing practitioners with new applications to use profiling in their practice when coaching individual and team sport athletes in order to better individualize physical preparation strategies. From this research, the following practical applications should be considered.

*Chapter 2: Mechanical profiling in team and individual sports*

1. Embedding a neuromuscular assessment such as F-v profiling within the sport training season provides ongoing insight to the change in mechanical characteristics in response to specific forms of training. This information may assist practitioners to reduce mechanical imbalances by optimizing and individualizing training programmes to further enhance jump and sprint performance. Ideally, mechanical assessments would occur at the beginning of the pre-season and then intermittently across the competitive season. This would allow practitioners to make immediate informed decisions to training based on current mechanical output. Depending on the sport, it is recommended mechanical assessments are performed every 2-4 weeks across a competitive sport season, rather than a single assessment at the start of the preseason. This, will provide practitioners with greater insight to the current state of the neuromuscular system, allowing for an individualized approach to enhance mechanical performance based on up-to-date mechanical data.

*Chapter 3: Reliability and Validity*

2. Free-weight exercises such as the barbell and hexbar countermovement jump arguably provide a more ecologically valid performance compared to a smith machine, but a box or band should be used to control the squat depth to ensure standardisation between jump types.
3. Kinematic changes may have impact jump strategy between barbell and hexbar due the position of the load closer to the body centre of mass (325). Interestingly, the hexbar F-v profiles showed greater agreement with the field method suggesting this jump type was less affected by variation in squat depth.

4. Load selection for vertical F-v profiling provided reliable linear regression models for all participants however future studies should potentially include loads which span the F-v continuum, closer to the $F_0$ and $v_0$ intercepts, plus use loads based off percentage of participants bodymass. Concerns with linear regression models using more proximal, moderate loads to predict mechanical characteristics at high forces have previously been raised (1).
5. The field method is reliable to determine mean force (N), velocity (m/s) and power (W) when performing barbell and hexbar CMJ actions. Therefore, from a practical point of view, coaches and scientists can use variables from the field method when monitoring the same athletes across the course of a season.

***Cross-sectional studies (team sport)***

***Cross-sectional study 1 (Chapter 4)***

6. Analysis of mechanical characteristics by position in field hockey demonstrates sex-specific characteristics for vertical F-v profiles. For example, male attackers displayed a more velocity-oriented profile, whereas female attackers displayed opposing characteristics showing a force-oriented profile. Defenders had opposite mechanical characteristics for each sex. This potentially reflects differences in game demands in male and female competition such as tactics, strategy and technical abilities (340).
7. Differences in mechanical characteristics, including maximal external power, between sex and position suggests gym-based and field-based physical preparation strategies should be individualized to develop the mechanical

characteristic most desirable at each position. For example, if male attackers display a more velocity-oriented profile, it suggests power expression relies on this dominant variable, which should be developed during training using exercises such as assisted jumping, medicine ball throws and plyometrics (214).

8. Once a baseline of mechanical characteristics has been established at each field position, it may provide the sport coach with the insight about where to position players on the field based on their F-v profile. This may allow coaches to match the demands of the field position with the mechanical characteristics of the player.

***Cross-sectional study 2 (Chapter 5)***

9. Given the significant relationships between matched characteristics for vertical and horizontal F-v profiles, it suggests in club-level athletes, profiling methodology could potentially be used interchangeably. If time-bound, it is recommended to determine mechanical characteristics via sprinting only as it provides both biomechanical (i.e., horizontally directed force, velocity and power) and technical (i.e., mechanical effectiveness) strengths and weaknesses which can be used to inform training interventions.
10. Maximal external power demonstrated the greatest correlation between vertical and horizontal profiles highlighting the importance of this variable in field hockey athletes. Plus, it also identifies the transferability of mechanical power between force-vectors in this population.
11. Power development appears independent of force orientation therefore opposing the force-vector theory (114). This has implications for strength and conditioning

coaches when selecting exercises which differ in force orientation to the action most frequent in the sport.

12. Regardless of force orientation, when analyzing performance outcomes from mechanical profiles as dependent variables in multiple linear regression analysis, the same mechanical variable ($v_0$) had a greater effect on improving jump height and sprint time. This identifies the underpinning mechanical characteristics explaining the performance outcome was the same between jumping and sprinting actions. Therefore, this could then be specifically targeted through physical preparation strategies.

***Experimental studies (team and individual sports)***

***Experimental study 1 (Chapter 6)***

13. In short term (7-week) interventional studies with junior Australian football (AF) players, it appears the horizontal F-v profile adapts to specific training stimulus, thereby changing the mechanical characteristics contributing to sprint performance.
14. Combined sprint training (CST [assisted and maximal sprint training]) significantly improved sprint performance over 20-metres due to changes to relative theoretical maximal force ($F_0$) and power ($P_{MAX}$).
15. The assisted sprint training component of the CST appears to have created a more force-dominant F-v profile and enhanced mechanical characteristics in the initial steps of the sprint (i.e., 0-10m) due to the transfer of training effect of the

supramaximal velocity stimulus from the elastic cord in the early acceleration phase and could therefore be used to enhance this aspect of the F-v continuum.

16. Maximal sprint training (MST) only, established a more velocity-oriented profile plus improved athletes' flying split time from 10-20m, and should therefore be a key component of a training programme where maximal sprint speed is desirable.
17. Significant changes to maximal power in the CST group suggests over this sprint distance, the improvements in $F_0$ may be of greater importance compared to $v_0$ when trying to improve power and sprint performance. This may therefore inform practitioners which side of the F-v continuum to place a greater focus on when attempting to improve sprint performance in junior AF players.

***Experimental study 2 (Chapter 7)***

18. Changes to periodisation models used in the preparation (PREP) and competition (COMP) phases led to significant mechanical changes to both 100-metre athletes, suggesting mesocycle and microcycle loading structures influence sprint mechanical characteristics.
19. For both athletes, positive mechanical changes and improved sprint performance observed during the early COMP phase was significantly correlated with increased step length and favourable step frequency.
20. Similar correlations for both athletes were evident between $F_0$ and $P_{MAX}$ from PREP to COMP phase however stronger correlations between spatio-temporal variables and $v_0$ exist once the periodisation structure moved into the COMP phase.

21. Inter-athlete differences were observed for correlations between $F_0$ and $P_{MAX}$ and 0–10 m in the PREP phase, and $v_0$ and 0–30 m during COMP phase.
22. Monitoring sprint F-v characteristics provides practitioners with greater insight into training program design and periodisation structure for athletes of similar performance levels, plus identifies the underpinning mechanical characteristics and step kinematics affecting sprint outcomes leading into national championships.

### *Chapter 8 and Chapter 9: Applied Practice*

23. The conceptual framework provides a system and structure for practitioners to address mechanical strengths, weaknesses and imbalances based on biomechanical and technical characteristics of sprint performance.
24. A quadrant and category-based approach to mechanical data allows coaches to apply training interventions using gym and sprint-specific training along with cueing strategies to improve the technical aspect of sprinting.
25. Recommendations are provided for practical training methods and gym-based and sprint specific program design to address individual F-v characteristics to enhance sprint performance.
26. The resistance training program used to address sprint mechanical characteristics should consist of exercises that focus on both horizontal and vertical force production, acknowledging the limitations to the force-vector theory; however, a priority could be placed on one orientation over the other depending on the phase of the training cycle or the needs of the athlete.

Despite the obvious benefits of mechanical profiling, several of which are identified across studies in this research, many National sports bodies (35) across the globe continue to investigate performance outcome (i.e., jump height, sprint time) at annual draft combines, thereby neglecting developing insight about the underpinning mechanisms contributing to the performance. Furthermore, as identified in Chapter 4, understanding positional mechanical characteristics (i.e., attacker vs defender) in team sports and establishing baseline data for desirable attributes expressed by players in these positions portrays a more concise picture of the performance, allowing sport coaches to better maximize individual mechanical strengths and weaknesses. Despite greater time and resources which may be required, implementing mechanical profiling from senior down to junior age groups in team or individual sport provides coaches with a mechanical roadmap of how to develop players using biomechanical data. Many field-based sports heavily rely on global positioning systems (GPS) (340) to quantify external game demands without considering the mechanical qualities underpinning the output. Therefore, mechanical profiling can provide a link between current and future practice thereby bridging the gap between biomechanical demands of performance, technical skill development and the required training to enhance both components.

## Strengths, Limitations and Future Directions

This PhD research has several strengths. First, the research used a range of study designs (i.e., narrative reviews cross-sectional, longitudinal and case-study designs, application reviews) to provide greater insight into the utility of mechanical profiling in new team and individual sport populations aimed at enhancing physical performance. Second, the diversity in participants across multiple sports, ages and sex may demonstrate the transferability of findings into other sports, events, and ability levels, however greater sample sizes across all studies would have provided greater scientific rigor and informed conclusions. Third, this program of research has investigated vertical and horizontal field-based F-v profiling methodology that are highly accessible, convenient, and relatively inexpensive for sports performance coaches to incorporate into the training schedule. Finally, this research was undertaken throughout the COVID-19 global epidemic which affected proposed research studies including length of studies and participant recruitment. Nevertheless, this body of research has the potential to influence sports biomechanists, physical preparation and sport coaches working with team and individual sport athletes.

It is also important to acknowledge the limitations of this research when interpreting the results. These will be addressed in chronological order as they appear throughout this research.

1. Before implementing field-based mechanical profiling methodologies into a sport setting, all measures should be validated against known gold-standard technology (i.e., pilot study). Within Study 5, we used Freelap Timing System (FTS) to collect position-time data. Prior to data collection we performed a pilot study (n=11, not published) measuring the agreement between FTS and radar gun and found acceptable levels of agreement.
2. Participant familiarization should occur over multiple sessions to ensure a high level of intra-athlete reliability with testing variables. For experienced senior athletes it is recommended to perform at least two familiarization sessions. For youth athletes, it is recommended to perform up to four familiarization sessions.
3. When performing vertical F-v profiling, a rigorous set of procedures must be followed to ensure the correct height of push-off ($h_{po}$), as measured during pre-

testing, is achieved for each countermovement jump trial. This can be done by constraining the squat depth with a band or box. Countermovement jump loads should be based off percentage of bodyweight, rather than fixed loads, occur in a randomized order, and span the F-v continuum to ensure the mechanical profile reflects current neuromuscular limits. Reduced proximity of selected loads will influence the relationship between mechanical characteristics and the performance outcomes (i.e., jump height).

4. The cross-sectional studies describe mechanical characteristics of youth and club-level athletes which may limit the transfer of findings to different population groups (i.e., elite athletes). Both of these population groups will likely have less experience in resistance training settings and therefore F-v characteristics and findings will differ between athletes at a senior level. Despite this, it provides reference data for similar cohorts and a baseline set of data for training.
5. Participant attrition should always be a consideration within interveniontal studies and this should be accounted for during the power analysis.
6. Specific to horizontal F-v profiling, the reliability of certain mechanical variables (i.e., $S_{FV}$, $D_{RF}$) was deemed unacceptable suggesting low utility for this data to inform training. This contradicted other recent studies but high levels of variability were observed in Chapter 6.
7. Sprint-based familiarization sessions must be incorporated into training sessions prior to horizontal F-v profiling as the selected distance may be greater that typical distances covered during their sport or event.
8. Kinematic data was limited during the interventional study with junior Australian football players due to resources and time constraints. Data such as

mean/instantaneous velocity, step length, step frequency, contact time and flight time, collected via video analysis/timing gates/radar would have provided greater insight into the effect of the combined sprint training intervention on sprint mechanical changes.

9. Despite the non-constant pulling force achieved using elastic cords providing a neuromuscular stimulus and enhancing mechanical characteristics, portable robotic devices with constant pulling force such as a 1080Sprint™, would likely provide a more standardized velocity approach yet at a much greater financial cost.
10. Although reflecting the ecological dynamics of training, when performing sprint profiling, practitioners must attempt to control as many environmental variables as possible to ensure a high level of intra and inter-day reliability of mechanical characteristics which can inform future training.
11. Between measurement methodology, considerations must be made on the practical application and ecological validity of testing and data collection (i.e., ease of setup for timing gates) compared to the scientific rigor of other types of technology such as in-ground force plates or a motorized pulley device.
12. Greater sample sizes in all studies would have provided greater certainty to results when using post-hoc analysis. Study 1 (0.57) and Study 4 (0.76) were both underpowered. Post-hoc analysis for both studies therefore identified mean differences would only be detected 57% and 76% of time respectively, which limits the conclusions for these studies.
13. Conceptual frameworks, training recommendations and guidelines specific to enhancing vertical and horizontal mechanical characteristics must be tested in an

interventional study using high-level athletes to further analyse the efficacy of this approach.

## Future Research Directions

Future directions regarding field-based mechanical profiling will likely involve the combination of smartphone applications, artificial intelligence, wearable technology and 'live' feedback. Existing smartphone applications currently determine mechanical characteristics however there remains several post-processing steps to obtain the data. Early stages of applications employing artificial intelligence to assess mechanical characteristics plus providing 'live' kinematic and segmental data have begun to surface across 2022. New applications of vertical and horizontal F-v profiling will continue to emerge, along with researchers establishing new relationships with mechanical characteristics and other training or sport-specific variables. However, the present 'roadblock' in methodology is the time constraint to actionable feedback to the coach and athlete. Currently, there remains significant time to collect and process data before feeding back to the sports performance or sport coach about how results should inform the next phase of training. The ability for a sports biomechanist or sports performance practitioner to use high-speed video (240FPS) and provide 'live feedback' during a training session would further enhance the methodology to the sport coach. This would allow the sport coach to make rapid data-driven, biomechanical and technical based decisions in an attempt to improve the physical performance of their athletes. A combination of this type of approach embedded into longitudinal training studies and monitoring practices would identify whether mechanical strengths, weaknesses and imbalances are changing based on specific training inputs or phases of training.

## Recommendations

Recommendations for sport biomechanists, physical preparation coaches and researchers are proposed based on this research:

### Sports biomechanists & Researchers

1. Practitioners should perform their own validation and reliabilty studies when using new mechanical profiling methology and determine measurement agreement with known gold standard technology.
2. A sensitivity analysis should be conducted on both mechanical charactetistics and performance variables to determine a 'true change' in response to training interventions, performance, illness and injury.
3. Although specific testing days may be required to profile large groups of athletes, practitioners should attempt to profile athletes within their usual training session, thereby creating more ecologically-dynamic sources of data.
4. Consider the use of field-based mechanical profiling in conjunction with video-analysis tools to provide greater insight about the biomechanical and technical aspects of performance.
5. Mechanical profiling should be embedded into the sport training session across the season for coaches to monitor changes to mechanical characteristics in response to training interventions, injury and illness.

### Physical preparation coaches

1. Mechanical profiling in an inidivual and team sport setting should form part of the bi-weekly or monthly diagnostic assessment to inform training decisions regarding the F-v continuum.

2. The specific type of profiling methodology (i.e., vertical or horizontal) should be considered within the context of the event or sport demands but also with the equipment which is available.
3. Gym-based and sprint-based training interventions can be designed based on data from F-v profiles by grouping athletes into quadrants or categories.
4. Once athletes have been placed into categories, physical preparations coaches can individualize their training based on their mechanical and technical strengths and weaknesses of the athlete.
5. If physical preparation coaches will be implementing mechanical profiling during training sessions independently from the sports biomechanists, ensure appropriate methodology is followed for reliability and validity purposes.

## Conclusions

This PhD looked to address the overarching aim of providing a comprehensive understanding of the utility of mechanical profiling in team and individual sports to improve physical performance. Furthermore, this research has highlighted new practical understanding and knowledge for sports performance coaches about how mechanical data can inform training interventions and physical preparation strategies in individual and team sport contexts. The outcomes from this body of work have significantly progressed aspects of the applied sports biomechanics and strength and conditioning fields specific to the mechanical characteristics of jumping and sprinting and identified strong links between performance outcomes, neuromuscular output, sport or event demands and individual biomechanical and technical characteristics. Future experimental research, possibly linked to artificial intelligence, wearable technology and smartphone applications should evaluate mechanical characteristics in ‘real-time’ and provide instantaneous feedback to coach and athlete about the most appropriate biomechanical and technical training recommendations to enhance mechanical characteristics in various sports and events.

