KINEMATIC CHARACTERISTICS OF RESISTED SPRINTING

A thesis submitted in fulfilment of the requirements for the degree of PhD to Technological University of the Shannon

2023

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

1RM - One repetition maximum

% - Percent

BM - Body mass

BS - Back squat

Cm - Centimetre

CMJ - Countermovement jump

COM - Centre of mass

CT - Contact time

CV% - coefficient of variation

DC - Dynamic correspondence

DJ - Drop jump

ES – Effect size

EG - Exer-Genie

ES - Effect size

F0 - Maximum theoretical force: The maximal force production of the lower limbs theoretically possible in the absence of velocity, as extrapolated from the linear Fv relationship

Ftot - Total force

FV - Force-velocity relationship

FVP - Force velocity profile

FT - Flight time

GRF - Ground reaction force

Hz - Hertz

HSC – High speed camera

HT – Hip thrust

ICC - Intraclass correlation coefficient

JH - Jump height

Kg - Kilogram

m - Metre

ms - Millisecond

N - Newton

Oz - Ounce

η^2p - partial eta squared

pprel - peak power relative to bm

RSI - reactive strength index

RF - Mean ratio of forces

RFD - Rate of force development

RSS - Resisted sled sprints

RST - Resisted sprint training

s - Second

SEM - Standard error of measurement

SF - Step frequency

SL - Step length

SP - Sprint performance

SF - Step frequency

SP - sprint performance

SSC - Stretch shortening cycle

TE - Typical error

TO - Toe-off

TD – Touch down

%Vdec - Velocity decrement

Wk – week

Y - Year

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"If you realize that all things change, there is nothing you will try and hold on to."

–Lao Tzu

Image of Florence Delorez Griffith Joyner, also known as Flo-Jo, right after winning the 100 m event, where she set the world records in 1988 for the 100 m and 200 m.

ABSTRACT

In recent years, the adoption of resisted sprint training (RST) has surged as a method to enhance sprint performance (SP) in various athletic domains [1-3]. Given the central role of sprinting in optimising athletic performance, RST has gained prominence as a potential tool applicable to a wide range of athletes. Coaches seeking to improve SP typically target two primary aspects: enhancing force production and refining technical execution [4]. The integration of external resistance into sprinting presents an opportunity to address both goals simultaneously, potentially offering a more 'sport-specific' form of resistance training. While the relationship between resisted sprints and SP has been explored in invasion-based team sports and track and field athletes, there remains a lack of clarity around how the addition of load influences running kinematics, what physical characteristics influence the kinematics adopted under loaded conditions, or how coaches interpret potential kinematic changes to inform load prescription during RST. The overarching aims that guided this research were:

- To explore coaches' perceptions of how RST affects kinematics and their methodologies for prescribing RST.
- To examine the reliability of an isotonic sprint device.
- To examine the impact of load and sporting population on kinematics during RST.
- To investigate if an athlete’s strength characteristics influences kinematic changes during RST.

The main findings of this research were: 1) Coaches unanimously acknowledged the value of RST in enhancing SP, drawing from their practical experiences and insights from scientific literature. However, trends emerged: coaches often favoured the use of body mass (%BM) as a load indicator over velocity decrement (%Vdec) due to its simplicity. Additionally, modalities of RST were frequently chosen based on practicality and availability rather than strict adherence to scientific literature. 2) The Exer-Genie produces fair to good within-session reliability but revealed less reliable between-session measurements. 3) Loading introduced significant changes to hip, knee, ankle, and trunk angle for touch-down and toe-off for the acceleration and maximum velocity phase ($p<0.05$). Knee, hip, and ankle angles became more flexed with increasing load, for touch-down and toe-off, for all groups during the acceleration phase, and trunk lean increased with increasing loading conditions. Although there were minimal differences observed between groups, RSS resulted in

acute changes in sprint kinematics which differed based on the phase of the sprint and magnitude of the load. 4) Strength characteristics could explain the variance observed in athlete's kinematics under loading conditions employed in study 3. Moreover, noteworthy negative correlations between strength metrics and changes in joint angles (hip, knee, and trunk) under different loading conditions were found.

Several practical applications may be offered from the findings. There is an existing gap between scientific research and practical coaching application in the context of RST. Considering the linear and dependable relationship between load and velocity, coaches are encouraged to tailor sled loads individually. Rather than applying a uniform load as a fixed %BM to all athletes, this approach involves prescribing loads based on the specific desired decrement in velocity for each athlete. When employing isotonic sprint devices, coaches should be aware of its reliability characteristics. While it offers fair to good within-session reliability, its between-session reliability is less dependable. This suggests that the Exer-Genie may be suitable for short-term training interventions but should be used cautiously for long-term training programs. Coaches should recognise that loading in RST significantly alters sprinting kinematics, particularly in hip, knee, ankle, and trunk angles during both the acceleration and maximum velocity phases and an athlete's strength characteristics have an influence on their kinematics during RST.
These findings empower coaches and practitioners to design more effective and tailored training programs, advancing the realm of sprinting performance enhancement in both athletic and team sport contexts.

Dedicated to Gertrud Osterwald

02 October 1928 † 24 September 2020

Ich widme diesen Doktortitel nicht nur meinen eigenen Leistungen, sondern auch dem Vermächtnis der Liebe und des Glaubens, das mir meine Familie geschenkt hat. Ich danke Ihnen aus tiefstem Herzen dafür, dass Sie mich zu der Person geformt haben, die ich heute bin.

AKNOWLEDGEMENTS

I would like to take this opportunity to express my heartfelt gratitude and appreciation to all those who have contributed to my journey and supported me throughout my PhD. Without the unwavering support, encouragement, and love from my dear family, professors, dedicated colleagues, cherished friends, and the participants of my studies, this milestone would not have been possible. Each of you has played a significant role in shaping my academic and personal growth, and for that, I am forever grateful.

This journey has been one of immense dedication, perseverance, and self-belief. However, this road has been also very rocky, full of doubts, tears, sleepless nights, with sometimes a lack of motivation and the feeling of not being good or smart enough. I acknowledge the countless hours of hard work, sacrifices, and determination that I have poured into my research. In the end it is through my own commitment and passion that I have reached this point in my academic career. I am so very proud of the resilience I have shown and the personal growth I have experienced along the way.

To my beloved parents, I cannot find enough words to express my gratitude. Your unwavering support, encouragement, and love have been my pillars of strength throughout this arduous journey. Your belief in my abilities has fuelled my determination, and I am forever grateful for the sacrifices you have made to ensure my success. I am forever indebted to my family. Thank you for being my guiding light.

I am deeply indebted to my mentors **Dr Ciarán Ó Catháin** and **Dr David T. Kelly** who have guided and shaped my academic path. **Ciarán** thank you so much for guiding me through this important journey. Your invaluable knowledge, expertise, encouragement and support have been instrumental in my development as a researcher. I am grateful for the countless hours you have dedicated to sharing your wisdom, challenging my research, and pushing me to excel.

I would like to express my sincere gratitude to everyone working in the research office of AIT for their unwavering support throughout my PhD journey. Your dedication, guidance, mental support and assistance have been instrumental in the successful completion of my research work. From providing valuable resources to offering administrative support, you have consistently gone above and beyond to facilitate my academic pursuits. I am truly grateful for the opportunities and resources that you have provided, enabling me to delve into my research and contribute to the knowledge in my field. Your commitment to fostering a conducive research environment is commendable, and I am honoured to have been a part of it. Thank you for being an integral part of my academic journey and for your continuous support.

To my dedicated colleagues, thank you for being my constant source of inspiration and support. Your collaboration, insightful discussions, and willingness to lend a helping hand have enriched my research journey. Thiago, Debora and Roger together, we have faced challenges, celebrated successes, and created a nurturing environment for intellectual growth. Your camaraderie and shared passion for knowledge have made this journey all the more rewarding.

To my dear friends and boyfriend, thank you for standing by me throughout this demanding journey. Your unwavering support, understanding, and encouragement have been a source of strength during both the highs and lows. Your presence in my life has brought joy, laughter, and a sense of balance amidst the academic demands. I am grateful for the cherished memories we have created and for being a constant reminder of the importance of maintaining a well-rounded life.

Lastly, I extend my appreciation to the participants of my studies. Without your willingness to dedicate your time and effort, my research would not have been possible. Your valuable contributions have provided the foundation for my findings, and I am deeply grateful for your involvement.

The completion of my PhD would not have been possible without the support and contributions of each and every person mentioned above. I am deeply grateful for your belief in me, the encouragement, support, and love that you have showered upon me. Your presence in my life has made this journey meaningful, fulfilling, and unforgettable. I will forever carry your kindness and generosity in my heart as I embark on the next chapter of my academic and personal endeavours.

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CHAPTER 1

1 OVERVIEW

1.1 ADMIN

1.1.1 Declaration of authorship

I declare that this manuscript is my work and that, to the best of my knowledge, it contains no material published or written by another (except where explicitly acknowledged). This thesis does not contain material that, to no extent, has been previously submitted for the award of any other degree or diploma of higher education. Various chapters of this dissertation contain work that has or will be submitted for dissemination in scholarly publications. All parties approved co-authored work for inclusion in this PhD dissertation.

DOCTORAL CANDIDATE

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24th July 2023

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1.1.2 Thesis publications

An investigation of resisted sprint training practices of coaches and their perception of how resisted sprinting influences kinematics	**Katja M. Osterwald,** David T. Kelly, Thomas M. Comyns, Ciarán Ó Catháin
Reliability of an isotonic sprint device	**Katja M. Osterwald,** David T. Kelly, Ciarán Ó Catháin
Resisted Sled Sprint Kinematics: The Acute Effect of Load and Sporting Population (*published*)	**Katja M. Osterwald,** David T. Kelly, Ciarán Ó Catháin
Do strength characteristics impact resisted sled sprint kinematics?	**Katja M. Osterwald,** David T. Kelly, Ciarán Ó Catháin

1.2 GENERAL INTRODUCTION

Sprinting is well regarded as not only essential for success in track and field events, but in many sports such as field-based invasion team sports [5-9]. It is clear that all competitors have the potential to develop their speed via progressive and periodised training, and this requires a variety of both physical and technical competencies (Figure 1) [10,11]. The interaction of physical, technical, environmental, tactical, and social factors present challenges to both athletes and coaches and drives research and development intending to increase performance. The physical profile of athletes is a crucial contributing factor to performance [12], where at the highest competitive level, mere milliseconds separate the top finishing athletes in sprint races or determine scoring success in field-based invasion team sports [13-15]. Physiological and psychological determinants have been revealed to account for a considerable proportion of the diversity associated with accomplished distance running, sprinting, and jumping among college-level athletes [12]. Moreover, an examination of track and field athletes with disabilities discovered that their physiological characteristics differed depending on the category of impairment, whereby particular impairments did not have a notable impact on muscular power and strength, endurance, and flexibility, highlighting the importance of considering the physiological profile in these athletes as well [16].

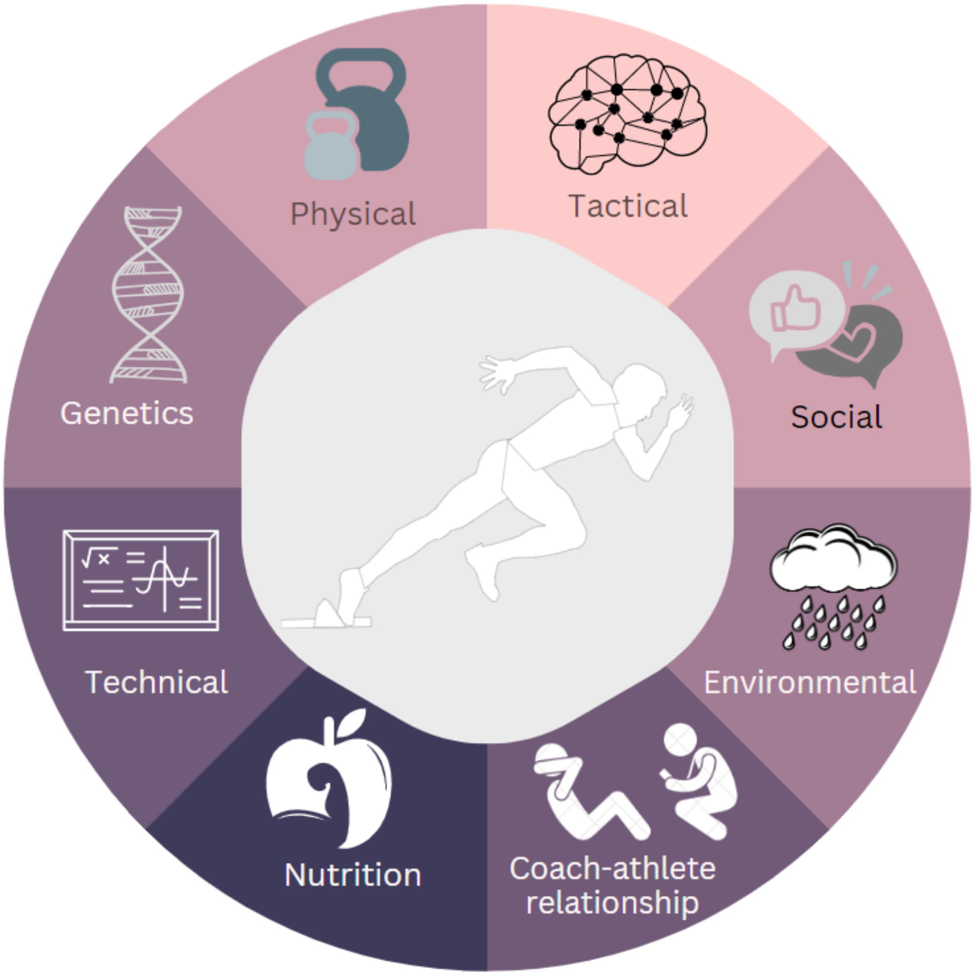

Figure 1 Factors affecting athletic performance

While debatable, this figure suggests the potential factors affecting athletic performance, modified from Stone, *et al.* [17]. The relative effect of each parameter is unknown, but all are interrelated.