## REFERENCES


1. Alcazar J, R. C, Ara I, and Alegre LM. On the Shape of the Force-Velocity Relationship in Skeletal Muscles: The Linear, the Hyperbolic, and the Double-Hyperbolic. *Frontiers in Physiology* 10: 1-21, 2019.
2. Alcazar J, Rodriguez-Lopez C, Ara I, Alfaro-Acha A, Manas-Bote A, Guadalupe-Grau A, Garcia-Garcia FJ, and Alegre LM. The Force-Velocity Relationship in Older People: Reliability and Validity of a Systematic Procedure. *International Journal of Sports Medicine* 38: 1097-1104, 2017.
3. Alcazar J, Rodriguez-Lopez C, Ara I, Alfaro-Acha A, Rodriguez-Gomez I, Navarro-Cruz R, Losa-Reyna J, Garcia-Garcia FJ, and Alegre LM. Force-velocity profiling in older adults: An adequate tool for the management of functional trajectories with aging. *Experimental Gerontology* 108: 1-6, 2018.
4. Alt T, Oeppert T, Zedler M, Goldmann J, Braunstein B, and Willwacher S. A novel guideline for the analysis of linear acceleration mechanics – outlining a conceptual framework of 'shin roll' motion. *Sports Biomechanics*: 1-19, 2022.
5. Arsac L and Locatelli E. Modeling the energetics of 100-m running by using speed curves of world champions. *Journal of Applied Physiology* 92: 1781-1788, 1985.
6. Asmussen E and Bonde-Petersen F. Storage of elastic energy in skeletal muscles in man. *Acta Physiologica Scandinavica* 91: 385-392, 1974.
7. Atkinson G and Nevill A. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine* 26, 1998.
8. Bachero-Mena B and Gonzalez-Badillo JJ. Effects of Resisted Sprint Training on Acceleration with three different loads accounting for 5, 12.5, and 20% of body mass. *The Journal of Strength & Conditioning Research* 28: 2954-2960, 2014.
9. Baena-Raya A, Jiménez-Reyes P, Romea E, Soriano-Maldonado A, and Rodríguez-Pérez M. Gender-Specific Association of the Sprint Mechanical Properties With Change of Direction Performance in Basketball. *Journal of Strength & Conditioning Research*, 2021.
10. Baker DG. Comparison of upper-body strength and power between professional and college-Aged Rugby Players. *Journal of Strength & Conditioning Research* 15: 30-35, 2001.
11. Baker DG and Newton RU. Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *Journal of Strength & Conditioning Research* 22: 153-158, 2008.
12. Balsalobre-Fernández C, Glaister M, and Lockey RA. The validity and reliability of an iPhone app for measuring vertical jump performance. *Journal of Sports Sciences* 33: 1574-1579, 2015.
13. Barr M, Sheppard JM, Agar-Newman D, and Newton R. Transfer Effect of Strength and Power Training to the Sprinting Kinematics of International Rugby Players. *Journal of Strength & Conditioning Research* 28: 2585-2596, 2014.
14. Bartolini J, Brown L, Coburn J, Judelson D, Spiering B, Aguirre N, Carney K, and Harris K. Optimal Elastic Cord Assistance For Sprinting In Collegiate Women Soccer Players. *Journal of Strength & Conditioning Research* 25: 1263-1270, 2001.
15. Bates D and Chambers M. Nonlinear Models in: *Statistical Models in S*. J Chambers, T Hastie, eds.: Wadsworth & Brooks/Cole, 1992, pp 1-34.

16. Bates D and Watts DG. Nonlinear Regression: Iterative Estimation and Linear Approximations, in: *Nonlinear Regression Analysis and Its Applications*. USA: John Wiley & Sons, Inc., 1988, pp 32-66.
17. Bayne H. Force-velocity-power profiles of elite sprinters: Inter- and intra-indiviudal determinants of performance, in: *36th Conference of the International Society of Biomechanics in Sports*. Auckland, New Zealand, , 2018.
18. Bellinger P, Bourne M, Duhig S, Lieven E, Kennedy B, Martin A, Cooper C, Tredrea M, Rice H, Derave W, and Minahan C. Relationships between lower limb muscle characteristics and force–velocity profiles derived during sprinting and jumping. *Medicine and Science in Sports & Exercise* 53: 1400-1411, 2021.
19. Benz A, Winkelman N, Porter J, and Nimphius S. Coaching instructions and cues for enhancing sprint performance. *Strength and Conditioning Journal* 38: 1-11, 2016.
20. Best C and Partridge R. The equation of motion of a runner, exerting a maximal effort. *Proceedings of the Royal Society of London Series B, Containing Papers of a Biological Character* 103: 218-225, 1928.
21. Bezodis IN, Kerwin D, Cooper S, and Salo AI. Sprint Running Performance and Technique Changes in Athletes During Periodized Training: An Elite Training Group Case Study. *International Journal of Sports Physiology & Performance* 13: 755-762, 2018.
22. Bezodis NE, Colyer SL, Nagahara R, Bezodis IN, Morin JB, Murata M, and Samozino P. Ratio of forces during sprint acceleration: A comparison of different calculation methods. *Journal of Biomechanics* 127: 1-6, 2021.
23. Bezodis NE and Razavet J. Alterations to the orientation of the ground reaction force vector affect sprint acceleration performance in team sports athletes. *Journal of Sport Sciences* 35, 2016.
24. Bezodis NE, Salo AI, and Trewartha G. Measurement Error in Estimates of Sprint Velocity from a Laser Displacement Measurement Device. *International Journal of Sports Medicine* 33: 439-444, 2012.
25. Bezodis NE, Trewartha G, and Salo AI. Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation. *Sports Biomechanics* 14, 2015.
26. Bland J and Altman D. Measuring agreement in method comparison studies. *Statistical methods in medical research* 8: 135-160, 1999.
27. Bland J and Altman D. Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement. *International Journal of Nursing Studies* 47: 931-936, 2010.
28. Blazevich AJ and Jenkins D. Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. *Journal of Sport Sciences* 20: 981-990, 2022.
29. Bobbert M, Lindberg K, Bjornsen T, Solberg P, and Paulsen G. The Force-Velocity Profile for Jumping: What it Is and What it Is Not. *Medicine and Science in Sports & Exercise*, 2023.
30. Bobbert MF. Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *Journal of Applied Physiology* 112: 1975-1983, 2012.
31. Bompa T and Haff GG. Annual Training Plan, in: *Periodization: Theory and Methodology of Training*. T Bompa, GG Haff, eds. USA: Human Kinetics, 2009, pp 125-185.
32. Bompa T and Haff GG. Principles of Training, in: *Periodization: Theory and Methodology of Training*. T Bompa, GG Haff, eds. USA: Human Kinetics, 2009, pp 32-55.

33. Bompa T and Haff GG. Training Cycles, in: *Periodization: Theory and Methodology of Training*. T Bompa, GG Haff, eds. USA: Human Kinetics, 2009, pp 203-233.
34. Bosco C, Luhtanen P, and Komi PV. A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology* 50: 273-282, 1983.
35. Burgess D, Naughton G, and Hopkins W. Draft-camp predictors of subsequent career success in the Australian football league. *Journal of Science & Medicine in Sport* 15: 561-567, 2012.
36. Cahill M, Oliver J, Cronin J, Clark K, Cross M, and Lloyd R. Influence of resisted sled-push training on the sprint forcevelocity profile of male high school athletes. *Scandavian Journal of Medicine and Science in Sports* 30: 442-449, 2019.
37. Cahill M, Oliver J, Cronin J, Clark K, Cross M, Lloyd R, and Lee J. Influence of Resisted Sled-Pull Training on the Sprint Force-Velocity Profile of Male HighSchool Athletes. *Journal of Strength & Conditioning Research* 34: 2751-2759, 2020.
38. Carlock JM, Smith SL, Hartman M, Morris R, Ciroslan D, Pierece K, Newton R, Harman E, Sands W, and Stone M. The relationship between vertical jump power estimates and weightlifting ability: A field-test approach. *Journal of Strength & Conditioning Research* 18: 534-539, 2004.
39. Cavagna GA, Komarek L, and Mazzoleni S. The mechanics of sprint running. *The Journal of Physiology* 217: 709-721, 1971.
40. Charalambous L, Irwin G, Bezodis IN, and Kerwin D. Lower limb joint kinetics and ankle joint stiffness in the sprint start push-off. *Journal of Sport Sciences* 30: 1-9, 2012.
41. Cissik J. Means and Methods of Speed Training, Part 1. *Strength and Conditioning Journal* 26: 24-29, 2004.
42. Cissik J. Means and Methods of Speed Training, Part 2. *Strength and Conditioning Journal* 27: 18-25, 2005.
43. Cissik J. Strength and Conditioning Considerations for the 100-m Sprinter. *Strength and Conditioning Journal* 32: 89, 2010.
44. Clark D, Kuhlman S, Sabick M, Pfeiffer R, Knigge N, and Shea K. Influence Of Towing Force Magnitude On The Kinematics Of Supramaximal Sprinting. *Journal of Strength & Conditioning Research* 23: 1162-1168, 2009.
45. Clark K. Determinants of Top Speed Sprinting: Minimum Requirements for Maximum Velocity. *Applied Sciences* 12: 1-8, 2022.
46. Clark K and Ryan LJ. Hip Torque Is a Mechanistic Link Between Sprint Acceleration and Maximum Velocity Performance: A Theoretical Perspective. *Frontiers in Sports and Active Living* 4: 1-7, 2022.
47. Clark K, Ryan LJ, Meng C, and Stearne D. Evaluation of maximum thigh angular acceleration during the swing phase of steady-speed running. *Sports Biomechanics*: 1-14, 2021.
48. Clark K and Weyand PG. Are running speeds maximized with simple-spring stance mechanics? *Journal of Applied Physiology* 117: 604-615, 2014.
49. Clark K and Weyand PG. Sprint running research speeds up: A first look at the mechanics of elite acceleration. *Scandinavian Journal of Medicine and Science in Sports* 25: 581-582, 2015.
50. Cleather D. Force-velocity profiling is a misnomer: Load-jump height profiling would be a better name, in: *SportRxiv*. 2019.
51. Cleather D, Goodwin J, and Bull A. An Optimization Approach to Inverse Dynamics Provides Insight as to the Function of the Biarticular Muscles During Vertical Jumping. *Annals of Biomedical Engineering* 39: 147-160, 2011.

52. Cohen J. The Significance of a Product moment R, in: *Statistical power analysis for the behavioral sciences*. J Cohen, ed. Hillsdale, NJ: England: Lawrence Erlbaum, 1988, pp 75-107.
53. Colyer SL, Nagahara R, Takai Y, and Salo AI. How sprinters accelerate beyond the velocity plateau of soccer players: Waveform analysis of ground reaction forces. *Scandanavian Journal of Medicine and Science in Sports*, 2018.
54. Colyer SL, Nagahara R, Takai Y, and Salo AI. The effect of biological maturity status on ground reaction force production during sprinting. *Scandanavian Journal of Medicine and Science in Sports* 30: 1387–1397, 2020.
55. Colyer SL, Stokes KA, Bilzon JLJ, Holdcroft D, and Salo AIT. Training-Related Changes in Force-Power Profiles: Implications for the Skeleton Start. *International Journal of Sports Physiology & Performance* 13: 412-419, 2018.
56. Comfort P, Bullock N, and Pearson S. Comparison of Maximal Squat Strength and 5-, 10-, and 20-Meter Sprint Times, in Athletes and Recreationally Trained Men. *Journal of Strength & Conditioning Research* 26: 937-940, 2012.
57. Conan R and DeBeliso M. The Relationship Between Back Squat Strength and Sprint Times Among Male NCAA Track Athletes. *International Journal of Sports Science* 10: 38-42, 2020.
58. Contreras B, Vigotsky A, Schoenfeld B, Beardsley C, McMaster DT, Reyneke J, and Cronin J. Effects of a six-week hip thrust vs. front squat resistance training program on performance in adolescent males: A randomized controlled trial. *Journal of Strength & Conditioning Research* 31: 999-1008, 2017.
59. Cormack S, Newton R, McGuigan M, and Doyle T. Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology & Performance* 3: 131-144, 2008.
60. Cormie P, McBride J, and McCaulley GO. Validation of power measurement techniques in dynamic lower body resistance exercises. *Journal of Applied Biomechanics* 23: 103-118, 2007.
61. Cormie P, McBride JM, and McCaulley GO. Power-time, force-time, and velocity-time curve analysis during the jump squat: impact of load. *Journal of Applied Biomechanics* 24: 112-120, 2008.
62. Cormie P, McCaulley GO, and McBride JM. Power versus strength-power jump squat training: influence on the load-power relationship. *Medicine and Science in Sports & Exercise* 39: 996-1003, 2007.
63. Cormie P, McCaulley GO, Triplett NT, and McBride JM. Optimal loading for maximal power output during lower-body resistance exercises. *Medicine and Science in Sports & Exercise* 39: 340-349, 2007.
64. Cormie P, McGuigan MR, and Newton RU. Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports & Exercise* 42: 1582-1598, 2010.
65. Cormie P, McGuigan MR, and Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine and Science in Sports & Exercise* 42: 1566-1581, 2010.
66. Cormie P, McGuigan MR, and Newton RU. Developing maximal neuromuscular power: Part 1 - Biological basis of maximal power production. *Sports Medicine* 41: 17-38, 2011.
67. Cormie P, McGuigan MR, and Newton RU. Developing maximal neuromuscular power: Part 2 - Training considerations for improving maximal power production. *Sports Medicine* 41: 125-146, 2011.

68. Corn R and Knudson D. Effect of elastic-cord towing on the kinematics of the acceleration phase of sprinting. *Journal of Strength & Conditioning Research* 17: 72-75, 2003.
69. Cortina J. What is coefficient alpha? An examination of theory and applications. *Journal of Applied Psychology* 78: 98-104, 1993.
70. Coutts A, Quinn J, Hocking J, Castagna C, and Rampinini E. Match running performance in elite Australian Rules Football. *Journal of Science & Medicine in Sport* 13: 543-548, 2010.
71. Coyne J, Coutts A, Newton R, and Haff GG. The Current State of Subjective Training Load Monitoring: Follow-Up and Future Directions. *Sports Medicine - Open* 8: 1-11, 2022.
72. Cronin J and Hansen K. Strength and power predictors of sports speed. *Journal of Strength & Conditioning Research* 19, 2005.
73. Cronin J and Sleivert G. Challenges in Understanding the Influence of Maximal Power Training on Improving Athletic Performance. *Sports Medicine* 35: 213-234, 2005.
74. Cross M, Brughelli M, Brown SR, Samozino P, Gill ND, Cronin JB, and Morin JB. Mechanical Properties of Sprinting in Elite Rugby Union and Rugby League. *International Journal of Sports Physiology & Performance* 10: 695-702, 2015.
75. Cross M, Brughelli M, Samozino P, Brown SR, and Morin JB. Optimal Loading for Maximising Power During Sled-resisted Sprinting. *International Journal of Sports Physiology & Performance*: 1-25, 2017.
76. Cross M, Brughelli M, Samozino P, and Morin JB. Methods of Power-Force-Velocity Profiling During Sprint Running: A Narrative Review. *Sports Medicine* 47: 1255-1269, 2017.
77. Cross M, Lahti J, Brown SR, Chedati M, Jimenez-Reyes P, Samozino P, Eriksrud O, and Morin JB. Training at maximal power in resisted sprinting: Optimal load determination methodology and pilot results in team sport athletes. *PLoS One*, 2018.
78. Cuk I, Mirkov D, Nedeljkovic A, Kukolj M, Ugarkovic D, and Jaric S. Force-velocity property of leg muscles in individuals of different level of physical fitness. *Sports Biomechanics* 15: 207-219, 2016.
79. Cummins C, Orr R, O'Connor H, and West C. Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Medicine* 43: 1025-1042, 2013.
80. Cuthbert M, Haff GG, Arent S, Ripley N, McMahon J, Evans M, and Comfort P. Effects of Variations in Resistance Training Frequency on Strength Development in Well-Trained Populations and Implications for In-Season Athlete Training: A Systematic Review and Meta-analysis. *Sports Medicine* 51: 1967–1982, 2021.
81. Davies C. Human power output in exercise of short duration in relation to body size and composition. *Ergonomics* 14: 245-256, 1971.
82. Davies C and Rennie R. Human Power Output. *Nature* 217: 770-771, 1968.
83. De Lacey J, Brughelli M, McGuigan M, Hansen K, Samozino P, and Morin JB. The effects of tapering on power-force-velocity profiling and jump performance in professional rugby league players. *Journal of Strength & Conditioning Research* 28: 3567-3570, 2014.
84. Delaney J, McKay B, Radcliffe J, Benton D, Samozino P, Morin JB, and Duthie G. Uphill sprinting load– and force–velocity profiling: Assessment and potential applications. *Journal of Sport Sciences* 40: 281-287, 2022.
85. Delaney J, Olson T, and Morin JB. Sprint acceleration mechanical profiling for the NFL draft. *SPSR* 1: 1-3, 2018.