Sprinting is a powerful action where the athlete produces high amounts of vertical and horizontal net force with each step [13]. The absolute physical capability of the body, and technical ability to apply this raw capacity in an effective manner appear crucial to sprinting success [18,19]. Therefore, when attempting to improve sprint performance (SP), and increase in the ability to produce force, and/or improved technical execution is targeted by coaches [4,20]. Resistance training in the form of strength (load) [21], power/ballistic and complex training (explosive strength) [22] and bodyweight plyometric training (reactive strength) [23], have all shown to be effective methods for athletes to develop speed and power [24,25], with sprinting itself often used as the method to improve technical execution and therefore SP [26,27]. Reviews suggest that resistance training is effective in improving SP, especially for distances ≤ 30 m [21,28], when using exercises like squats, power cleans, and deadlifts commonly used in strength and conditioning programs [24,25,29]. However, considering that movement similarity is an important aspect of the principle of specificity [30,31], it could be inferred that incorporating external load during a sprint could potentially better replicate the sprinting motion and enhance force and power output by providing additional resistance [27]. Several systematic reviews have suggested that RST demonstrates positive effects on SP under various loading conditions (5–80%BM), principally during the acceleration phase ($p = 0.0001$; effect size (ES) 0.61) [4,32]. It is important to note that not all reviews have found a positive effect on maximum velocity performance ($p = 0.25$; ES 0.27) [32]. According to Petrakos, Morin and Egan [4], the adaptation of acceleration and maximum velocity depends on the weight of the sled. Their review indicates that lighter to moderately loaded sleds (<20%BM) may be more beneficial than heavier loads when the goal is to improve maximum velocity sprinting. This may be due to lower horizontal force and higher velocity characteristics observed during maximum velocity running and mimicked during light resisted sprints. Light loads do, however, enable athletes to maintain a relatively higher running velocity, as they do not significantly compromise the horizontal force production required for sprinting at high speeds. Additionally, lighter loads may facilitate a more efficient running technique with shorter ground contact times compared to heavier load [33]. It is important to mention that in some research light loads during resisted sprinting have been shown to be effective for improving acceleration performance without having an impact on sprint technique [34,35]. Additionally, training with heavier sled loads is found to be effective for improving the initial acceleration phase of sprinting. During the acceleration phase, sprinters need to generate larger horizontal forces to overcome inertia and increase their running speed. Heavier loads provide the necessary resistance to stimulate force production and power development, specifically targeting the initial acceleration phase where horizontal force production is crucial [35-37].

Understanding the biomechanical requirements of each sprint phase enables coaches to tailor resisted sprinting training to the specific needs of their athletes and optimise performance outcomes. Additionally, understanding the effects of load on sprint technique during RST is crucial for coaches and athletes aiming to optimise the benefits of this training method. Resisted sprinting may provide a unique opportunity to simultaneously train the technical and physical components of sprint performance. By incorporating load, athletes can target specific aspects of their sprinting technique while also developing the necessary strength and power. However, the addition of load in RST causes acute changes to running kinematics, but it remains uncertain as to whether these changes persist during unloaded running after an extended duration of RST. Furthermore, it is unclear whether any potential negative effects on kinematics are ameliorated over time as athletes adapt and receive appropriate coaching. Therefore, coaches and athletes need to have a clear understanding of how load influences sprint technique during RST and what factors contribute to the magnitude of observed technical changes. By recognising the distinctive effects of various loads on sprint technique, coaches can make informed decisions regarding the selection and progression of resistive loads in training programs. This knowledge can guide the prescription of RST and help coaches design effective training interventions to enhance sprint performance.

Furthermore, understanding the factors that influence the magnitude of technical changes during RST can provide valuable insights for individualising training programs. Strength is a critical component that can significantly impact an athlete's ability to adapt and perform optimally during resisted sprint training [38]. To achieve enhancement in sprint performance, an athletes strength training ought to be based on their unique characteristics while emphasising the development of maximal and speed strength [39]. According to research, strength measures are correlated with sprinting performance, with different strength qualities being more critical for starting ability versus maximum speed sprinting [40]. Longitudinal studies have also demonstrated the significance of strength development for better running speed [41]. Moreover, an athlete's previous training history, particularly in strength training and resisted exercises, can influence their technical changes during resisted sprint training [42]. Athletes with experience in resisted exercises may adapt more quickly and effectively to the additional load [43]. Resistance training has been shown to have a significant impact on a variety of body systems, including the muscular and neural systems, which are crucial for athletic performance [43]. Furthermore, alterations in motor performance resulting from training are dependent on improved neuromuscular control as well as morphological adaptations of muscles and tendons. This suggests that experienced athletes may be more proficient in their adaptation to resistance training [44]. Coaches can consider various factors such as athlete characteristics, training history, and specific performance goals when determining the appropriate load and monitoring the athlete's response to RST. This personalised approach can optimise the training stimulus and ensure that athletes make progress [45].

To date it is unclear how coaches incorporate the available literature into their training programs. Bridging the gap between scientific findings and coaching practice is challenging, as coaches prefer informal communication methods over academic journals [46]. As an example of how there is often gaps between coaching practice and best practice (literature), a recent survey revealed that coaches very often prescribe lighter loads for short sprints, which may not always be optimal for improving acceleration [47]. Coaches are tasked with making critical decisions that directly impact their athletes' performance and well-being. They must draw from a combination of their personal experiences, intuition, and available research to create training programs. However, their decisions might not always align with what the scientific literature proposes as "best practice." Several factors may contribute to this gap. Coaches often have practical limitations such as time, budget, and resources, which can influence their decision-making [48]. They may prioritise convenience and feasibility in their coaching environment, even if it goes against the recommended "best practice" supported by research. Coaches also rely on their experience and traditional methods that have worked in the past, even if they don't align with current research. They prefer informal communication methods over academic journals, possibly due to the complexity of research papers or limited access to academic resources [46]. Additionally, coaches recognise that each athlete is unique and may adapt training methods based on individual needs, even if it differs from general research recommendations.

Understanding why coaches make specific decisions and their perceptions about training methods is crucial for bridging the gap between scientific findings and coaching practice. By gaining insights into coaches' decision-making processes, researchers can frame their findings in a way that is more practically relevant to coaching. This alignment between research and practice will help coaches integrate evidence-based approaches into their training programs more effectively, leading to improved athlete performance and reduced risk of injury.

Overall, gaining a comprehensive understanding of how load influences sprint technique during RST and the factors that influence these changes is essential for coaches and athletes. It allows for the development of evidence-based training strategies that maximise the benefits of RST while minimising potential risks, ultimately leading to improved sprint performance.

1.3 THESIS OVERVIEW

Overarching aims associated with this thesis were (Figure 2):

- To explore coaches' perceptions of how RST affects kinematics and their methodologies for prescribing RST.
- To examine the reliability of an isotonic sprint device.
- To examine the impact of load and sporting population on kinematics during RST.
- To investigate if an athlete’s strength characteristics influences kinematic changes during RST.

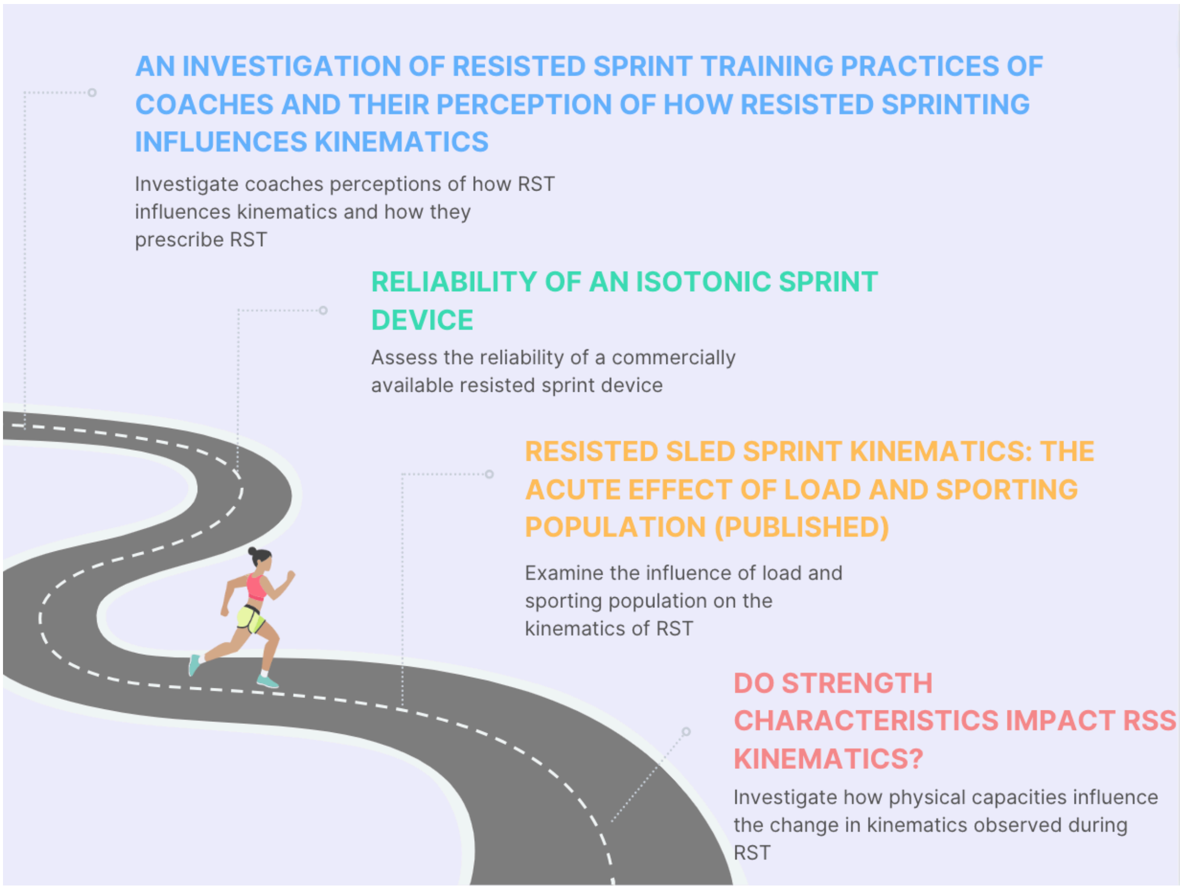

Figure 2 Thesis aims

1.3.1 **Thesis format**

This thesis is given in a format that resembles a thesis by publication. As a result, chapter three, four, five and six have been structured for submission to academic journals. Each section includes an introduction, methods, findings, and discussion section and was intended to be understood independently of the thesis body. The text has been modified to be consistent and avoid excessive repetition, although it's possible that certain themes and phrases will recur.

1.3.2 **Thesis structure**

This thesis is built around three main experimental "Themes", bookended by a general scientific literature review and a summary and conclusion chapter. The author’s published work associated with the chapter, are presented in the opening pages. The rationale is summarised in a brief prelude within each experimental chapter.

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CHAPTER 2

2 LITERATURE REVIEW

2.1 COMPETITIVE SPORT AND TRACK SPRINTING

2.1.1 Overview

This section provides an overview of sprinting and its role for different sports. The meticulous labour of prior PhD candidates and researchers influenced the creation of the content that follows [37,49-54].

2.1.2 Methods for Literature Review

This literature review was conducted using a systematic approach. Comprehensive searches were performed across prominent academic databases, including but not limited to PubMed and Google Scholar. The search strategy involved the utilisation of specific keywords such as "resisted sprint training," "sprint kinematics," "athletic performance," and related terms. Boolean operators such as "AND" and "OR" were employed to refine search results. Additionally, a manual search of relevant journals and reference lists from key articles was conducted to identify pertinent studies. This rigorous search methodology ensured the inclusion of a diverse and representative body of literature, enhancing the comprehensiveness and reliability of this review.

2.1.3 **Competitive Track Sprinting**

In the sprint, competitors must cover a short (100 metre (m)), predetermined distance as quickly as they can. In August of 2009, Usain Bolt secured the world record of 9.58 seconds, breaking his own previous record of 9.69 seconds for the 100 m. The women's world record is 10.49 seconds and was set in by Florence Griffith-Joyner in 1988 [55]. Many sports that involve achieving a target or a goal very fast use the term sprinting. Athletes in track and field events start from blocks placed in staggered positions and run in lanes, with the exception of the 100 m race, in which all runners start behind the same line. On running tracks, sprints are performed at distances of 100, 200 and 400 m outdoors and over 60 m indoors [56,57]. At the highest level of competition, the gap between the top athletes is often only a few milliseconds. Winning on the world stage represents significant success for athletes. Winning an Olympic medal is often the biggest achievement of an athlete's career [58].

2.1.4 Performance

Both sprinting and accelerating quickly are crucial for track and field as well as field-based invasion team sports. [59,60]. Numerous team sports, including soccer, rugby, American football, hurling, and Gaelic football, depend heavily on sprinting. [59,61-64]. In Australian professional National Rugby League competition straight line sprints account for 15.8 to 35.2% of activity [65]. Elite rugby union backs and forwards spend between 4% to 25% of the game sprinting [66]. The relationship between physical capacity and match performance in professional soccer was examined in English [67] and German leagues. In the German Soccer League straight line sprinting is the most frequent action in goal situations (45% of goals) [62]. Out-of-possession running, is as important as in-possession running [68], as previous studies reported a strong association between in-possession running and success of a match [69,70]. More than 90% of all sprints in matches are shorter than 20 m with an average sprint time of two to four seconds (s) [26]. Therefore, sprint acceleration ability is of major importance [26,71-74].

Despite this, maximum velocity sprinting is also important in invasion-based team sports [72]. Although during soccer longer sprints (over 5 seconds) occur much less frequently than short sprints, they account for 10% of the sprints [75]. Field-based invasion team sport athletes achieve maximum velocity, from a static start, usually between 30-40 m [66,76-78]. Linear sprinting velocity (both acceleration and maximum velocity) distinguishes athletes from different performance levels [79], with professional players from the best European soccer leagues demonstrating faster sprint times than professional soccer players from lower-ranked soccer nations [26]. Of the soccer players tested, the national team and 1st-division players were faster ($P < 0.05$) than 2nd-division (1.0–1.4%), 3rd- to 5th-division (3.0–3.8%), junior national-team (1.7–2.2%), and junior players (2.8–3.7%) [80]. Professional rugby and soccer players have become faster over time, indicating that sprinting skills are becoming more important for professional field-based invasion team-sports [13,63,79,81,82].

2.1.5 Comparison of sporting populations

Team sport, and sprinting, an individual athletic discipline, have notable differences in terms of the physical requirements, muscle composition [83], gender discrepancies, competitive levels, training focus, and effects on the musculoskeletal system [84]. Elite soccer players, as observed by Rampinini, Impellizzeri, Castagna, Coutts and Wisløff [70],Rampinini*, et al.* [85], face the challenge of covering long distances during matches, which requires high levels of aerobic endurance, agility, and the ability to sprint repeatedly, thus require the development of aerobic, anaerobic, and phosphocreatine systems. On the other hand, sprinters, primarily focus on intense, anaerobic efforts, concentrating on explosive power and maximum speed over short distances [86,87]. Soccer players tend to have a combination of muscle fibre types, including slow-twitch (Type I) for endurance and fast-twitch (Type II) for sprinting and agility [88]. In contrast, sprinters have a higher proportion of fast-twitch muscle fibres (Type II), which are optimised for quick and forceful muscle contractions [89]. Additionally, training emphasis varies; team sport athletes engage in diverse training programs that include endurance, strength, and agility to meet the multifaceted demands of their sport [90]. In contrast, sprinters place a strong emphasis on specialised training to maximise explosive power, sprinting speed, and coordination of the nerves and muscles [91].

Team sport athletes and sprint athletes have distinct physical requirements and training priorities due to the contrasting demands of their respective sports. These differences in physical demands, including directional changes in team sports and linear sprinting in track and field, as well as variations in training methods and workout durations, can lead to diverse physiological and neuromuscular adaptations. Consequently, athletes from these different sports may exhibit varying characteristics and responses to RST. This research specifically targets these diverse athlete populations.