86. Devismesa M, Aeles J, Philips J, and Vanwanseele B. Sprint force-velocity profiles in soccer players: impact of sex and playing level. *Sports Biomechanics*: 1-11, 2019.
87. DeWeese B, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength–power training in track and field. Part 1: Theoretical aspects. *Journal of Sport and Health Science* 4: 308-317, 2015.
88. Di Prampero P, Botter A, and Osgnach C. The energy cost of sprint running and the role of metabolic power in setting top performances. *European Journal of Applied Physiology* 115: 451-469, 2015.
89. Di Prampero P, Fusi S, Sepulcri L, Morin JB, Belli A, and Antonutto G. Sprint running: a new energetic approach. *The Journal of Experimental Biology* 208: 2809-2816, 2005.
90. Dias J, Dal Pupo J, Ries D, Borges L, Santos S, Moro A, and Borges Jr N. Validity of two methods for estimation of vertical jump height. *Journal of Strength & Conditioning Research* 25: 2034-2039, 2011.
91. Djuric S, Cuk I, Sreckovic S, Mirkov D, Nedeljkovic A, and Jaric S. Selective Effects of Training Against Weight and Inertia on Muscle Mechanical Properties. *Int J Sports Physiol Perform* 11: 927-932, 2016.
92. Donaldson B, Bayne H, and Bezodis NE. A comparison of trunk and shank angles between elite and sub-elite sprinters during sprint acceleration. Presented at 38th International Society of Biomechanics in Sport Conference, Online, July 20-24, 2020.
93. Donaldson B, Bezodis NE, and Bayne H. Inter- and intra-limb coordination during initial sprint acceleration. *Biology Open* 11: 1-11, 2022.
94. Dorel S, Couturier A, Lacour J, Vandewalle H, Hautier C, and Hug F. Force-velocity relationship in cycling revisited: benefit of two-dimensional pedal forces analysis. *Medicine and Science in Sports & Exercise* 42: 1174-1183, 2010.
95. Dorel S, Hautier C, Rambaud O, D. R, Van Praagh E, Lacour J, and Bourdin M. Torque and power-velocity relationships in cycling: relevance to track sprint performance in world-class cyclists. *International Journal of Sports Medicine* 26: 739-746, 2005.
96. Duthie G, Pyne D, Ross A, Livingstone S, and Hooper SL. The reliability of ten-meter sprint time using different starting techniques. *Journal of Strength & Conditioning Research* 20: 246-251, 2006.
97. Ebben W, Davies J, and Clewien R. Effect of the Degree of the Slope on Acute Downhill Running Velocity & Acceleration. *Journal of Strength & Conditioning Research* 22: 898-902, 2008.
98. Edouard P, Lahti J, Nagahara R, Samozino P, Navarro L, Guex K, Rossi J, Brughelli M, Mendiguchia J, and Morin JB. Low Horizontal Force Production Capacity during Sprinting as a Potential Risk Factor of Hamstring Injury in Football. *International Journal of Environmental Research and Public Health* 18: 1-13, 2021.
99. Edwards T, Banyard HG, Piggott B, Haff GG, and Joyce C. Sprint acceleration profiles of junior Australian football players: Intra-individual determinants of performance. *Journal of Science & Medicine in Sport* 24: S71-S72, 2021.
100. Edwards T, Banyard HG, Piggott B, Haff GG, and Joyce C. Reliability and Minimal Detectable Change of Sprint Times and Force-Velocity-Power Characteristics. *Journal of Strength & Conditioning Research* 36: 268-272, 2022.
101. Edwards T, Piggott B, Banyard H, Haff GG, and Joyce C. The Effect of a Heavy Resisted Sled-Pull Mesocycle on Sprint Performance in Junior Australian Football Players. *Journal of Strength & Conditioning Research*: 1-6, 2022.

102. Edwards T, Piggott B, Banyard HG, Haff GG, and Joyce C. Sprint acceleration characteristics across the Australian football participation pathway. *Sports Biomechanics*: 1-13, 2020.
103. Edwards T, Piggott B, Banyard HG, Haff GG, and Joyce C. Sprint acceleration force-velocity-power characteristics in drafted vs non-drafted junior Australian football players: preliminary results. *Science and Medicine in Football* 5: 204-207, 2020.
104. Edwards T, Weakley J, Banyard HG, Cripps A, Piggott B, Haff GG, and Joyce C. Influence of Age and Maturation Status on Sprint Acceleration Characteristics in Junior Australian Football. *Journal of Sport Sciences* 39: 1585-1593, 2021.
105. Escobar-Álvarez JA, Fuentes-García JP, Da Conceicao F, and Jiménez-Reyes P. Individualized Training Based on Force–Velocity Profiling During Jumping in Ballet Dancers. *International Journal of Sports Physiology & Performance* 15: 788-794, 2020.
106. Escobar-Álvarez JA, Fuentes-García JP, Pérez-Sousa MA, and Calleja-González J. Effect of six weeks of individualized training based on the optimal force-velocity profile during jumping in dancers. Presented at ICTS VI International Conference in Team Sports, Marzo, Sevilla, 2018.
107. Escobar-Álvarez JA, Fuentes-García JP, Viana-da-Conceicao F, and Jimenez-Reyes P. Association between vertical and horizontal force-velocity-power profiles in netball players. *Journal of Human Sport and Exercise* 17, 2022.
108. Faude O, Koch T, and Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sport Sciences* 30: 625-631, 2012.
109. Faul F, Erdfelder E, Lang AW, and Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods* 39: 175-191, 2007.
110. Feeney D, Stanhope SJ, Kaminski TW, Machi A, and Jaric S. Loaded Vertical Jumping: Force-Velocity Relationship, Work, and Power. *Journal of Applied Biomechanics* 32: 120-127, 2016.
111. Fenn WO and Marsh BS. Muscular force at different speeds of shortening. *The Journal of Physiology* 85: 277-297, 1935.
112. Fernández-Galván L, Boullosa D, Jiménez-Reyes P, Cuadrado-Peñafiel V, and Casado A. Examination of the Sprinting and Jumping Force-Velocity Profiles in Young Soccer Players at Different Maturational Stages. *International Journal of Environmental Research and Public Health* 18: 1-11, 2021.
113. Fessi I, Wiesinger H, and Kröll J. Power–Force–Velocity Profiling as a Function of Used Loads and Task Experience. *International Journal of Sports Physiology & Performance* 17: 694-700, 2022.
114. Fitzpatrick D, Cimadoro G, and Cleather D. The Magical Horizontal Force Muscle? A Preliminary Study Examining the "Force-Vector" Theory. *Sports* 7: 1-9, 2019.
115. Flansbjer U, Holmba A, Downham D, Patten C, and Lexcell J. Reliability of gait performance tests in men and women with hemiparesis after stroke. *Journal of Rehabilitation Medicine* 37: 75-82, 2005.
116. Furlan L and Sterr A. The Applicability of Standard Error of Measurement and Minimal Detectable Change to Motor Learning Research—A Behavioral Study. *Frontiers in Human Neuroscience* 12: 1-10, 2018.
117. Furusawa K, Hill AV, and Parkinson J. The dynamics of "sprint" running. *Proceedings of the Royal Society of London* 102: 29-42, 1927.
118. Gabbett T. GPS analysis of elite women's field hockey training and competition. *Journal of Strength & Conditioning Research* 4: 1321-1324, 2010.

119. Gajer B, Thépaut-Mathieu C, and Lehénaff D. Evolution of stride and amplitude during course of the 100 m event in athletics. *New Studies in Athletics* 14: 43-50, 1999.
120. Garcia-Ramos A, Jaric S, Perez-Castilla A, Padial P, and Feriche B. Reliability and magnitude of mechanical variables assessed from unconstrained and constrained loaded countermovement jumps. *Sports Biomechanics* 16: 514-526, 2017.
121. Garcia-Ramos A, Perez-Castilla A, and Jaric S. Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics*: 274-289, 2021.
122. Garcia-Ramos A, Stirn I, Strojnik V, Padial P, De la Fuente B, Arguelles-Cienfuegos J, and Feriche B. Comparison of the force-, velocity-, and power-time curves recorded with a force plate and a linear velocity transducer. *Sports Biomechanics* 15: 329-341, 2016.
123. Garcia Ramos A and Jaric S. 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, 2017.
124. Garhammer J. A Comparison of Maximal Power Outputs between Elite Male and Female Weightlifters in Competition. *International Journal of Sport Biomechanics* 7: 3-11, 1991.
125. Ghigiarelli JJ, Ferrara KJ, Poblete KM, Valle CF, Gonzalez AM, and Sell KM. Level of Agreement, Reliability, and Minimal Detectable Change of the MusclelabTM Laser Speed Device on Force–Velocity–Power Sprint Profiles in Division II Collegiate Athletes. *Sports* 10: 1-16, 2022.
126. Giavaria D. Understanding Bland Altman analysis. *Biochemia Medica* 25: 141-151, 2015.
127. Girard O, Brocherie F, Morin JB, and Millet G. Intrasession and Intersession Reliability of Running Mechanics During Treadmill Sprints. *International Journal of Sports Physiology & Performance* 11: 432-439, 2016.
128. Girard O, Brocherie F, Morin JB, and Millet G. Neuro-mechanical determinants of repeated treadmill sprints - Usefulness of an "hypoxic to normoxic recovery" approach. *Frontiers in Physiology* 6: 1-14, 2015.
129. Giroux C, Rabita G, Chollet D, and Guilhem G. What is the Best Method for Assessing Lower Limb Force-Velocity Relationship? *International Journal of Sports Medicine* 36: 143-149, 2014.
130. Giroux C, Rabita G, Chollet D, and Guilhem G. Optimal Balance Between Force and Velocity Differs Among World-Class Athletes. *Journal of Applied Biomechanics* 32: 59-68, 2016.
131. Goodwin J and Cleather D. The biomechanical principles underpinning strength and conditioning, in: *Strength & Conditioning for Sports Performance*. I Jeffreys, J Moody, eds. New York, NY: Routledge, 2016, pp 100-101.
132. Goodwin L and Leech N. Understanding Correlation: Factors That Affect the Size of r. *The Journal of Experimental Education* 74: 249-266, 2006.
133. Haff GG and Nimphius S. Training Principles for Power. *Strength and Conditioning Journal* 34: 2-12, 2012.
134. Hakkinen K, Komi PV, and Alen M. Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica* 125: 587-600, 1985.
135. Haley S and Fragala-Pinkham M. Interpreting change scores of tests and measures used in physical therapy. *Physical therapy* 86: 735-743, 2006.

136. Halperin I, Williams KJ, Martin D, and Chapman D. The effects of attentional focusing instructions on force production during isometric midthigh pull. *Journal of Strength & Conditioning Research* 30: 919-923, 2015.
137. Harman E, Rosenstein M, Frykman P, Rosenstein R, and Kraemer WJ. Estimation of human power output from vertical jump. *Journal of Strength & Conditioning Research* 5: 116-120, 1991.
138. Harris N, Cronin J, Hopkins WG, and Hansen K. Squat Jump Training at Maximal Power Loads vs. Heavy Loads: Effect on Sprint Ability. *Journal of Strength & Conditioning Research* 22: 1742-1749, 2008.
139. Haugen T, Breitschadel F, and Seiler S. Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PLoS One*: 1-14, 2019.
140. Haugen T, Breitschädel F, and Seiler S. Sprint Mechanical Properties in Handball and Basketball Players. *International Journal of Sports Physiology & Performance* 14: 1388-1394, 2019.
141. Haugen T, Breitschädel F, and Seiler S. Countermovement jump height in national team athletes of various sports: a framework for practitioners and scientists. *International Journal of Sports Physiology & Performance* 16: 184-189, 2020.
142. Haugen T, McGhie D, and Ettema G. Sprint running: from fundamental mechanics to practice—a review. *Europrean Journal of Applied Physiology* 119: 1273-1287, 2019.
143. Haugen T, Seiler S, Sandbank O, and Tonnessen E. The Training and Development of Elite Sprint Performance: an Integration of Scientific and Best Practice Literature. *Sports Medicine - Open* 5: 1-16, 2019.
144. Haugen T, Tønnessen E, Hisdal J, and Seiler S. The Role and Development of Sprinting Speed in Soccer. *International Journal of Sports Physiology & Performance* 9: 432-441, 2014.
145. Haugen TA, Breitschädel F, and Samozino P. Power-force-velocity profiling of sprinting athletes: methodological and practical considerations when using timing gates. *Journal of Strength & Conditioning Research* 34: 1769-1773, 2018.
146. Helland C, Haugen T, Rakovic E, Eriksrud O, Seynnes O, Mero A, and Paulsen G. Force–velocity profiling of sprinting athletes: single-run vs. multiplerun methods. *European Journal of Applied Physiology*, 2019.
147. Hicks D. Resisted and Assisted Sprint Training: Determining the Transfer to Maximal Sprinting. *New Studies in Athletics* 32: 35-51, 2017.
148. Hicks D, Drummond C, Williams K, and van den Tillaar R. Exploratory Analysis of Sprint Force-Velocity Characteristics, Kinematics and Performance across a Periodized Training Year: A Case Study of Two National Level Sprint Athletes. *International Journal of Environmental Research and Public Health* 19: 1-16, 2022.
149. Hicks D, Drummond C, and Williams KJ. Measurement Agreement Between Samozino's Method and Force Plate Force-Velocity Profiles During Barbell and Hexbar Countermovement Jumps. *Journal of Strength & Conditioning Research* 36: 3290-3300, 2021.
150. Hicks D, Schuster J, Samozino P, and Morin JB. Improving Mechanical Effectiveness During Sprint Acceleration: Practical Recommendations and Guidelines. *Strength and Conditioning Journal* 42: 45-62, 2019.
151. Hill AV. The Heat of Shortening and the Dynamic Constants of Muscle. *Proceedings of the Royal Society of London B* 159: 297-318, 1938.
152. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Medicine* 30: 1-15, 2000.
153. Hopkins WG. How to interpret changes in an athletic performance test. *SportScience* 8: 1-7, 2004.

154. Hopkins WG. Spreadsheets for Analysis of Validity and Reliability, in: *SportScience* Melbourne, Australia, 2015, pp 36-42.
155. Hopkins WG, Marshall SW, Batterham AM, and Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports & Exercise* 41: 3-13, 2009.
156. Hunter J, Marshall R, and McNair P. Interaction of step length and step rate during sprint running. *Medicine and Science in Sports & Exercise* 36: 261-271, 2004.
157. Hunter J, Marshall RN, and McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics* 21: 31-43, 2005.
158. Impellizzeri FM, Marcora SM, and Coutts AJ. Internal and external training load: 15 years on. *International Journal of Sports Physiology & Performance* 14: 270-273, 2019.
159. Jagim A, Luedke J, Fitzpatrick A, Winkelman G, Erickson J, Askow A, and Camic C. The Impact of COVID-19-Related Shutdown Measures on the Training Habits and Perceptions of Athletes in the United States: A Brief Research Report. *Frontiers in Sports and Active Living* 2: 1-6, 2020.
160. Janicijevica D, Knezevic O, Mirkov D, Pérez-Castilla A, Petrovic M, and García-Ramos A. Magnitude and reliability of mechanical outputs obtained during loaded squat jumps performed from different knee angles. *Sports Biomechanics* 20: 925-937, 2021.
161. Janicijevica D, Knezevic O, Mirkov D, Pérez-Castilla A, Petrovic M, Samozino P, and García-Ramos A. 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, 2020.
162. Jaric S. Force-velocity Relationship of Muscles Performing Multi-joint Maximum Performance Tasks. *International Journal of Sports Medicine*, 2015.
163. Jaric S. Two-Load Method for Distinguishing Between Muscle Force, Velocity, and Power-Producing Capacities. *Sports Medicine* 46: 1585-1589, 2016.
164. Jaric S and Markovic G. Leg Muscles Design: The Maximum Dynamic Output Hypothesis. *Medicine and Science in Sports & Exercise* 41: 780-787, 2009.
165. Jarvis P, Cassone N, Turner A, Chavda S, Edwards M, and Bishop C. Heavy barbell hip thrusts do not effect sprint performance: An 8-week randomized controlled study. *Journal of Strength & Conditioning Research* 33, 2019.
166. Jasko´lska A, Goossens P, B. V, Jasko´lska A, and Skinner J. Treadmill measurement of the force-velocity relationship and power output in subjects with different maximal running velocities. *Sports Medicine Training Rehabilitation* 8: 347-358, 1999.
167. Jennings D, Cormack S, Coutts A, and Aughey R. International field hockey players perform more high-speed running than national-level counterparts. *Journal of Strength & Conditioning Research* 26: 947-952, 2012.
168. Jidovtseff B, Harris N, Crielaard J, and Cronin J. Using the load-velocity relationship for 1RM prediction *Journal of Strength & Conditioning Research* 25: 267-270, 2001.
169. Jiménez-Reyes P, Cross M, Ross A, Samozino P, Brughelli M, Gill N, and Morin JB. Changes in mechanical properties of sprinting during repeated sprint in elite rugby sevens athletes. *European Journal of Sport Science* 19: 585-594, 2019.
170. Jiménez-Reyes P, Garcia-Ramos A, Cuadrado-Penafiel V, Parraga-Montilla JA, Morcillo-Losa JA, Samozino P, and Morin JB. Differences in Sprint Mechanical Force-Velocity Profile Between Trained Soccer and Futsal Players. *International Journal of Sports Physiology & Performance*: 1-21, 2018.