2.2 SPRINT PERFORMANCE

2.2.1 Prelude

The following is a narrative account of the biomechanics research pertaining to sprinting performance (SP) and speed development. For the purpose of this thesis, we will use sprint performance when making reference to competitive sprint athletes, and speed when referring to the speed required in team sports. Notable summary and commentary works can be found in Morin, Edouard and Samozino [13],Morin*, et al.* [92], Young and Choice [93], Mero*, et al.* [94], Bergamini [95], Mattes, *et al.* [96], Ansari*, et al.* [97],Bezodis*, et al.* [98] and von Lieres Und Wilkau*, et al.* [99] that cover each topic in this overview in greater detail.

2.2.2 Overview

Sprinting is a core capacity that underlies performance in many sports, and subsequently there is a large body of scientific literature devoted to sprint training. Sprint training research appears in the published literature as early as 1916, with biomechanical analysis appearing first in the late 1960s [100-103]. It is widely acknowledged that sprinting is a potent physical exertion that engenders the generation of substantial vertical and horizontal net force by the lower limb muscles with each step [13]. The goal is to achieve the largest average velocity possible over a set distance. Sprinting performance, as in many sports, relies on a variety of factors. While inevitably interrelated and interacting, these capabilities typically fall under either internal or external control [104]. Athletes are unable to directly manage that fall under external control (i.e. environmental factors like wind) [105]. The internal control is more pertinent to this thesis because it provides a better understanding of the biomechanical limitations of sprinting and enables coaches to better prepare athletes for those events by enhancing their physical capacity and/or technical ability to execute this capacity.

Sprinting performance is influenced by both force and power [106-109]. The time required to develop maximal strength is significantly longer than that required for most specific sports. Due to the short duration of certain sports movements, it is not possible to perform them with maximum strength. For example, some sports, such as sprinting, have a contraction time of less than 250 milliseconds (ms) [110]. Therefore, the maximum force parameter is of little significance in relation to explosive force, which reflects the ability to exert maximum force in the shortest amount of time. Of particular importance to coaches is the relationship between force-time curve variables and actual athletic performance measures. Contractile rate of force development (RFD) for strength development is a major factor in the maximum power and velocity achievable in rapid limb movements. Therefore, RFD is inherently important to athletes participating in sports that involve such explosive muscle action [110].

The role of force (strength) and power in relation to sprint performance and speed development will be discussed in greater detail later in this literature review. It is necessary to understand the factors related to improving sprint performance in order to build effective sprint training methods.

2.2.3 Phases of sprinting

To understand the key factors affecting performance, researchers have broken down sprint performance into shorter phases - acceleration, maximal velocity, and deceleration [94]. Overall, acceleration is defined as the distance needed to attain maximal velocity [111] and this is specific to the sport and the athletes' individual characteristics. However, the acceleration phase can be separated into two parts: initial acceleration (start block and reaction) and late acceleration (from the third step) [112]. The maximal velocity phase is the phase where the highest velocity is achieved during a sprint [113].

In a field-based invasion team sport setting more than 90% of all sprints are shorter than 20 m, demonstrating the importance of sprint acceleration ability [26,71-74]. However, sprinting at top speed is also crucial for many sports [72]. Maximum velocity is reached at 30-40 m for field-based invasion team sport athletes [93] and at 40-70m for elite sprinters [18].

Although long-distance sprints are far less common in field-based invasion team sport athletes than short-distance sprints [71,114], maximum velocity can usually be achieved when sprinting from a moving starting point [66]. Since most sports involve sprinting [79], sprinting ability (i.e., the ability to accelerate quickly, reach top running speed, and maintain top speed) can be considered critical for performance [18].

Additionally, the sprinting phases of acceleration and maximum velocity are separate sprint performance capabilities with distinct biomechanical characteristics [115]. Understanding the biomechanical factors that affect acceleration and maximal velocity is crucial for properly evaluating and developing sprint capability.

2.2.4 Biomechanical determinants of sprint performance

The biomechanical investigations of sprint acceleration and maximum velocity sprinting can be broadly divided into kinetic and kinematic analysis. While a kinematic analysis focuses on the resulting movement of the body, a kinetic analysis explores the forces applied to the ground, and the subsequent application of force by the ground on the body [116].

2.2.4.1 Deterministic modelling

Dr. Hay is the pioneer of deterministic model use in biomechanical analyses. He developed a model to gain an understanding of the variables which govern sprinting and to explore the interactions of different variables and their relative influence on velocity. Biomechanical deterministic models describe the mechanical factors that directly influence performance, with all factors of a level completely determining the factors of the level above [116]. Hunter*, et al.* [117] later adapted the deterministic model to provide a framework of how maximal velocity is achieved. Deterministic models identify the kinetic and kinematic variables that impact upon step frequency (SF) or step rate (Figure 3) and step length (SL) (Figure 4) and divide SF and SL into sub-components of ground contact time, flight time, stance distance, and flight distance and then clearly convey the interaction of ground reaction forces (GRF), kinematics, and spatiotemporal parameters on these sub-components [116].

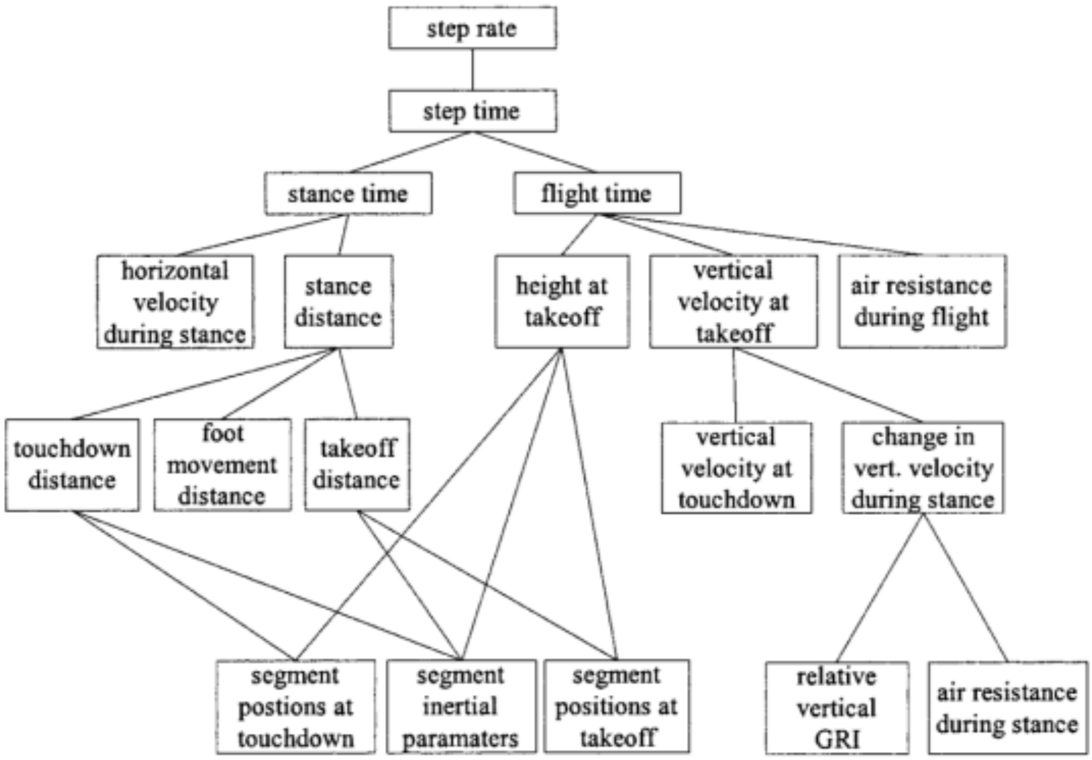

Figure 3 An image depicting the deterministic model of step rate (frequency) as a component of sprint performance [116].

Note that the terms "step" and "stride" are frequently utilised interchangeably in literature. To clarify, a "step" denotes half of a gait pattern (i.e. left foot to right foot contact), while a "stride" pertains to a full gait pattern (i.e. left foot to left foot contact) according to Hunter, Marshall and McNair [117]. Unless otherwise specified, the term "step" will be used as a preference.