171. Jiménez-Reyes P, Garcia Ramos A, Parraga-Montilla JA, Morcillo-Losa JA, Cuadrado-Penafiel V, Castano-Zambudio F, Samozino P, and Morin JB. Seasonal Changes in the Sprint Acceleration Force-Velocity Profile of Elite Male Soccer Players. *Journal of Strength & Conditioning Research* 36: 70-74, 2022.
172. Jiménez-Reyes P, Samozino P, Brughelli M, and Morin J-B. Effectiveness of an Individualized Training Based on Force-Velocity Profiling during Jumping. *Frontiers in Physiology* 7: 1-13, 2016.
173. Jiménez-Reyes P, Samozino P, Cuadrado-Penafiel V, Conceicao F, Gonzalez-Badillo JJ, and Morin JB. Effect of countermovement on power-force-velocity profile. *European Journal of Applied Physiology* 114: 2281-2288, 2014.
174. Jiménez-Reyes P, Samozino P, Garcia Ramos A, Cuadrado-Penafiel V, Brughelli M, and Morin JB. Relationship between vertical and horizontal force-velocity-power profiles in various sports and levels of practice. *PeerJ*: 1-18, 2018.
175. Jiménez-Reyes P, Samozino P, and Morin JB. Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. *PLoS One* 15: 1-20, 2019.
176. Jiménez-Reyes P, Samozino P, Pareja-Blanco F, Conceicao F, Cuadrado-Penafiel V, Gonzalez-Badillo JJ, and Morin J-B. Validity of a Simple Method for Measuring Force-Velocity-Power Profile in Countermovement Jump. *International Journal of Sports Physiology & Performance* 12: 36-43, 2017.
177. Johnston RD, Black GM, Harrison PW, Murray NB, and Austin DJ. Applied Sport Science of Australian Football: A Systematic Review. *Sports Medicine* 48: 1673-1694, 2018.
178. Jovanovic M. *bmbstats: Bootstrap Magnitude-based Statistics for Sports Scientists.* Belgrade, Serbia: Self Published, 2020.
179. Jovanovic M. *shorts: Short Sprints.* Belgrade, Serbia: Self Published, 2021.
180. Junge N, Lundsgaard A, Hansen M, Samozino P, Morin JB, Aagaard P, Contreras B, and Nybo L. Force-velocity-power profiling of maximal effort sprinting, jumping and hip thrusting: Exploring the importance of force orientation specificity for assessing neuromuscular function. *Journal of Sport Sciences*: 1-8, 2021.
181. Kaneko M, Fuchimoto T, Toji H, and Suei K. Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Med Sci Sports* 5: 50-55, 1983.
182. Kawamori N and Haff GG. The optimal training load for the development of muscular power. *Journal of Strength & Conditioning Research* 18: 675-684, 2004.
183. Kawamori N, Newton R, Hori N, and Nosaka K. Effects of weighted sled towing with heavy versus light load on sprint acceleration ability. *Journal of Strength & Conditioning Research* 28: 2738-2745, 2014.
184. Kiely J. Periodization Paradigms in the 21st Century: Evidence-Led or Tradition-Driven? *International Journal of Sports Physiology & Performance* 7: 242-250, 2012.
185. King D, Burnie L, Nagahara R, and Bezodis NE. Linearity of the ratio of forces-veloctity relationship is not related to initial acceleration performances in sprinting, in: *39th International Society of Biomechanics in Sport Conference*. Canberra, Australia, 2021, pp Sept 3-6, 2021.
186. Komi PV. Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. *Exercise and Sport Science Reviews* 12: 81-122, 1984.
187. Kotani Y, Lake J, Guppy S, Poon W, Nosaka K, Hori N, and Haff GG. Reliability of the Squat Jump Force-Velocity and Load-Velocity Profiles. *Journal of Strength & Conditioning Research* 00: 1-8, 2021.

188. Koziel S and Malina R. Modified Maturity Offset Prediction Equations: Validation in Independent Longitudinal Samples of Boys and Girls. *Sports Medicine* 48: 221-236, 2018
189. Kraemer WJ and Ratamess NA. Fundamentals of Resistance Training: Progression and Exercise Prescription. *Medicine and Science in Sports & Exercise* 36: 674-688, 2004.
190. Kristensen G, Van den Tillaar R, and Ettema G. Velocity specificity in early-phase sprint training. *Journal of Strength & Conditioning Research* 20: 833-837, 2006.
191. Kugler F and Janshen L. Body position determines propulsive forces in accelerated running. *Journal of Biomechanics* 43: 343-348, 2010.
192. Lacome M, Owen C, Peeters A, Piscione J, LeMeur Y, and Leduc C. Force velocity proling with GPS: is it reliable? *SPSR* July, 2020.
193. Laffaye G, Wagner P, and Tombleson T. Countermovement jump height: gender and sport-specific differences in the force-time variables. *Journal of Strength & Conditioning Research* 28: 1096-1105, 2014.
194. Lahti J, Huuhka T, Romero V, Bezodis IN, Morin JB, and Hakkinen K. Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players. *PeerJ*: 1-26, 2020.
195. Lahti J, Jiménez-Reyes P, Simond-Cote B, Ahtiainen J, Cross M, Samozino P, Chassaing P, and Morin JB. Individual Sprint Force-Velocity Profile Adaptations to In-Season Assisted and Resisted Velocity-Based Training in Professional Rugby. *Sports* 8: 1-15, 2020.
196. Lake JP, Mundy P, Comfort P, and McMahon J. Concurrent Validity of a Portable Force Plate Using Vertical Jump Force–Time Characteristics. *Journal of Applied Biomechanics* 34, 2017.
197. Lara A, Abián J, Alegre L, Jiménez L, and Aguado X. Assessment of power output in jump tests for applicants to a sports sciences degree. *The Journal of Sports Medicine and Physical Fitness* 46: 419-424, 2006.
198. Lara A, Alegre L, Abian J, Jimenez L, Urena A, and Aguado X. The selection of a method for estimating power output from jump performance. *Journal of Human Movement Studies* 50: 399-410, 2006.
199. Lindberg K, Solberg P, BjørnsenI T, Helland C, Rønnestad B, Frank M, Haugen T, S. Ø, Kristoffersen M, Midttun M, Sæland F, and Paulsen G. Force-velocity profiling in athletes: Reliability and agreement across methods. *PLoS One* 16: 1-20, 2021.
200. Lindberg K, Solberg P, Ronnestad B, Frank M, Larsen T, Abusdal G, Bernsten S, Paulsen G, Sveen O, Seynnes O, and Bjornsen T. Should we individualize training based on force-velocity profiling to improve physical performance in athletes? *Scandanvian Journal of Medicine and Science in Sports* 31: 2198-2210, 2021.
201. Linthorne N. The correlation between jump height and mechanical power in a countermovement jump is artificially inflated. *Sports Biomechanics* 20: 3-21, 2021.
202. Loturco I, Contreras B, Kobal R, Fernandes V, Moura N, and Siqueira F. Vertically and horizontally directed muscle power exercises: Relationships with top-level sprint performance. *PLoS One* 13: 1-13, 2018.
203. Loturco I, Nakamura FY, Kobal R, Gil S, Cal Abad CC, Cuniyochi R, Pereira L, and Roschel H. Training for power and speed: Effects of increasing or decreasing jump-squat velocity in elite young soccer players. *Journal of Strength & Conditioning Research* 29: 2771-2779, 2015.
204. Loturco I, Pereira LA, Kobal R, Zanetti V, Kitamura K, Abad CC, and Nakamura FY. Transference effect of vertical and horizontal plyometrics on sprint performance of high-level U-20 soccer players. *Journal of Sport Sciences* 33: 2182-2191, 2015.

205. Loturco I, Tricoli V, Roschel H, Nakamura FY, Cal Abad CC, Kobal R, Gil S, and González-Badillo J. Transference of traditional versus complex strength and power training to sprint performance. *Journal of Human Kinetics* 41: 265-273, 2014.
206. Ludbrook J. Comparing Methods of Measurement. *Clinical and Experimental Pharmacology & Physiology* 24: 193-203, 1997.
207. Ludbrook J. A Primer for Biomedical Scientists on How to Execute Model II Linear Regression Analysis. *Clinical and Experimental Pharmacology & Physiology* 39: 329-335, 2012.
208. Lythe J and Kilding A. Physical demands and physiological responses during elite field hockey. *International Journal of Sports Medicine* 32: 523-528, 2011.
209. Macutkiewicz D and Sunderland C. The use of GPS to evaluate activity profiles of elite women hockey players during match-play. *Journal of Sport Sciences* 29: 967-973, 2011.
210. Makaruk B, Stempel P, and Makaruk H. The effects of assisted sprint training on sprint running performance in women. *Acta Kinesiologica* 13: 5-10, 2019.
211. Malina R, Koziel S, Kralik M, Chrzanowska M, and Suder A. Prediction of maturity offset and age at peak height velocity in a longitudinal series of boys and girls. *American Journal of Human Biology*: 1-15, 2020.
212. Marcote-Pequeño R, García-Ramos A, Cuadrado-Peñafiel V, González-Hernández J, Ángel Gómez M, and Jiménez-Reyes P. Association between the force-velocity profile and performance variables obtained in jumping and sprinting in elite female soccer players. *International Journal of Sports Physiology & Performance* 24: 1-21, 2018.
213. Margaria R, Aghemo P, and Rovelli E. Measurement of muscular power (anaerobic) in man. *Journal of Applied Physiology* 21: 1662-1664, 1962.
214. Markovic G and Jaric S. Positive and negative loading and mechanical output in maximum vertical jumping. *Medicine and Science in Sports & Exercise* 39: 1757-1764, 2007.
215. Markstrom JL and Olsson CJ. Countermovement jump peak force relative to body weight and jump height as predictors for sprint running performances: (in)homogeneity of track and field athletes? *Journal of Strength & Conditioning Research* 27: 944-953, 2013.
216. McBride J, Blow D, Kirby T, Haines T, Dayne AM, and Triplett NT. Relationship between maximal squat strength and five, ten and forty yard sprint time. *Journal of Strength & Conditioning Research* 23: 1633-1636, 2009.
217. McBride JM, Kirby TJ, Haines TL, and Skinner J. Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. *International Journal of Sports Physiology & Performance* 5: 484-496, 2010.
218. McBride JM, Triplett-McBride T, Davie A, and Newton RU. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. *Journal of Strength & Conditioning Research* 16: 75-82, 2002.
219. McGuinness A, Malone S, Hughes B, Collins K, and Passmore D. Physical Activity and Physiological Profiles of Elite International Female Field Hockey Players Across the Quarters of Competitive Match Play. *Journal of Strength & Conditioning Research* 33: 2513-2522, 2019.
220. McMahon J, Lake J, and Comfort P. Reliability of and Relationship between Flight Time to Contraction Time Ratio and Reactive Strength Index Modified. *Sports* 6: 1-10, 2018.

221. McMahon J, Rej S, and Comfort P. Sex Differences in Countermovement Jump Phase Characteristics. *Sports* 5, 2017.
222. McMahon J, Suchomel TJ, Lake JP, and Comfort P. Understanding the Key Phases of the Countermovement Jump Force-Time Curve. *Strength and Conditioning Journal* 40: 96-106, 2018.
223. Mendiguchia J, Edouard P, Samozino P, Brughelli M, Cross M, Ross A, Gill N, and Morin JB. Field monitoring of sprinting power–force–velocity profile before, during and after hamstring injury: two case reports. *Journal of Sports Sciences* 34: 535-541, 2016.
224. Mero A and Komi P. Force-, EMG-, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. *European Journal of Applied Physiology and Occupational Physiology* 55: 553-561, 1986.
225. Mero A and Komi PV. Effects of supramaximal velocity on biomechanical variables in sprinting. *International Journal of Sport Biomechanics* 1: 240-252, 1985.
226. Mero A and Komi PV. Effects of stimulated supramaximal sprinting on force production, neural activation and blood lactate, in: *XI International Congress of Biomechanics*. Amsterdam, Netherlands, 1987.
227. Mero A and Komi PV. Electromyographic activity in sprinting at speeds ranging from submaximal to supramaximal. *Medicine and Science in Sports & Exercise* 19: 266-274, 1987.
228. Mero A, Komi PV, and Gregor RJ. Biomechanics of Sprint Running. A Review. *Sports Medicine* 13: 376-392, 1992.
229. Mirwald R, Baxter-Jones A, Bailey D, and Beunen G. An assessment of maturity from anthropometric measurements. *Medicine and Science in Sports & Exercise* 34: 689-694, 2002.
230. Moir GL. Three Different Methods of Calculating Vertical Jump Height from Force Platform Data in Men and Women. *Measurement in Physical Education and Exercise Science* 12: 207-218, 2008.
231. Moir GL. Biomechanics of Fundamental Movements: Sprint Running, in: *Strength and Conditioning A Biomechanical Approach*. Burlington, MA: Jones & Bartlett Learning, 2015, pp 523-574.
232. Moir GL, Gollie JM, Davis SE, Guers JJ, and Witmer CA. The effects of load on system and lower-body joint kinetics during jump squats. *Sports Biomechanics* 11: 492-506, 2012.
233. Moir GL, Lamont H, and Snyder B. Mechanical Limitations to Sprinting and Biomechanical Solutions: A Constraints-Led Framework for the Incorporation of Resistance Training to Develop Sprinting Speed. *Strength and Conditioning Journal* 40: 47-67, 2018.
234. Montenij L, Buhre W, Jansen J, Kruitwagen C, and de Waal E. Methodology of method comparison studies evaluating the validity of cardiac output monitors: a stepwise approach and checklist. *British Journal of Anaesthesia* 116: 750-757, 2016.
235. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, and Lacour JR. Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology* 112: 3921-3930, 2012.
236. Morin JB, Edouard P, and Samozino P. Technical ability of force application as a determinant factor of sprint performance. *Medicine and Science in Sports & Exercise* 43: 1680-1688, 2011.
237. Morin JB, Edouard P, and Samozino P. New Insights Into Sprint Biomechanics and Determinants of Elite 100m Performance. *New Studies in Athletics* 28: 87-103, 2013.

238. Morin JB, Jimenez-Reyes P, Brughelli M, and Samozino P. When Jump Height is not a Good Indicator of Lower Limb Maximal Power Output: Theoretical Demonstration, Experimental Evidence and Practical Solutions. *Sports Medicine*, 2019.
239. Morin JB, Le Mat Y, Osgnach C, Baranbob A, Pilati A, Samozino P, and Di Prampero PE. Individual acceleration-speed profile in-situ: a proof of concept in professional football players. *Journal of Biomechanics*: 1-8, 2021.
240. Morin JB and McMillan S. Speed Training, in: *High Performance Training for Sports*. D Joyce, D Lewindon, eds. Champaign, IL: Human Kinetics, 2022, pp 149-162.
241. Morin JB, Petrakos G, Jimenez-Reyes P, Brown S, Samozino P, and Cross M. Very-Heavy Sled Training for Improving Horizontal Force Output in Soccer Players. *International Journal of Sports Physiology & Performance*, 2016.
242. Morin JB and Samozino P. Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training. *International Journal of Sports Physiology and Performance* 11: 267-272, 2016.
243. Morin JB and Samozino P. JUMP FVP profile spreadsheet. Nice, France: Self published, 2017.
244. Morin JB and Samozino P. Spreadsheet for Sprint acceleration force-velocity-power profiling. Nice, France: Self Published, 2017.
245. Morin JB, Samozino P, Bonnefoy R, Edouard P, and Belli A. Direct measurement of power during one single sprint on treadmill. *Journal of Biomechanics* 43: 1970-1975, 2010.
246. Morin JB, Samozino P, Cross M, and Nagahara R. A simple method for computing sprint acceleration kinetics from running velocity data: replication study with improved design. *Journal of Biomechanics* 94: 82-87, 2019.
247. Morin JB, Slawinski J, Dorel S, de Villareal ES, Couturier A, Samozino P, Brughelli M, and Rabita G. Acceleration capability in elite sprinters and ground impulse: Push more, brake less? *Journal of BIomechanics* 48: 3149-3154, 2015.
248. Morris C, Weber J, and Netto K. Relationship Between Mechanical Effectiveness in Sprint Running and Force-Velocity Characteristics of a Countermovement Jump in Australian Rules Football Athletes. *Journal of Strength & Conditioning Research* 36: 59-65, 2022.
249. Morrison M, Martin D, Tapley S, Scalan A, Delaney J, Halson S, and Weakley J. A Systematic Review on Fitness Testing in Adult Male Basketball Players: Tests Adopted, Characteristics Reported and Recommendations for Practice. *Sports Medicine* 52: 1491-1532, 2022.
250. Mullineaux D, Barnes C, and Batterham AM. Assessment of Bias in Comparing Measurements: A Reliability Example. *Measurement in Physical Education and Exercise Science* 3: 195-205, 1999.
251. Murray T and Hansen D. Off-Season, in: *High Performance Training for Sports*. D Joyce, D Lewindon, eds. Champaign, IL: Human Kinetics, 2022, pp 301-314.
252. Nagahara R, Kanehisa H, Matsuo A, and Fukunaga T. Are peak ground reaction forces related to better sprint acceleration performance? *Sports Biomechanics*: 1-10, 2019.
253. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Association of Step Width with Accelerated Sprinting Performance and Ground Reaction Force. *International Journal of Sports Medicine* 38: 534-540, 2017.
254. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Association of Sprint Performance With Ground Reaction Forces During Acceleration and Maximal Speed Phases in a Single Sprint. *Journal of Applied Biomechanics* 34: 104-110, 2018.

255. Naito H, Kariyama Y, Yamamoto K, and Tanigawa S. Sprint step-type specific characteristics of anthropometric and kinematic variables in sprinting acceleration, in: *33rd International Conference of Biomechanics in Sports*. F Colloud, M Domalain, T Monnet, eds. Poitiers, France, 2015.
256. Newton R, Murphy A, Humphries B, Wilson G, Kraemer W, and Ha¨kkinen K. Influence of load and stretch shortening cycle on the kinematics, kinetics and muscle activation that occurs during explosive upper-body movements. *European Journal of Applied Physiology* 75: 333-342, 1997.
257. Nicholson B, A. D, Jones B, Heyward O, and Till K. Sprint development practices in elite football code athletes. *International Journal of Sport Science and Coaching* 0: 1-19, 2021.
258. Nicholson B, Dinsdale A, Jones B, and Till K. Sprint and Jump Mechanical Profiles in Academy Rugby League Players: Positional Differences and the Associations between Profiles and Sprint Performance. *Sports* 9: 1-18, 2021.
259. Nuell S, Illera-Domı´nguez V, Carmona G, Alomar X, Padullés J, Lloret M, and Cadefau J. Sex differences in thigh muscle volumes, sprint performance and mechanical properties in national-level sprinters. *PloS One* 14: 1-13, 2019.
260. Pavei G, Zamparo P, Fujii N, Otsu T, Numazu N, Minetti A, and Monte A. Comprehensive mechanical power analysis in sprint running acceleration. *Scandanavian Journal of Medicine and Science in Sports*, 2019.
261. Pérez-Castilla A, Ramirez-Campillo R, Fernandes J, and García-Ramos A. Feasibility of the 2-point method to determine the load−velocity relationship variables during the countermovement jump exercise. *Journal of Sport and Health Science*, 2021.
262. Philpott L, Forrester S, van Lopik K, Hayward S, Conway P, and West A. Countermovement jump performance in elite male and female sprinters and high jumpers. *Journal of Sports Engineering and Technology* 235: 131-138, 2021.
263. Plisk S and Stone M. Periodization Strategies. *Strength and Conditioning Journal* 25: 19-37, 2003.
264. Puig-Divı´ A, Escalona-Marfil C, Padulle´s-Riu J, Busquets APs-C, X., and Marcos-Ruiz D. Validity and reliability of the Kinovea program in obtaining angles and distances using coordinates in 4 perspectives. *PLoS One* 14: 1-14, 2019.
265. Pyne D, Gardner A, Sheehan K, and Hopkins W. Fitness testing and career progression in AFL football. *Journal of Science and Medicine in Sport* 8: 321-332, 2005.
266. Rabita G, Dorel S, Slawinski J, Saez-de-Villarreal E, Couturier A, Samozino P, and Morin JB. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scandanavian Journal of Medicine and Science in Sports* 25: 583-594, 2015.
267. Rahmani A, Samozino P, Morin JB, and Morel B. A Simple Method for Assessing Upper-Limb Force-Velocity Profile in Bench Press. *International Journal of Sports Physiology and Performance* 13: 200-207, 2018.
268. Rakovic E, Paulsen G, Helland C, Eriksrud O, and Haugen TA. The effect of individualized sprint training in elite female team sport athletes: A pilot study. *Journal of Sports Sciences*: 1-7, 2018.
269. Randall D, Cronin J, Keogh JW, and Gill N. Transference of Strength and Power Adaptation to Sports Performance—Horizontal and Vertical Force Production. *Strength and Conditioning Journal* 32: 100-106, 2010.
270. Reiser R, Rocheford E, and Armstrong C. Building a Better Understanding of Basic Mechanical Principles Through Analysis of the Vertical Jump. *Strength and Conditioning Journal* 28: 70-80, 2006.

271. Rhea M, Ball S, Phillips W, and Burkett L. A Comparison of Linear and Daily Undulating Periodized Programs with Equated Volume and Intensity for Strength. *Journal of Strength & Conditioning Research* 17: 82-87, 2003.
272. Rienzi E, Drust B, Reilly T, Carter J, and Martin A. Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *The Journal of Sports Medicine and Physical Fitness* 40: 162-169, 2000.
273. Robertson S, Woods C, and P. G. Predicting higher selection in elite junior Australian Rules football: The influence of physical performance and anthropometric attributes. *Journal of Science and Medicine in Sport* 18: 601-606, 2015.
274. Romero-Franco N, Jimenez-Reyes P, Castano-Zambudio F, Capelo-Ramirez F, Rodríguez-Juan J, Toscano-Bendala F, Cuadrado-Penafiel V, and Balsalobre-Fernandez C. Sprint performance and mechanical outputs computed with an iPhone app: Comparison with existing reference methods. *European Journal of Sport Science*, 2016.
275. Ross A, Leveritt M, and Riek S. Neural influences on sprint running training adaptations and acute responses. *Sports Medicine* 31: 409-425, 2001.
276. Sakpal T. Sample Size Estimation in Clinical Trial. *Perspectives in Clinical Research* 1: 67-69, 2010.
277. Salacinski A, Alford M, Drevets K, Hart S, and Hunt B. Validity and Reliability of a Glucometer Against Industry Reference Standards. *Journal of Diabetes Science and Technology* 8: 95-99, 2014.
278. Salo AI, Bezodis IN, Batterham AM, and Kerwin D. Elite sprinting: are athletes individually step-frequency or step-length reliant? *Medicine and Science in Sports and Exercise* 43: 1055-1062, 2011.
279. Samozino P. 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*. JB Morin, P Samozino, eds. Switzerland: Springer, 2018, pp 95-119.
280. Samozino P. A Simple Method for Measuring Force, Velocity and Power Capabilities and Mechanical Effectiveness During Sprint Running, in: *Biomechanics of Training and Testing Innovative Concepts and Simple Field Methods*. JB Morin, P Samozino, eds. Switzerland: Springer, 2018, pp 237-313.
281. Samozino P. A simple method for measuring lower limb force, velocity and power capabilities during jumping, in: *Biomechanics of training and testing: Innovative concepts and simple field methods*. JB Morin, P Samozino, eds. Gewerbestrasse, Switzerland: Springer, 2018, pp 65-96.
282. Samozino P, Edouard P, Sangnier S, Brughelli M, Gimenez P, and Morin JB. Force-velocity profile: imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine* 35: 505-510, 2014.
283. Samozino P, Morin JB, Hintzy F, and Belli A. A simple method for measuring force, velocity and power output during squat jump. *Journal of Biomechanics* 41: 2940-2945, 2008.
284. Samozino P, Morin JB, Hintzy F, and Belli A. Jumping ability: a theoretical integrative approach. *Journal of Theoretical Biology* 264: 11-18, 2010.
285. Samozino P, Peyrot N, Edouard P, Nagahara R, Jimenez-Reyes P, Vanwanseele B, and Morin JB. Optimal Mechanical Force-Velocity Profile for Sprint Acceleration Performance. *Scandanavian Journal of Medicine and Science in Sports* 00: 1-7, 2021.
286. Samozino P, Rabita G, Dorel S, Slawinski J, Peyrot N, Saez de Villarreal E, and Morin JB. A simple method for measuring power, force, velocity properties, and

mechanical effectiveness in sprint running. *Scandanavian Journal of Medicine and Science in Sports* 26: 648-658, 2016.
287. Samozino P, Rejc E, di Prampero PE, Belli A, and Morin J-B. Force-velocity properties' contribution to bilateral deficit during ballistic push-off. *Medicine & Science in Sports and Exercise* 46: 107-114, 2014.
288. Samozino P, Rejc E, Di Prampero PE, Belli A, and Morin JB. Optimal force-velocity profile in ballistic movements--altius: citius or fortius? *Medicine and Science in Sports and Exercise* 44: 313-322, 2012.
289. Samozino P, Riviere JR, Rossi J, Morin JB, and Jimenez-Reyes P. How Fast Is a Horizontal Squat Jump? *Int J Sports Physiol Perform* 13: 910-916, 2018.
290. Samozino P, Romain Rivière J, Jimenez-Reyes P, Cross M, and Morin JB. Is the Concept, Method, or Measurement to Blame for Testing Error? An Illustration Using the Force-Velocity-Power Profile. *International Journal of Sports Physiology and Performance*: 1-9, 2022.
291. Sandau I and Granacher U. Long-Term Monitoring of Training Load, Force-Velocity Profile, and Performance in Elite Weightlifters: A Case Series With Two Male Olympic Athletes. *Journal of Strength and Conditioning Research* 36: 3446-3455, 2022.
292. Šarabon N, Kozinc Z, Garcia Ramos A, Knežević O, Coh M, and Mirkov DM. Reliability of Sprint Force-Velocity-Power Profiles Obtained with KiSprint System. *Journal of Sports Science and Medicine* 20: 357-364, 2021.
293. Šarabon N, Kozinc Ž, and Marković G. Force–velocity profile during vertical jump cannot be assessed using only bodyweight jump and isometric maximal voluntary contraction tasks. *Scientific Reports* 10: 1-12, 2020.
294. Sargeant AJ, Hoinville E, and Young A. Maximum leg force and power output during short-term dynamic exercise. *Journal of Applied Physiology*: 1175-1182, 1981.
295. Sarto F, Impellizzeri FM, Sporri J, Porcelli S, Olmo J, Requena B, Suarez-Arrones L, Arundale A, Bilsborough J, Buchheit M, Clubb J, Coutts A, Nabhan D, Torres-Ronda L, Mendez-Villanueva A, Mujika I, Maffiuletti N, and Franchi M. Impact of Potential Physiological Changes due to COVID-19 Home Confinement on Athlete Health Protection in Elite Sports: a Call for Awareness in Sports Programming. *Sports Medicine* 50: 1417–1419, 2020.
296. Schiffer J. The Sprints. *New Studies in Athletics* 24: 7-17, 2009.
297. Schuster J, Howells D, Robineau J, Couderc A, Natera A, Lumley N, Gabbett T, and Winkelman N. Physical-Preparation Recommendations for Elite Rugby Sevens Performance. *International Journal of Sports Physiology and Performance* 13: 255-267, 2018.
298. Schuster J, McMaster DT, Samozino P, Lacey S, and Winkelman N. Mechanical determinants of sprinting performance in elite women's rugby sevens. *Journal of Australian Strength and Conditioning* 26, 2018.
299. Seitz L, Reyes A, Tran TT, Saez De Villarreal E, and Haff GG. Increases in Lower-Body Strength Transfer Positively to Sprint Performance: A Systematic Review with Meta-Analysis. *Sports Medicine* 44: 1693-1702, 2014.
300. Sharma H and Kailashiya J. Effects of a 6-week sprint-strength and agility training on body composition, cardiovascular, and physiological parameters of male field hockey players. *Journal of Strength and Conditioning Research* 32: 894-901, 2017.
301. Sheppard JM, Cormack S, Taylor KL, McGuigan MR, and Newton RU. 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, 2008.

302. Simperingham KD, Cronin JB, Pearson SN, and Ross A. Reliability of horizontal force-velocity-power profiling during short sprint-running accelerations using radar technology. *Sports Biomechanics*: 1-12, 2017.
303. Simperingham KD, Cronin JB, and Ross A. Advances in Sprint Acceleration Profiling for Field-Based Team-Sport Athletes: Utility, Reliability, Validity and Limitations. *Sports Medicine* 46: 1619-1645, 2016.
304. Simpson A, Waldron M, Cushion E, and Tallent J. Optimized force-velocity training during pre-season enhances physical performance in professional rugby league players. *Journal of Sport Sciences* 39: 91-100, 2021.
305. Singh U, Ramachandran A, Baxter B, and Allen S. The correlation of force-velocity-power relationship of a whole-body movement with 20 m and 60 m sprint performance. *Sports Biomechanics*, 2021.
306. Singh W. Temporal evaluation of sprint bounding in sprinters and jumpers. *British Journal of Sports Medicine* 44, 2010.
307. Slawinski J, Bonnefoy A, Ontanon G, Leveque J, Miller C, Riquet A, Cheze L, and Dumas R. Segment-interaction in sprint start: analysis of 3D angular velocity and kinetic energy in elite sprinters. *Journal of Biomechanics* 43: 1494-1502, 2010.
308. Slawinski J, Termoz N, Rabita G, Guilhem G, Dorel S, Morin JB, and Samozino P. How 100-m event analyses improve our understanding of world-class men's and women's sprint performance. *Scandanavian Journal of Medicine and Science in Sports* 27: 45-54, 2017.
309. Sleivert G and Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *European Journal of Applied Physiology* 91: 46-52, 2004.
310. Soriano M, Jimenez-Reyes P, Rhea M, and Marın P. The Optimal Load for Maximal Power Production During Lower-Body Resistance Exercises: A Meta-Analysis. *Sports Medicine* 45: 1191-1205, 2015.
311. Spencer M, Bishop D, and Lawrence S. Longitudinal assessment of the effects of field-hockey training on repeated sprint ability. *Journal of Science and Medicine in Sport* 7: 323-334, 2014.
312. Spencer M, Lawrence S, Rechichi C, and Bishop D. Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. *Journal of Sport Sciences* 22: 843-850, 2004.
313. Spiriev B. World Athletics Scoring Tables of Athletics. Monaco: World Athletics, 2022, pp 1-540.
314. Stavridis I, Economou T, Walker J, Bissa A, Tsopanidou A, and Paradis G. Sprint mechanical characteristics of sub-elite and recreational sprinters. *Journal of Physical Education and Sport* 22: 1126-1133, 2022.
315. Stavridis I and Paradisis G. Association between Sprinting Performance and Force-Velocity Mechanical Profile of Men’s and Women’s World-Class Sprinters. Presented at 9th Greek Conference of Biochemistry and Physiology of Exercise, Thessaloniki, Greece, 2019.
316. Stavridis I, Smilios I, Tsopanidou A, Economou T, and Paradisis G. Differences in the Force Velocity Mechanical Profile and the Effectiveness of Force Application During Sprint-Acceleration Between Sprinters and Hurdlers. *Frontiers in Physiology* 1: 1-8, 2019.
317. Stavridis I, Tsopanidou A, Tsolakis C, Zacharogiannis E, Koulouvaris P, and Paradisis G. Force-velocity relationship between sprinting and jumping testing procedures. Presented at 38th International Society of Biomechanics in Sport Conference, Virtual, Jul 20-24, 2020.