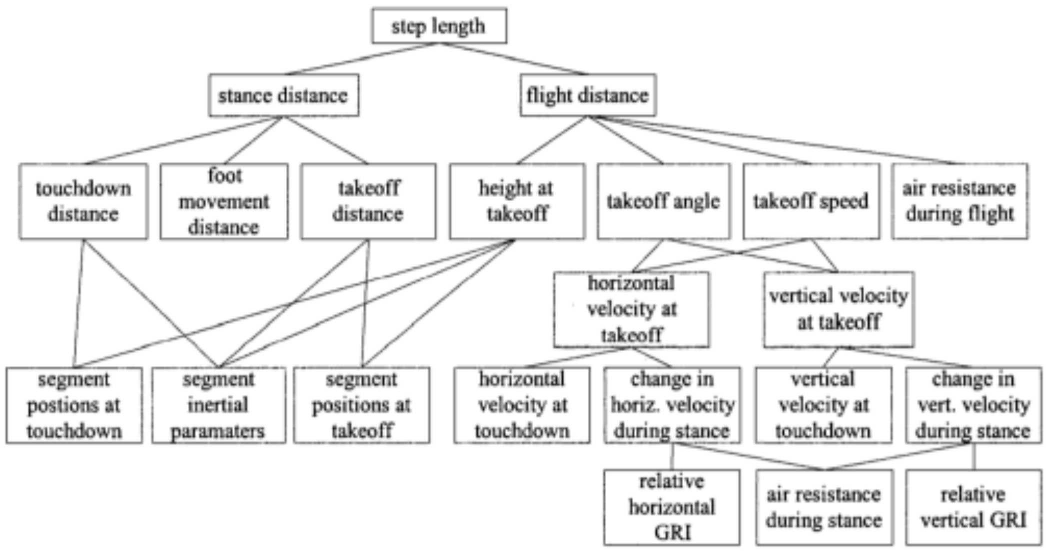

Figure 4 An image depicting the deterministic model of step length as a component of sprint performance [116].

Within a kinematic examination of acceleration and maximum velocity sprinting, the spatial and temporal aspects of the sprint gait, including step SL and SF, respectively, are frequently investigated. Maximal velocity sprinting is defined biomechanically as the product of SL and SF [116]. SL can be defined as a complete left foot to right foot cycle and includes two consecutive steps [118,119]. SF describes the number of strides which are taken in a given time [118]. Researchers have established a negative interaction between SF and SL, therefore an increase in one of these variables could possibly lead to a decrease in the other variable [117,120]. The opposing demands of producing large GRF impulses through longer ground contact times, to enhance SL and the desire to shorten ground contact times, which may increase SF can be used to explain this negative interaction [117,121]. The negative interactions and the deterministic models taken together shed light on the complexity of the maximum sprint velocity. It also emphasises how various kinetic, kinematic, and spatiotemporal elements interact to produce the properties of SL and SF. It is likely that the SF and SL that are optimal for performance will be specific to the individual athlete [120]. It is worth noting that individuals who do not heavily rely on SF or SL tend to be the fastest sprinters, as suggested by Salo, Bezodis, Batterham and Kerwin [120] and Debaere, *et al.* [122]. However, the exact reasons behind SL or SF reliance are not yet fully understood. Some possible causes that have been hypothesised include differences in strength and power and training history, as suggested by Meyers [123].

It is important to note that forces serve as the primary cause of movement [93] and therefore, it would be valuable to consider the role of forces in generating movement as the deterministic model mainly focuses on kinematic variables which have limited influence.

2.2.4.2 Biomechanical differences between the acceleration and maximum velocity phases

In order to maintain an organised structure, I have chosen to address different issues separately, even though they may be interconnected or repetitive at times. Although the focus is on sprint running in athletics, most of the information provided can be applied to other sports, including team sports that involve short bursts of acceleration. I would like to explore the differences between sprinting mechanics during the acceleration and maximum velocity phases in separate sections.

As previously mentioned, understanding the specific requirements and distinctions during each phase of a sprint is crucial for improving an athlete's overall performance.

These include differences in:

1. The basic temporal and kinematic factors such as SL , SF, flight (FT) and contact times (CT) [124] or

2. Differences in force production [18,19,125], i.e., differences in the magnitude and direction of the GRF during stance, and the kinematic and kinetic patterns exhibited by the ankle, knee and hip joints [124].

Since forces are ultimately the underlying cause of movement, and movement impacts the magnitude of forces, an understanding of how these forces are produced and the differences in the forces acting during the sprint will enable the coach to have a much better understanding of accelerative and maximum velocity sprinting.

2.2.5 **Kinetic determinants**

The importance of the magnitude and orientation of force produced has been demonstrated through significant research on the kinetics of acceleration and maximum velocity sprinting. Horizontal and vertical GRFs are frequently used to describe the kinetic analysis of the forces the body experiences and exerts when sprinting [126,127]. Additionally, the stance phase of a sprint is frequently divided into a braking phase followed by a propulsive phase, which correspond to, respectively, a decrease and a rise in an athlete's centre of mass (COM) velocity [126]. As the overall sprint acceleration progresses, braking impulses increase and propulsive impulses decrease resulting in decreases in net horizontal impulse and thus, lower step-to-step acceleration [127].

To increase sprinting speed and achieve high levels of performance it is paramount that athletes generate large forces in the opposite direction of COM displacement, relative to body weight (BW), in the shortest ground contact time possible, in order to produce the impulse required to overcome inertia and gravity [18,128-130]. However, how this impulse is achieved by faster sprinters, differs from how slower sprinters achieve this. They develop less force over a longer time period [129,131]. Data suggests that the magnitude of horizontal propulsive impulse accounts for 57% of variance in sprint velocity [130] and the orientation of GRF application has been suggested to be more important than the magnitude of force produced [13].

Increasing impulse: It appears that in order to enhance performance in several sports, the aim should be to amplify the impulse utilised during a movement by increasing the area under the force-time curve. There are essentially three techniques that can be employed to achieve this objective [132]. One way to increase the total force applied is by increasing the magnitude of the force during a specific part of the movement. For example, if the peak force during the propulsive phase of a vertical jump is increased, the area under the force-time curve will also increase (Figure 5). It's important to note that increasing the height of any part of the curve will increase the area under the curve. The average force can also be increased without changing the peak force, resulting in an increase in impulse [132]. Another approach is to enhance the speed at which force is generated (RFD). By doing so, the curve representing the relationship between force and time will become steeper, allowing the athlete to achieve maximum force output faster. As a result, the curve will have a broader top and greater area (Figure 5) [132]. The final way to increase impulse is by making the force application last longer. However, this may not be possible or beneficial for all skills. For example, in sprinting, the duration of each foot contact is usually around 0.1 s and increasing it would harm the athlete's performance. The limitations of applying force during sprint acceleration over shorter periods of ground contact highlight the impact of impulse on performance. If the impulse is high, acceleration performance may be restricted as force production takes longer during ground contact [133]. Therefore, to maximise impulse in sprinting, athletes should focus on improving their maximum force capabilities or rate of force development. Nonetheless, in movements where it is feasible and advantageous, extending the force application time can increase impulse. It's crucial to understand that different methods of increasing impulse can impact each other, so an increase in one factor doesn't necessarily lead to an overall increase in impulse. For example, an athlete may raise their peak force output but shorten the duration of force application, resulting in a decrease in impulse. This is why measuring impulse is more valuable than measuring peak force, average force, or RFD [132].

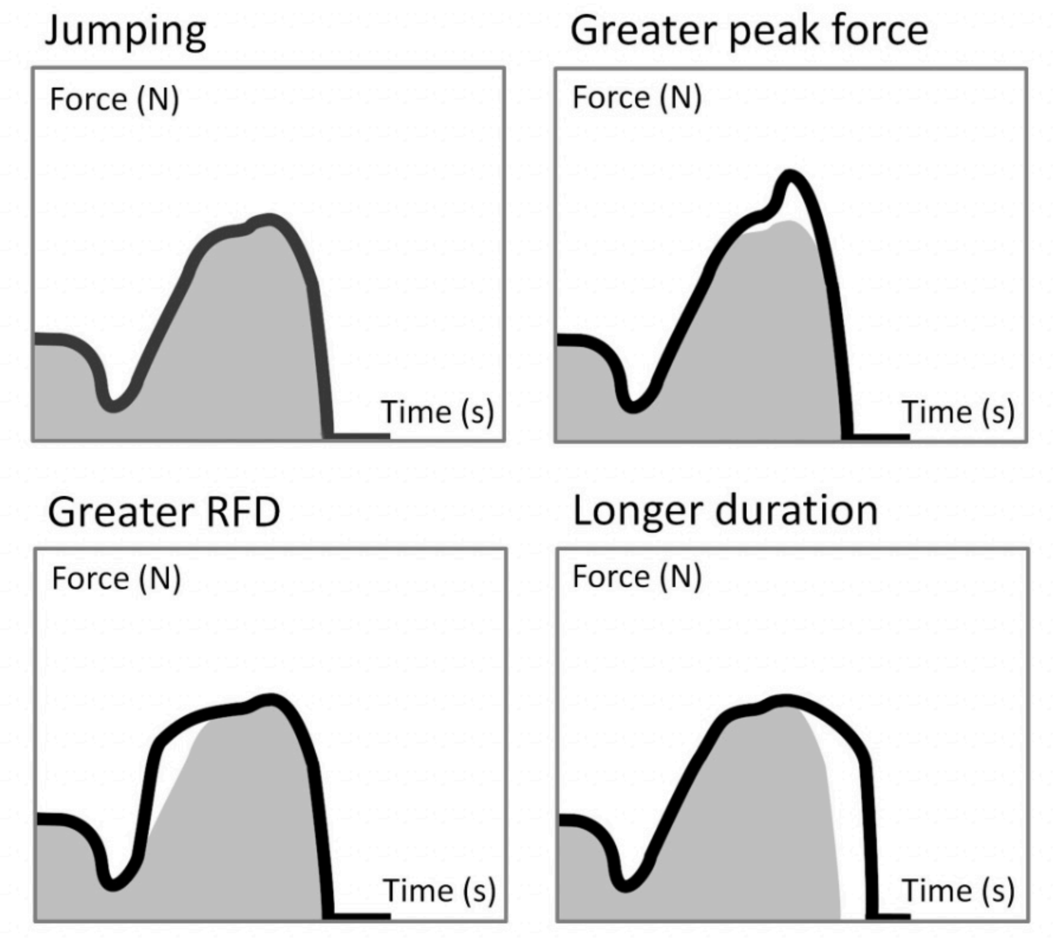

Figure 5 The representation of impulse during a vertical jump.

Note that the original jump is shown in the top left panel, while the other three panels demonstrate ways to increase the impulse during vertical jumping. This can be achieved by increasing the peak force, RFD, and duration of force application, as indicated by the greater area under the curve. By implementing these techniques, athletes can improve their jump height and overall performance. Figure taken from: [132].

Equally important, when attempting to accelerate a body and move it horizontally, a significant amount of horizontal force is required. However, due to the gravitational constraints of maintaining a forward lean during acceleration, the body's ability to produce force is compromised [13,18]. As a result, only the horizontal component of force is directed forward, while the vertical force serves to counteract rotation around the COM [13,18]. Previous research has shown that the relative horizontal impulse is a strong predictor of sprinting velocity during acceleration [130]. Morin, Edouard and Samozino [13] introduced a method for evaluating an athlete's force application technique by determining the mean ratio of forces applied to the ground (RF) (Figure 6). This technique allows for the analysis of differences in horizontal force and net forward acceleration, even when the total force applied to the ground (Ftot) is the same for two athletes [13].

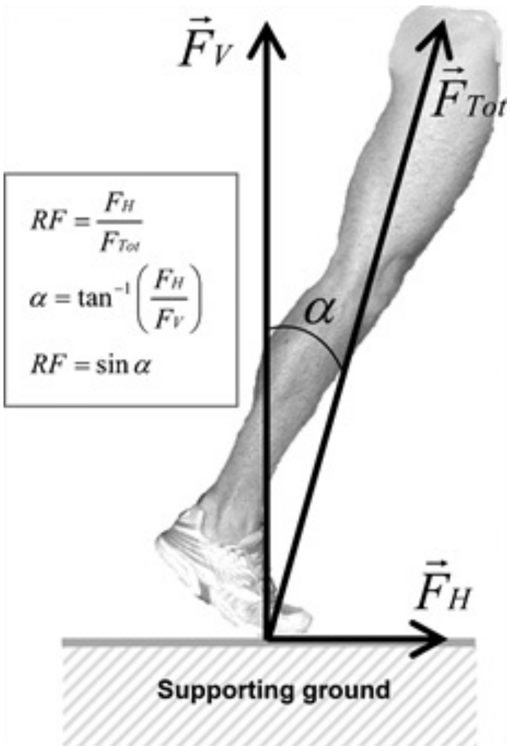

Figure 6 The schematic representation of the ratio of forces and mathematical expression as a function of the total and net positive horizontal GRF.

Note that the forward orientation of the total GRF vector is represented by the angle α [13]. Figure taken from: [13].

Morin, Edouard and Samozino [13] demonstrated that the fastest sprinters were able to produce greater net horizontal impulse compared with their sub elite counterparts. Additionally, it is worth noting that research has revealed that successful sprinters are able to sustain their impulse throughout the entire acceleration phase, even as their velocity increases and ground contact diminishes. This factor is imperative to achieving optimal performance [133]. The position of the athlete's body when sprinting, whether accelerating or at maximal velocity, influences application and orientation of force [124]. Athletes with faster sprinting abilities are capable of maintaining a more significant forward lean for an extended period of time, which results in less decrease in RF during acceleration. This allows them to accelerate more efficiently and attain higher maximum velocities due to their superior technical application of force [13,18,131,134]. Faster athletes also demonstrate a capacity to maintain a more horizontally oriented GRF during maxV than slower athletes [13,18,19,92,130,134]. However, when an athlete runs at their maximum speed while in an upright position, they heavily rely on achieving high GRF with a vertical orientation to minimise the time they spend on the ground. This strategy helps in reducing deceleration [133]. Moreover, orientation of force is also affected by the touch-down or ground contact distance in reference to the athletes body COM on ground contact [135].

In Figure 7 it is demonstrated how the magnitude and direction in which these forces are applied appears to differ as a sprint progresses [131]. As mentioned above during the acceleration phase, the ratio of horizontal to vertical forces should favour horizontal, so resultant force is oriented more horizontally [126,127]. In general, as sprint velocity increases and maximum velocities are attained, horizontal force decreases and the magnitude of vertical force increases [94]. Vertical force production may become increasingly important to sprint performance as maximum speed has been associated with the average vertical force per unit body weight applied at top speed during over ground sprinting [127]. It has been proposed that faster runners are capable of attaining higher maximum velocities by means of their ability to generate efficient vertical impulses within shorter ground contact periods, enabling them to achieve the necessary aerial times to adjust their limbs for the next contact [129]. Although, it is important to consider the horizontal and vertical force components separately, as they can aid the understanding of sprinting. It is worth mentioning that they are part of a single GRF vector and thus cannot be independently altered [124]. The positioning of the limbs when the foot strikes the ground has an impact on the orientation of the force vector, which can either be more vertical or horizontal.