318. Stone MH, Moir G, Glaister M, and Sanders R. How much strength is necessary? *Physical Therapy in Sport* 3: 88-96, 2002.
319. Stone MH, O'Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and Maximum Strength Relationships During Performance of Dynamic and Static Weighted Jumps. *Journal of Strength & Conditioning Research* 17: 140, 2003.
320. Suarez D, Wagle J, Cunanan A, Sausaman R, and Stone M. Dynamic Correspondence of Resistance Training to Sport: A Brief Review. *Strength and Conditioning Journal* 41: 80-88, 2019.
321. Suchomel T, Lamont H, and Moir GL. Understanding Vertical Jump Potentiation: A Deterministic Model. *Sports Medicine* 46: 809-828, 2015.
322. Suchomel TJ, Nimphius S, Bellon C, and Stone M. The Importance of Muscular Strength: Training Considerations. *Sports Medicine*, 2018.
323. Suchomel TJ, Nimphius S, and Stone MH. The Importance of Muscular Strength in Athletic Performance. *Sports Medicine* 46: 1419-1449, 2016.
324. Swinton P, Stewart A, Agouris I, Keogh J, and Lloyd R. A biomechanical analysis of straight and hexagonal barbell deadlifts using submaximal loads. *Journal of Strength and Conditioning Research* 25: 2000-2009, 2011.
325. Swinton P, Stewart AD, Lloyd R, Agouris I, and Keogh JW. Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. *Journal of Strength and Conditioning Research* 26: 906-913, 2012.
326. Thomas G, Kraemer WJ, Spiering B, Volek J, Anderson J, and Maresh C. Maximal power at different percentages of one repetition maximum: Influence of resistance and gender. *Journal of Strength and Conditioning Research* 21: 336-342, 2007.
327. Thorstensson A, Grimby G, and Karlsson J. Force-velocity-power characteristics and fiber composition in human knee extensor muscles. *Journal of Applied Physiology* 40: 12-16, 1976.
328. Tihanyi J, Apor P, and Fekete G. Force-velocity-power characteristics and fiber composition in human knee extensor muscles. *European Journal of Applied Physiology and Occupational Physiology* 48: 331-343, 1982.
329. Toji H and Kaneko M. Effect of multiple-load training on the force-velocity relationship. *Journal of Strength and Conditioning Research* 18: 792-795, 2004.
330. Toji H, Suei K, and Kaneko M. Effects of combined training loads on relations among force, velocity and power development. *Canadian Journal of Applied Physiology* 22: 328-336, 1997.
331. Tønnessenm E, Haugen T, and Shalfawi S. Reaction Time Aspects of Elite Sprinters in Athletic World Championships. *Journal of Strength and Conditioning Research* 27: 885-892, 2013.
332. Turner A, Comfort P, McMahon J, Bishop C, Chavda S, Read P, Mundy P, and Lake JP. Developing Powerful Athletes, Part 1: Mechanical Underpinnings. *Strength and Conditioning Journal* 42: 30-39, 2020.
333. Turner A, Walker S, Stembridge M, Coneyworth P, reed G, Birdsey L, Barter P, and Moody J. A Testing Battery for the Assessment of Fitness in Soccer Players. *Strength and Conditioning Journal* 33: 29-39, 2011.
334. Upton D. The Effect Of Assisted And Resisted Sprint Training On Acceleration And Velocity In Division IA Female Soccer Athletes. *Journal of Strength and Conditioning Research* 25: 2645-2652, 2011.
335. Uth N. Anthropometric Comparison of World-Class Sprinters and Normal Populations. *Journal of Sports Science and Medicine* 4: 608-616, 2005.
336. Valenzuela P, Sánchez-Martínez G, Torrontegi E, Vázquez-Carrio´n J, Montalvo Z, and Haff GG. 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: 1001-1007, 2020.
337. van den Tillaar R. Comparison of development of stepkinematics of assisted 60m sprints with different pulling forces between experienced male and female sprinters. *PLoS One* 17: 1-13, 2021.
338. van den Tillaar R, Haugen M, and Falch H. A Comparison of Sprint Mechanical Parameters Measured With Timing Gates and a Laser Gun. *Frontiers in Sports and Active Living* 4: 1-5, 2022.
339. van den Tillaar R and P. G. Comparison of step-by-step kinematics of resisted, assisted and unloaded 20-m sprint runs. *Sports Biomechanics* 18: 539-552, 2019.
340. van der Merwe F and Haggie M. GPS analysis of a team competing in a national under 18 field hockey tournament. *Journal of Australian Strength and Conditioning* 27: 6-11, 2019.
341. van Ingen Schenau G, Jacobs R, and de Koning JJ. Can cycle power predict sprint running performance? *European Journal of Applied Physiology and Occupational Physiology* 63: 255-260, 1991.
342. Vandewalle H, Peres G, Heller J, Panel J, and Monod H. 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, 1987.
343. Vanwanseele B and Aeles J. Mechanical determinants of sprint performance in elite and sub-elite field hockey players. Presented at 34 International Conference on Biomechanics in Sport, Tsukuba, Japan, July, 18-22, 2016.
344. Varley H, Gabbett T, and Aughey R. Activity profiles of professional soccer, rugby league and Australian football match play. *Journal of Sport Sciences*: 1-9, 2013.
345. Verkhoshansky Y and Siff M. *Supertraining.* Rime, Italy: Ultimate Athlete Concepts, 2009.
346. Vescovi JD. Impact of maximum speed on sprint performance during high-level youth female field hockey matches: female athletes in motion (FAiM) study. *International Journal of Sports Physiology and Performance* 9: 621-626, 2014.
347. Vigotsky A, Lake JP, Contreras B, and Hinrichs R. Mechanical Misconceptions: Have we lost the “mechanics” in “sports biomechanics”? *Journal of Biomechanics* 93: 1-5, 2019.
348. Vincent W. *Statistics in Kinesiology.* Champaign, IL: Human Kinetics, 1999.
349. von Lieres und Wilkau H, Irwin G, Bezodis NE, Simpson S, and Bezodis IN. Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases. *Sports Biomechanics* 19: 141-156, 2018.
350. Wagemans J, Catteeuw P, Vandenhouten J, Jansen J, de Corte X, Ceusters C, and Vissers D. The Impact of COVID-19 on Physical Performance and Mental Health—A Retrospective Case Series of Belgian Male Professional Football Players. *Frontiers in Sports and Active Living* 3, 2021.
351. Watkins C, Storey A, McGuigan M, Downes P, and Gill N. Horizontal Force-Velocity-Power Profiling of Rugby Players: A Cross-Sectional Analysis of Competition-Level and Position-Specific Movement Demands. *Journal of Strength and Conditioning Research*: 1-10, 2021.
352. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology* 89: 1991-1999, 2000.

353. Wild J, Bezodis NE, North J, and Bezodis IN. Characterising initial sprint acceleration strategies using a whole-body kinematics approach. *Journal of Sport Sciences*: 1-13, 2021.
354. Williams KJ, Chapman D, Phillips E, and Ball K. Load-Power relationship during a countermovement jump: A joint level analysis. *Journal of Strength and Conditioning Research* 32: 955-961, 2018.
355. Wilson G, Newton MJ, Murphy A, and Humphries B. The optimal training load for the development of dynamic athletic performances. *Medicine and Science in Sports and Exercise* 25: 1279-1286, 1993.
356. Winter EM, Abt G, Brookes C, Challis JH, Fowler NE, Knudson DV, Knuttgen HG, Kraemer WJ, Lane AM, Van Mechelen W, Morton H, Newton R, Williams C, and Yeodon M. Misuse of "Power" and Other Mechanical Terms in Sport and Exercise Science Research. *Journal of Strength & Conditioning Research* 30: 292-300, 2015.
357. Wisløff U, Castagna C, Helgerud J, Jones R, and Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *British Journal of Sports Medicine* 38: 285-288, 2004.
358. Yamauchi J and Ishii N. Relations between force-velocity characteristics of the knee-hip extension movement and vertical jump performance. *Journal of Strength and Conditioning Research* 21: 703-709, 2007.
359. Yamauchi J, Mishima C, Fujiwara M, Nakayama S, and Ishii N. Steady-state force-velocity relation in human multi-joint movement determined with force clamp analysis. *Journal of Biomechanics* 40: 1433-1442, 2007.
360. Yamauchi J, Mishima C, Nakajima S, and Ishii N. Force-velocity, force-power relationships of bilateral and unilateral leg multi-joint movements in young and elderly women. *Journal of Biomechanics* 42: 2151-2157, 2009.
361. Young W. Transfer of Strength and Power Training to Sports Performance. *International Journal of Sports Physiology and Performance* 2: 74-83, 2006.
362. Yu J, Sun Y, Yang C, Wang D, Yin K, Herzog W, and Liu Y. Biomechanical Insights Into Differences Between the Mid-Acceleration and Maximum Velocity Phases of Sprinting. *Journal of Strength & Conditioning Research* 30: 1906-1916, 2016.
363. Zabaloy S, Pereja-Blanco F, Giraldez J, Rasmussen J, and Gonzalez J. Effects of individualized training programmes based on the force-velocity imbalance on physical performance in rugby players. *Isokinetics and Exercise Science* 28: 181-190, 2020.
364. Zatsiorsky V and Kraemer W. *Science and Practice of Strength Training.* Human Kinetics, 2006.
365. Zhang Q, Pommerell F, Owen A, Trama R, Martin C, and Hautier C. Running patterns and force-velocity sprinting profiles in elite training young soccer players: A cross-sectional study. *European Journal of Sport Science*: 1-9, 2021.
366. Zivkovic MZ, Djuric S, Cuk I, Suzovic D, and Jaric S. Muscle Force-Velocity Relationships Observed in Four Different Functional Tests. *Journal of Human Kinetics* 56: 39-49, 2017.
367. Zweifel M. Importance of Horizontally Loaded Movements to Sports Performance. *Strength and Conditioning Journal* 39: 21-26, 2017.

# APPENDICES

## LIST OF APPENDICES

**Appendix J**

Chapter 7 published in the *International Journal of Environmental Research and Public Health.*

**Appendix K**

Chapter 8 published in the *Strength and Conditioning Journal.*

**Appendix L**

Chapter 9 published in the *Strength and Conditioning Journal.*

**Appendix M**

Co-author on a review published in the *Journal of Aging and Physical Activity.*

**Appendix N**

An article written for Sportsmith discussing my research in force-velocity profiling.

*https://www.sportsmith.co/articles/force-velocity-profiling/*

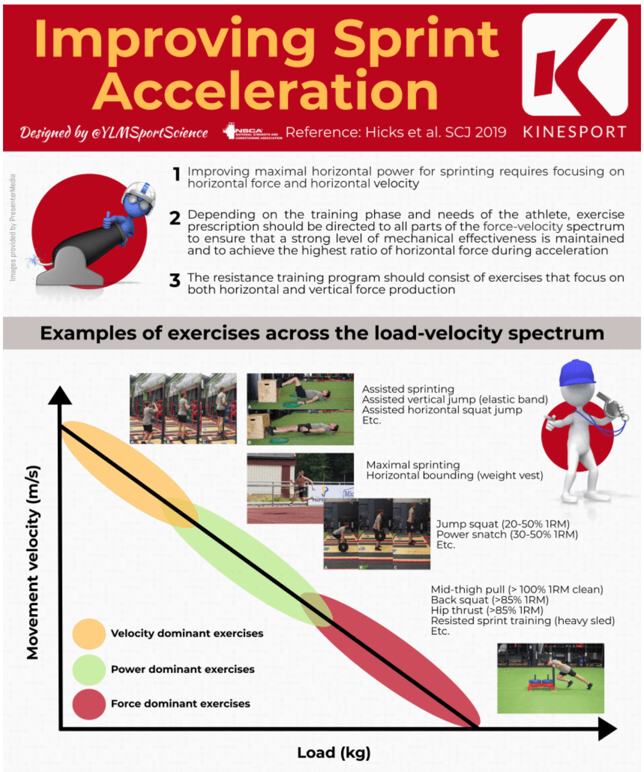
**Appendix O**

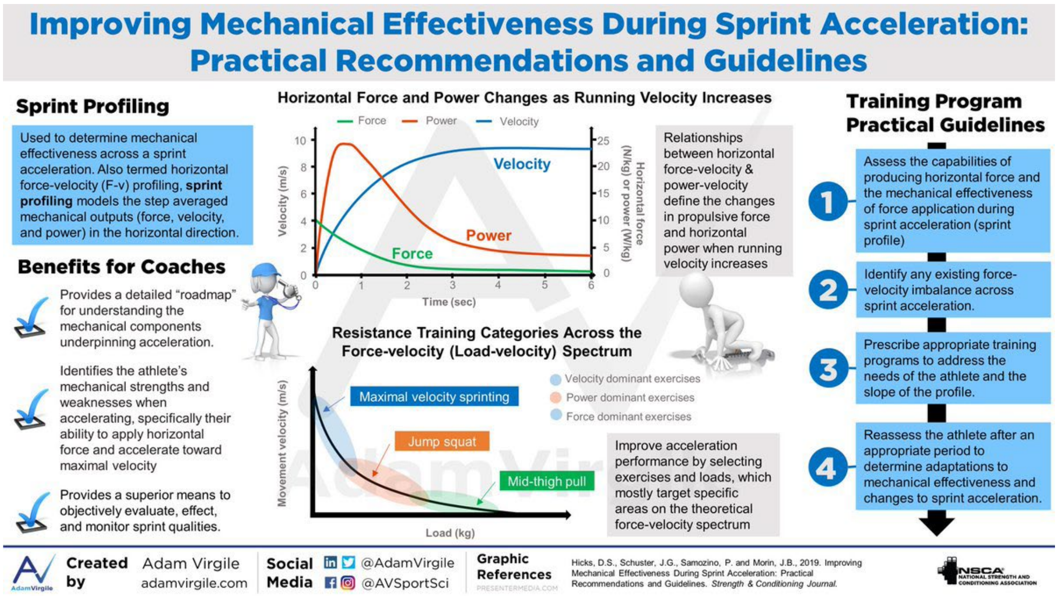
An article written for Simplifaster discussing my understanding of research methods within an applied practice setting.

*https://simplifaster.com/articles/training-part-time-professional-athlete-dylan-hicks/*

## Appendix A

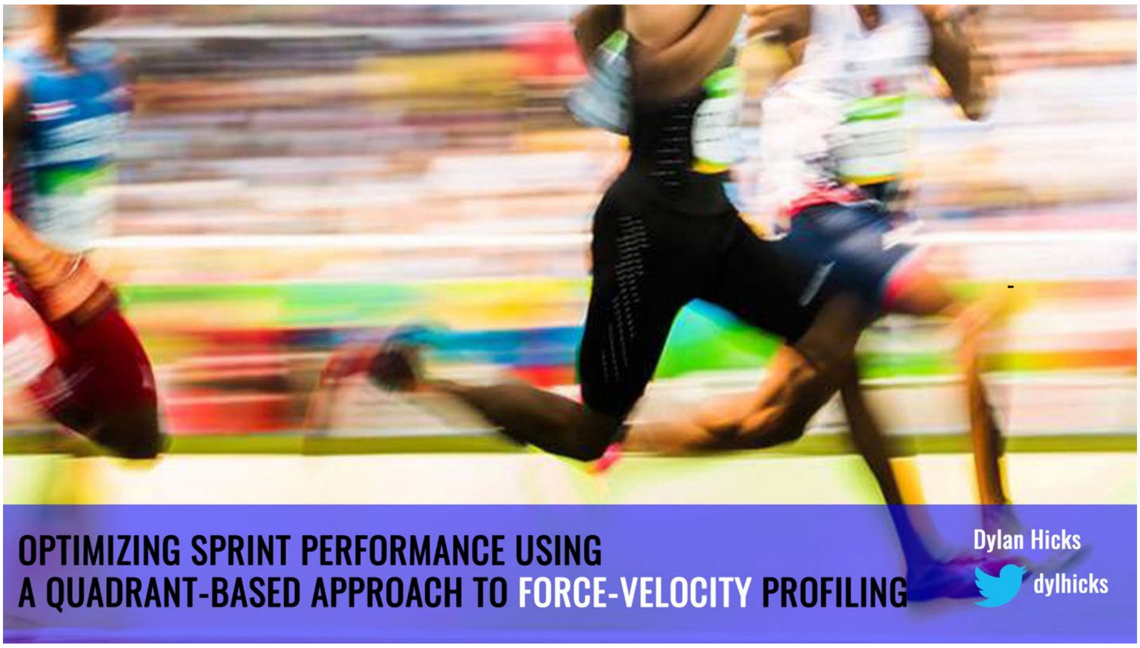
Infographics produced following the publication of Chapter 9, *Improving mechanical effectiveness during sprint acceleration: practical recommendations and guidelines.*



**Appendix B**

Lecture Presentation (YHOP) at the 2021 ASCA International Conference on Applied Strength & Conditioning, Gold Coast.



**Appendix C**

ASCA Podcast - https://www.strengthandconditioning.org/podcast/3301-asca-podcast-76-dylan-hicks

**Appendix D**

Working with Athletics Australia Biomechanics team at the Gold Coast Performance Centre preparing for the 2022 World Athletics Championships (Oregon) and Commonwealth Games (Birmingham). L-R (Adam Didyk/AA, DH, Emma Millet/NSWIS).

**Appendix E**

Presentation at the ESSA Hybrid Sports Science Meet-Up: Training Adolescent Athletes.

https://www.essa.org.au/EventDetail?EventKey=23SSMUSA

**Appendix F**

Chapter 3 published in the *Journal of Strength and Conditioning Research.*



# Measurement Agreement Between Samozino's Method and Force Plate Force-Velocity Profiles During Barbell and Hexbar Countermovement Jumps

**Dylan S. Hicks, Claire Drummond, and Kym J. Williams**

*Exercise Science, Flinders University, SHAPE Research Centre, Bedford Park, Australia*

**Abstract**

Hicks, DS, Drummond, C, and Williams, KJ. Measurement agreement between Samozino's method and force plate force-velocity profiles during barbell and hexbar countermovement jumps. *J Strength Cond Res* XX(X): 000–000, 2021—This study aimed to measure agreement between using Samozino's method and force plates to determine mean force, velocity, and power during unloaded and loaded barbell and hexbar countermovement jumps. Twenty-one subjects performed countermovement jumps against incremental loads using both loading conditions. Ground reaction force was recorded using a dual-force plate system (1,000 Hz) and used as the criterion method to compare with Samozino's method. Reliability and validity was determined by intraclass correlation coefficients (ICCs), coefficient of variation (CV), limits of agreement plots, and least products regression analysis. Samozino's method provided acceptable levels of reliability for mean force, velocity, and power (ICC > 0.90, CV% < 5.5) across both loading conditions. Limits of agreement analysis showed the mean bias was 2.7, 15.4, and 7.2% during barbell countermovement jumps and 1.8, 12.4, and 5.0% during hexbar countermovement jumps for mean force, velocity, and power, respectively. Based on these findings, Samozino's method not only is reliable when measuring mean force, velocity, and power during loaded and unloaded barbell and hexbar countermovement jumps but also identifies limitations regarding concurrent validity compared with the gold standard. Across loading conditions, Samozino's method overestimated mean force (0.5–4.5%) and underestimated mean velocity (11.81–16.78%) and mean power (2.26–7.85%) compared with the force plates. Because of fixed and proportional bias between criterion and predictor, the results do not support the use of Samozino's method to measure mean force, velocity, and power. Therefore, it is not recommended for practitioners to use Samozino's method to estimate mechanical variables during loaded and unloaded countermovement jump actions using a barbell and hexbar.

**Key Words:** ballistic, jumping, power, training, validity

## Introduction

Force-velocity (F-v) profiling is a methodological approach used to assess the overall mechanical capabilities of the neuromuscular system (48). A force-velocity (F-v) profile describes the slope ($S_{FV}$) between the intercepts of both mechanical variables, theoretical maximal force ($F_0$) and theoretical maximal velocity ($v_0$), and represents the individual ratio between force and velocity qualities (44). Understanding these mechanical qualities is of interest to sports scientists to identify strengths and weaknesses of the athlete (38), along with directing and monitoring training interventions (25).

Ballistic actions such as the countermovement jump (CMJ) embody many of the neuromuscular and mechanical qualities demonstrated in lower-limb sport-specific movements (6,55) and therefore are frequently used by sports scientists to profile the force-velocity relationship (10,12,13,18,19,25–27,45,46). The force-velocity relationships established within a CMJ profile describe changes to external force and power production at increasing movement velocities (48) while also identifying the underlying neuromuscular and biomechanical factors contributing to jump performance. Jumping actions are largely limited by force-velocity, power-velocity, and length-tension relationships of the lower-limb muscles (5,8) and provide insights to potential performance changes. Therefore, in sports which frequently expose athletes to vertical jump actions, such as basketball and volleyball, quantifying these capabilities may provide training-related insights to enhance neuromuscular performance.

In many settings, lower-limb force-velocity profiling typically involves subjects performing unloaded (body mass) and loaded CMJ actions against a series of incremental loads using either a traditional barbell or a Smith machine. In a laboratory setting, vertical jump kinetics are measured from ground reaction force using in-ground or portable force plates while the center of mass velocity is derived from ground reaction force-time data through a forward dynamics approach (11). However, methods for measuring force, velocity, and power during jumping actions using limited technology and basic anthropometric measures have recently gained greater prevalence in biomechanics and sports science because of the simple approach to obtaining mechanical data (12,26,27,34,57).

A simple method to determine vertical force-velocity profiles has previously been proposed by Samozino et al. (2008), hereinafter referred to as the "SAM method" (46). The SAM method

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*Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (http://journals.lww.com/nsca-jscr).*

*Journal of Strength and Conditioning Research 00(00)/1–11*

## Appendix G

Chapter 4 published in the *Journal of Sport Science and Medicine.*

©Journal of Sports Science and Medicine (2023) **22**, 142-155
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2023.142

**Research article**

# Force-Velocity Profiling in Club-Based Field Hockey Players: Analyzing The Relationships Between Mechanical Characteristics, Sex, and Positional Demands

**Dylan S. Hicks [1]✉, Claire Drummond [1], Kym J. Williams [1] and Roland van den Tillaar [2]**
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[2] Dept. of Sport Science & Physical Education, Nord University, Norway

**Abstract**

The purpose of this study was to investigate differences between sex and positional demands in club-based field hockey players by analyzing vertical force-velocity characteristics. Thirty-three club-based field hockey athletes (16 males - age: 24.8 ± 7.3yrs, body mass: 76.8 ± 8.2kg, height: 1.79 ± 0.05m; 17 females - age: 22.3 ± 4.2yrs, body mass: 65.2 ± 7.6kg, height: 1.66 ± 0.05m) were classified into two key positional groups (attacker or defender) based on dominant field position during gameplay. Force-velocity (F-v) profiles were established by performing countermovement jumps (CMJ) using a three-point loading protocol ranging from body mass (i.e., zero external mass, 0%) to loads corresponding to 25% and 50% of their own body mass. Across all loads, between-trial reliability of F-v and CMJ variables was determined by intraclass correlation coefficients (ICCs) and coefficient of variation (CV) and deemed to be acceptable (ICC: 0.87 - 0.95, CV% 2.8 - 8.2). Analysis by sex identified male athletes had significantly greater differences in all F-v variables (12.81 - 40.58%, $p \leq 0.001$, ES = 1.10 - 3.19), a more enhanced F-v profile (i.e., greater theoretical maximal force, velocity, and power values), plus overall stronger correlations between relative maximal power ($P_{MAX}$) and jump height ($r = 0.67$, $p \leq 0.06$) when compared to female athletes ($-0.71 \leq r \geq 0.60$, $p = 0.08$). Male attackers demonstrated a more 'velocity-oriented' F-v profile compared to defenders due to significant mean differences in theoretical maximal velocity ($v_0$) (6.64%, $p \leq 0.05$, ES: 1.11), however differences in absolute and relative theoretical force ($F_0$) (15.43%, $p \leq 0.01$, ES = 1.39) led to female attackers displaying a more 'force-oriented' profile in comparison to defenders. The observed mechanical differences identify the underpinning characteristics of position specific expression of $P_{MAX}$ should be reflected in training programmes. Therefore, our findings suggest F-v profiling is acceptable to differentiate between sex and positional demands in club-based field hockey players. Furthermore, it is recommended field hockey players explore a range of loads and exercises across the F-v continuum through on-field and gym-based field hockey strength and conditioning practices to account for sex and positional mechanical differences.

**Key words:** Force, velocity, power, neuromuscular, mechanical, field hockey

## Introduction

Field hockey is a high-intensity, intermittent-based team sport with high mechanical demands requiring players to accelerate, decelerate, change speed and direction quickly, and in addition requires advanced skill to be an effective player (Sharma and Kailashiya, 2017). Recent literature on field hockey has characterized movement patterns, activity profiles and repeated-sprint ability (Spencer et al., 2014; Spencer et al., 2004) using time-motion analysis (i.e., global positioning systems [GPS] (Gabbett, 2010; Macutkiewicz and Sunderland, 2011; Vescovi, 2014) which quantified different game-based demands based on specific positional groups including speed and distance of sprint efforts. Studies on age groups ranging from youth to international level field hockey also identified a significant demand for high-speed running during the game, with midfielders and attackers accumulating a greater number of high intensity actions compared to defenders (Jennings et al., 2012; Lythe and Kilding, 2011; Macutkiewicz and Sunderland, 2011; McGuinness et al., 2019; van der Merwe and Haggie, 2019). Despite extensive analysis of movement patterns within the sport of field hockey, mechanical characteristics contributing to on-field performance including force, velocity and power are yet to be fully explored.

Comparisons between high-intensity actions such as sprinting, and positional groups during field hockey games have previously highlighted significant differences between the number of sprints performed, velocities achieved during sprint efforts and the position of the player on the field (Gabbett, 2010; Macutkiewicz and Sunderland, 2011; Spencer et al., 2004; Vescovi, 2014), suggesting the biomechanical demands and therefore F-v characteristics required at each position are different. For example, in elite women's hockey, midfielders spend a greater portion of game time at velocities greater than 7 $m.s^{-1}$, when compared to attackers and defenders, while midfielders and attackers spend a greater portion of game time above 5 $m.s^{-1}$, when compared with defenders (Gabbett, 2010). This comparison between position groups also identified attackers (also known as strikers) as likely to have a greater maximal velocity during game-play compared to midfielders and defenders, demonstrating their exposure to a greater mechanical load (Macutkiewicz and Sunderland, 2011). Similarities have been observed in elite men's field hockey where differences between high intensity actions and positional groups identified inside-forwards (n = 39 ± 1) and strikers (n = 42 ± 15) performed a greater number of sprint actions when compared with full-backs (n = 18 ± 1) and half-backs (n = 22 ± 7) (Spencer et al., 2004). Therefore, quantifying the on-field movement characteristics via time-motion analysis, along with analyzing the underpinning mechanical determinants and F-v relationship of the lower limbs contributing to performance may provide greater insight to further enhance field hockey strength and conditioning practice.

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**Appendix H**

Chapter 5 published in the *International Journal of Strength and Conditioning.*

International Journal of Strength and Conditioning

Hicks, D. S., Drummond, C., Williams, K. J., & Van Den Tilaar, R. (2023).Investigating Vertical and Horizontal Force-Velocity Profiles in Club-Level Field Hockey Athletes: Do Mechanical Characteristics Transfer Between Orientation of Movement?. International Journal of Strength and Concitioning

https://doi.org/10.47206/ijsc.v3i1.188

# Investigating Vertical and Horizontal Force-Velocity Profiles in Club-Level Field Hockey Athletes: Do Mechanical Characteristics Transfer Between Orientation of Movement?

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**ABSTRACT**

To inform physical preparation strategies in field hockey athletes, this cross-sectional study investigated the transfer of mechanical characteristics in different force-vectors and determined the correlations between vertical and horizontal force-velocity (F-v) profiles and performance outcomes (i.e., jump height, sprint time). Thirty-one club-level field hockey athletes (age: 23.1 ± 4.3yrs, body mass: 70.6 ± 10.3kg, height: 1.72 ± 0.09m) performed vertical force-velocity profiles by completing countermovement jumps at three incremental loads (bodymass[BM], BM+25% externally added mass relative to BM, BM+50% externally added mass relative to BM), and horizontal force-velocity profiles by performing maximal 30-meter sprint efforts. When comparing matched mechanical variables between F-v profiles in each force orientation, small to moderate significant correlations $r$ = (0.37–0.62, $p \leq 0.03$) were observed for relative theoretical maximal force ($F_0$), power ($P_{MAX}$) and theoretical maximal velocity ($v_0$). The performance outcomes of both F-v profiles highlighted a large, significant negative correlation ($r$ = -0.86, $p$ = 0.001) between variables. Multiple linear regression analysis of F-v profiles identified $F_0$ and $v_0$ accounted for 74% and 94% of the variability in jump height and sprint time respectively; however, $v_0$ appeared to be a greater predictor of both performance outcomes. Due to the significant relationships between variables, the results of this study suggest vertical and horizontal F-v profiling may explain the same key lower-limb mechanical characteristics, despite the orientation of the movement task. With club-level field hockey athletes, coaches could potentially use mechanical profiling methods interchangeably to prescribe physical preparation interventions, however for greater neuromuscular and mechanical insight, it is likely worthwhile to assess mechanical strengths and weaknesses in both force-vectors.

Keywords: force, velocity, power, transfer, mechanical, field hockey

**Appendix I**

Chapter 6 published in *PeerJ.*

PeerJ

# The effect of a combined sprint training intervention on sprint force-velocity characteristics in junior Australian football players

Dylan Shaun Hicks[1], Claire Drummond[1], Kym J. Williams[1] and Roland van den Tillaar[2]

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[2] Sport Science & Physical Education, Nord University, Levanger, Norway

## ABSTRACT

**Background**. Sprint performance in junior Australian football (AF) players has been shown to be a differentiating quality in ability level therefore developing sprint characteristics via sprint-specific training methods is an important aspect of their physical development. Assisted sprint training is one training method used to enhance sprint performance yet limited information exists on its effect on sprint force-velocity characteristics. Therefore, the main aim of this study was to determine the influence of a combined sprint training intervention using assisted and maximal sprint training methods on mechanical characteristics and sprint performance in junior Australian football players.

**Methods**. Upon completing familiarization and pre-testing, twenty-two male junior Australian football (AF) players (age 14.4 ± 0.3 years, body mass 58.5 ± 10.0 kg, and height 1.74 ± 0.08 m) were divided into a combined sprint training (CST) group (n = 14), and a maximal sprint training (MST) group (n = 8) based on initial sprint performance over 20-meters. Sprint performance was assessed during maximal 20-meter sprint efforts via a radar gun (36 Hz), with velocity-time data used to derive force-velocity characteristics and split times. All subjects then completed a 7-week in-season training intervention consisting of maximal sprinting (MST & CST groups) and assisted sprinting (CST only), along with their usual football specific exercises.

**Results**. Moderate to large pre-post within group effects ($-0.65 \leq$ ES $\geq 0.82$. $p \leq 0.01$) in the CST group for relative theoretical maximal force ($F_0$) and power ($P_{max}$) were reflected in improved sprint performance from 0–20 m, thereby creating a more force-oriented F-v profile. The MST group displayed statistically significant pre-post differences in sprint performance between 10–20 m only (ES = 0.18, $p = 0.04$). Moderate to high relative reliability was achieved across all sprint variables (ICC = 0.65–0.91), except for the force-velocity slope ($S_{FV}$) and decrement in ratio of forces ($D_{RF}$) which reported poor reliability (ICC = 0.41–0.44), while the CST group exceeded the pre-post minimal detectable change (MDC) in most sprint variables suggesting a 'true change' in performance across the intervention.

**Conclusion**. It is concluded that implementing a short-term, combined sprint training intervention consisting of assisted and maximal sprint training methods may enhance sprint mechanical characteristics and sprint performance to 20-meters in junior AF players.

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Academic editor
Filipe Clemente

Additional Information and Declarations can be found on page 17

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**Appendix J**

Chapter 7 published in the *International Journal of Environmental Research and Public Health.*

International Journal of *Environmental Research and Public Health*

MDPI

*Case Report*

# Exploratory Analysis of Sprint Force-Velocity Characteristics, Kinematics and Performance across a Periodized Training Year: A Case Study of Two National Level Sprint Athletes

**Dylan Shaun Hicks [1,*], Claire Drummond [1], Kym J. Williams [1] and Roland van den Tillaar [2,*]**

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[2] Department of Sport Science and Physical Education, Nord University, 7601 Levanger, Norway
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**Abstract:** Abstract:**Objective:** This case study aimed to explore changes to sprint force-velocity characteristics across a periodized training year (45 weeks) and the influence on sprint kinematics and performance in national level 100-meter athletes. Force-velocity characteristics have been shown to differentiate between performance levels in sprint athletes, yet limited information exists describing how characteristics change across a season and impact sprint performance, therefore warranting further research. **Methods:** Two male national level 100-meter athletes (Athlete 1: 22 years, 1.83 m, 81.1 kg, 100 m time: 10.47 s; Athlete 2: 19 years, 1.82 cm, 75.3 kg, 100 m time: 10.81 s) completed 12 and 11 force-velocity assessments, respectively, using electronic timing gates. Sprint mechanical characteristics were derived from 30-meter maximal sprint efforts using split times (i.e., 0–10 m, 0–20 m, 0–30 m) whereas step kinematics were established from 100-meter competition performance using video analysis. **Results:** Between the preparation (PREP) and competition (COMP) phase, Athlete 1 showed significantly large within-athlete effects for relative maximal power ($P_{MAX}$), theoretical maximal velocity ($v_0$), maximum ratio of force ($RF_{MAX}$), maximal velocity ($V_{MAX}$), and split time from 0 to 20 m and 0 to 30 m ($-1.70 \leq ES \geq 1.92$, $p \leq 0.05$). Athlete 2 reported significant differences with large effects for relative maximal force ($F_0$) and $RF_{MAX}$ only (ES: $\leq -1.46$, $p \leq 0.04$). In the PREP phase, both athletes reported almost perfect correlations between $F_0$, $P_{MAX}$ and 0–20 m ($r = -0.99$, $p \leq 0.01$), however in the COMP phase, the relationships between mechanical characteristics and split times were more individual. Competition performance in the 100-meter sprint ($10.64 \pm 0.24$ s) showed a greater reliance on step length ($r \geq -0.72$, $p \leq 0.001$) than step frequency to achieve faster performances. The minimal detectable change (%) across mechanical variables ranged from 1.3 to 10.0% while spatio-temporal variables were much lower, from 0.94 to 1.48%, with Athlete 1 showing a higher 'true change' in performance across the season compared to Athlete 2. **Conclusions:** The estimated sprint force-velocity data collected across a training year may provide insight to practitioners about the underpinning mechanical characteristics which affect sprint performance during specific phases of training, plus how a periodized training design may enhance sprint force-velocity characteristics and performance outcomes.

**Keywords:** force; velocity; power; sprint; training; biomechanics; profile

check for updates

**Citation:** Hicks, D.S.; Drummond, C.; Williams, K.J.; van den Tillaar, R. Exploratory Analysis of Sprint Force-Velocity Characteristics, Kinematics and Performance across a Periodized Training Year: A Case Study of Two National Level Sprint Athletes. *Int. J. Environ. Res. Public Health* **2022**, *19*, 15404. https://doi.org/10.3390/ijerph192215404

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## 1. Introduction

Across a training year, sprint athletes typically progress through a periodized training program aimed at peaking towards major competitions including national championships. Training components within a sprint program generally include acceleration and maximal velocity sprinting, resistance training and plyometrics [1] which aim to enhance neuromuscular, biomechanical and technical sprint characteristics. However, the overall aim of all sprint programs should be to improve an athlete's ability to run fast. Sprint running requires athletes to overcome inertia and accelerate from a stationary start to a high maximal

**Appendix K**

Chapter 8 published in the *Strength and Conditioning Journal.*

# Individualization of Training Based on Sprint Force-Velocity Profiles: A Conceptual Framework for Biomechanical and Technical Training Recommendations

Dylan S. Hicks, MSc, CSCS,[1] Claire Drummond, PhD,[1] Kym J. Williams, PhD,[1] Craig Pickering, DProf,[2] and Roland van den Tillaar, PhD[3]
[1]SHAPE Research Center, Flinders University, Bedford Park, Australia; [2]Athletics Australia, Melbourne, Australia; and [3]Department of Sport Science and Physical Education, Nord University, Norway

## ABSTRACT

The purpose of this article is to provide practitioners with a system to categorize and individualize training prescription from sprint force-velocity (F-v) profiles to enhance performance in team and individual sport athletes. Despite F-v variables presenting key information about the underpinning mechanisms contributing to sprint performance, the overall data interpretation may be limited for the practitioner to implement applied training interventions compared with the researcher. Therefore, this article provides a conceptual framework for appropriate training prescriptions based on individual biomechanical and technical characteristics contributing to sprint performance.

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## INTRODUCTION

Acceleration ability is one of the key components to success in athletic sprint events yet also an essential skill in many team-based field and court sports. Faster team sport players can often reposition themselves on the field more quickly during decisive moments of the game such as challenges for the ball and during goal-scoring opportunities (26,62); therefore, identifying the mechanical characteristics underpinning acceleration and sprint performance is desirable. Key performance indicators during the acceleration phase of a sprint action include propulsive impulse (31,36), thereby producing and applying a high level of anteroposterior (horizontal direction) force (54) under time constraints; increased magnitude of maximal external power (65); plus the continued ability to orient the force vector horizontally as running velocity increases (38,54,61). To quantify the mechanical determinants contributing to sprint performance, a field method known as force-velocity (F-v) profiling has been proposed (66).

Sprint F-v profiling is a diagnostic tool used to determine the maximal mechanical capabilities of the neuromuscular system (66) and describes the linear F-v relationship. Sprint F-v profiling has gained greater interest in the sports performance literature more recently because of simple field method approaches (61,66) providing performance characteristics, which can be used to individualize training interventions (45,46), plus identify the

**KEY WORDS:**
force; velocity; power; acceleration; maximal velocity; sprinting; biomechanics

**Appendix L**

Chapter 9 published in the *Strength and Conditioning Journal.*

# Improving Mechanical Effectiveness During Sprint Acceleration: Practical Recommendations and Guidelines

Dylan Shaun Hicks, MSc,[1] Jake George Schuster, MSc,[2] Pierre Samozino, PhD,[3] and Jean-Benoit Morin, PhD[4]
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## ABSTRACT

Sport scientists and strength and conditioning coaches are showing growing interest in the magnitude, orientation, and application of ground reaction force during acceleration actions in sport, as it can identify the key mechanical determinants of performance. Horizontal force-velocity profiling or sprint profiling helps practitioners understand the capacity of the mechanical force production during the acceleration phase of a sprint. This review examines the methods used in the field for determining horizontal force-velocity (sprint) profiles. It also includes recommendations for practical training methods to address individual force-velocity characteristics, mechanical effectiveness, thereby optimizing acceleration performance.

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## INTRODUCTION

Strength and conditioning coaches are interested in understanding the limitations in mechanical performance during activities involving linear and multidirectional speed. High-speed running (sprinting) is the fundamental component of many team sports and involves 2 key phases: acceleration and maximal velocity (7). The ability to accelerate and reach the highest velocity possible in the shortest period is underpinned by the mechanical components of the neuromuscular system, force, velocity, and power, and specifically the force-velocity (F-v) profile (73). Within the strength and conditioning literature, methods to identify these mechanical components during acceleration have been limited, making it unclear the most appropriate training prescription that should be used to improve these qualities. Therefore, if a resistance training program is designed to enhance sprint acceleration, should strength and conditioning coaches select exercises, which focus on force, velocity, and power, or prioritize one variable over the other?

During the stance phase of a sprint action, a ground reaction force (GRF) is produced, which includes both horizontal and vertical components of the GRF (referred to as horizontal and vertical forces for simplicity), along with the resultant GRF. The stance or contact phase can be divided into braking and propulsive phases in the anteroposterior direction, followed by a flight phase when the limbs are repositioned in the air before contacting the ground again (58). This ongoing exchange of kinematic positions defines sprinting as a ballistic action (58). In comparison with various track and field events where only linear speed is required, in team sports such as Australian rules football and rugby, jumping actions followed by a sprint acceleration in multiple directions are common. These constant changes in velocity require athletes to accelerate

**KEY WORDS:**
power; force; velocity; acceleration; sprinting; resistance training

## Appendix M

Co-author on a review published in the *Journal of Aging and Physical Activity.*

***Journal of Aging and Physical Activity*, (Ahead of Print)**
https://doi.org/10.1123/japa.2020-0302


Human Kinetics
SCHOLARLY REVIEW

# Why Are Masters Sprinters Slower Than Their Younger Counterparts? Physiological, Biomechanical, and Motor Control Related Implications for Training Program Design

**Craig Pickering, Dylan Hicks, and John Kiely**

Elite sprint performances typically peak during an athlete's 20s and decline thereafter with age. The mechanisms underpinning this sprint performance decline are often reported to be strength-based in nature with reductions in strength capacities driving increases in ground contact time and decreases in stride lengths and frequency. However, an as-of-yet underexplored aspect of Masters sprint performance is that of age-related degradation in neuromuscular infrastructure, which manifests as a decline in both strength and movement coordination. Here, the authors explore reductions in sprint performance in Masters athletes in a holistic fashion, blending discussion of strength and power changes with neuromuscular alterations along with mechanical and technical age-related alterations. In doing so, the authors provide recommendations to Masters sprinters—and the aging population, in general—as to how best to support sprint ability and general function with age, identifying nutritional interventions that support performance and function and suggesting useful programming strategies and injury-reduction techniques.

***Keywords***: neuromuscular, resistance training, strength, type-II

Lifelong physical activity is an important determinant of health and well-being (Kannus, 1999), and this becomes increasingly important as we age with increased levels of muscle mass—and the maintenance of that mass—associated with better preservation of function and lower rates of all-cause mortality in older adults (Cooper, Kuh, & Hardy, 2010; Rantanen, 2003). As a result of increased awareness of the relationship between activity and health as we age, more older adults are turning to organized sports as a way to enhance their motivation to maintain their fitness, and one increasingly popular area is that of Masters athletics (Dionigi, Baker, & Horton 2011). Like its mainstream counterparts, the World Athletics Championships and Olympic Games, Masters athletics has a competitive arm, which includes World and European Championships, and competing in these championships drives the motivation of many Masters athletes to improve and progress (Young, 2013).

It is well-established that elite sprint performance—as quantified by race time—decreases with age (Aguiar et al., 2020; Arampatzis, Degens, Baltzopoulos, & Rittweger, 2011; Korhonen, Haverinen, & Degens, 2014) and that this decrease accelerates after approximately 70 years of age (Ganse, Ganse, Dahl, & Degens, 2018), detailed in Figure 1 as follows. A glance at the histories of the fastest male 100-m runners of all time (data not shown) further demonstrates the modifying effect of age; of the 24 athletes to have run 9.86 s or faster, the median age of personal best is 24.5 years with the oldest on that list, Justin Gatlin, the M35 100-m world record (WR) holder, having achieved his personal best time of 9.74 s at the age of 33 years. Finally, there is evidence of a "constituent age effect" in Masters sprinters with the younger athletes within each 5-year age group appearing to be both overrepresented at competitions (Medic, Lares, & Young, 2018; Medic, Starkes, Weir, Young, & Grove, 2009; Medic, Starkes, & Young, 2007) and more likely to be age group WR holders (detailed in Figure 2). However, there are exceptions to this trend; well-trained young adult sprint athletes are more likely to experience a greater decline with age, whereas Masters sprinters who did not take part in organized training until a relatively older age may experience either less of a decline with age or, in some cases, improvements (Korhonen et al., 2014). Kim Collins, the 2003 100-m World Champion (aged 27 years) ran his 100-m personal best (9.93) at the age of 40 years, and Merlene Ottey ran her personal best (10.74) and won an Olympic 100-m Silver medal in her 36th year. Nevertheless, the overwhelming trend is for a decrease in absolute sprint performance after approximately 20–30 years of age (Korhonen et al., 2014).

That sprint performance decreases with age, therefore, is clear and somewhat unsurprising; however, it is crucial to understand why this age-related degradation in elite performance occurs. An understanding of the underpinning reasons—be they physiological, biomechanical, or more holistic in origin—would better assist elite Masters athletes and their coaches in the design and development of training programs aimed at reducing this age-related decline. Furthermore, evidence of efficacy in elite older athletes may increase our understanding of maintaining function in all older adults, opening the door for improved population health initiatives aimed at improving health span as opposed to lifespan (Christensen, Doblhammer, Rau, & Vaupel, 2009). Accordingly, the aim of this article is to answer two related questions:

(a) Why are elite Masters sprinters slower than their younger counterparts? and

(b) How can we use this knowledge to enhance performance?

Although this review will focus on the physiological, biomechanical, and motor control-related aspects of Masters sprint performance, it is important to acknowledge that there is considerable evidence that both psychological and social factors likely contribute to the slowing of sprint speed—or at least sprint performance—with

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**Appendix N**

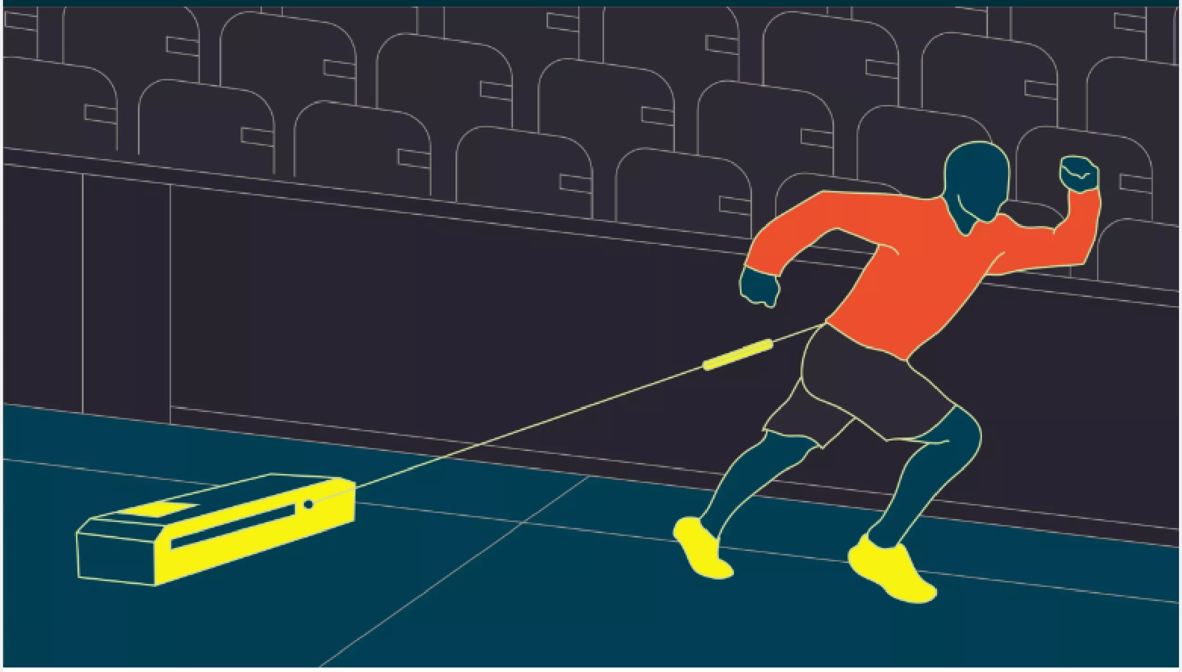
An article written for Sportsmith discussing my research in force-velocity profiling.

*https://www.sportsmith.co/articles/force-velocity-profiling/*

ARTICLE

# Force-velocity profiling: Is the juice worth the squeeze?

By Dylan Hicks



**Appendix O**

An article written for Simplifaster discussing my understanding of research methods within an applied practice setting.

*https://simplifaster.com/articles/training-part-time-professional-athlete-dylan-hicks/*

# Training the Part-Time Professional Athlete with Dylan Hicks

Freelap Friday Five | By Dylan Hicks

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