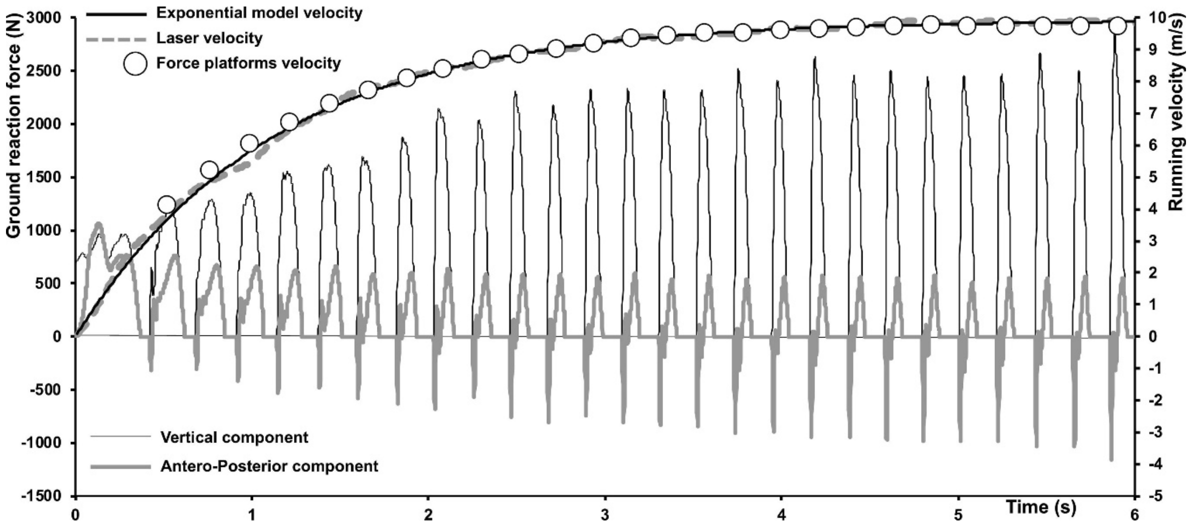

Figure 7 Raw data of sprinting velocity, and vertical and horizontal components of the GRF

The image shows the GRF during the first 6 seconds of a 60 metre sprint acceleration, taken from: [136]. The circles represent the average values of running velocity for each step after the initial push-off from the starting block. The running velocity trace captured by the laser system and the exponential fitting are closely intertwined.

2.2.6 **Kinematic determinants**

Reviewing the literature shows that the following kinematic variables have received the most attention in sprint research [19,94,99,113,125,130,134,137-142]:

- Spatiotemporal variables (e.g., stride length, stride frequency, contact time, flight time, joint and segment angles)
- Lower-limb segment velocities immediately prior to touchdown or during ground contact

The acceleration phase of sprinting typically follows a pattern whereby kinematic parameters, such as stride length, stride frequency, contact time and flight time change dramatically as the acceleration progresses [94]. In contrast, during the maximum velocity phase where athletes try to maintain their maximum velocity as much as possible, the kinematics and kinetics of sprinting remain more consistent [136].

Acceleration: During the acceleration phase, it can be observed that CTs tend to be longer and display a gradual decrease as an athlete continues to accelerate towards their maximum velocity. On the other hand, FT gradually increases throughout the sprint [19]. For elite sprinters this has been observed over their first two steps. Data indicates that the duration of CT decreases from around 0.160 - 0.194 s (first step), to 0.150 - 0.181 s (second step) [94]. The longer CTs during the acceleration provide the athlete with the opportunity to generate larger net propulsive impulses [137]. Applying this larger net horizontal impulse relative to BM leads to larger horizontal acceleration of the COM of the athlete during each ground contact (according to the impulse-momentum relationship) [143].

Maximum Velocity: When sprinters reach their maximum velocity, they have to produce a significant amount of force in a short time [94,144], which results in shorter contact times compared to the acceleration phase (range from 0.094 to 0.111 s) [94]. Research demonstrates that a shorter CT can be achieved by a greater hip extension and high backswing velocity of the foot prior to ground contact as well as less knee flexion and extension during the ground contact (i.e. high joint stiffness) [144]. Mattes, Wolff and Alizadeh [96] demonstrated less knee flexion and knee and hip extension during initial ground contact appears to be essential for producing CTs under 100 ms. This shorter ground contact time results in increased SF without a concurrent decrease in SL [129].

Research has demonstrated that faster athletes achieve shorter CTs during sprinting, without significant differences in FT, compared to slower athletes [64,131,145,146]. There is also a difference in CTs between sprint and team sport athletes, as demonstrated in Table 1.

Table 1 Contact times of sprint and team sport athletes [147].

		First Ground Contact (s)	Second Ground Contact (s)	MaxV Ground Contact (s)
Load	**Group**	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
0%	Sprint	0.17 (±0.01)	0.14 (±0.01)	0.11 (±0.01)
	Team	0.20 (±0.02)	0.16 (±0.01)	0.13 (±0.06)

However, according to Murata, *et al.* [147], it seems that a more effective acceleration may be achieved by taking longer steps and pushing off with more force during the first 8 steps. Additionally, a faster step frequency with shorter contact and flight times, during steps 9 to 20 can also contribute to a better acceleration.

The following section describes key joint angles for the critical instants of touchdown (TD) and toe-off (TO) for elite sprinters as well as footballers. The data presented is adapted from the biomechanical report of the IAAF-World-Championships 2017 in London [148] and IAAF-World-Indoor-Championships 2018 in Birmingham. Table 2 highlights differences between acceleration and maximal velocity sprinting and differences between TD and TO for elite sprinters.

Table 2 Joint angles at touch down and toe off for acceleration and maximum velocity in elite sprinters.

		Touch down		Toe off	
		Mean	**SD**	**Mean**	**SD**
Acceleration	**Hip(°)**	142.6	3.1	203.7	5.9
	Knee(°)	153.1	5.1	151.7	10.9
	Ankle(°)	117.2	5	131.2	9.8
	Trunk(°)	78.4	1.9	85.6	1.5
Maximum Velocity	**Hip(°)**	140.1	4.1	201.9	4
	Knee(°)	154.5	6.6	168.1	4.8
	Ankle(°)	116.3	6.8	168.1	4.8
	Trunk(°)	76	3.3	79.4	2.9
TO was defined as the first frame in the video where the foot had left the ground and TD the first frame where the foot had contact with the ground *[149].*					

The angle of the trunk is relative to the horizontal and considered to be 90° in the upright position. This table is adapted from the biomechanical report of the IAAF-World-Championships 2017 in London [148].

The sprinting abilities of elite sports teams have occasionally been studied, although typically only through simplified data processing techniques, such as split times in elite Australian rules football players [76]. To the authors knowledge there have been no published data on multiple different joint angles for professional team sports. Very recently though researchers examined the differences in sprint technique characteristics between elite sprinters and professional football players [150]. Significant mean differences between footballers and sprinters in spatiotemporal and kinematic variables for both acceleration and maximum velocity sprinting can be seen in the Table 3 below. Across both phases of sprinting, elite sprinters consistently contacted the ground further back. What is more, during both phases of sprinting, elite sprinters had significantly higher SF, showing a higher leg turnover speed compared to football athletes. During acceleration sprinting elite sprinters displayed significantly shorter flight times with no significant difference in ground contact time. During maximal velocity sprinting elite sprinters displayed significantly shorter CTs with no significant difference in FT compared to football athletes.

Table 3 Sprint characteristics during acceleration and maximum velocity.

	Footballers (mean ± std)	Sprinters (mean ± std)	Effect Size (Cohen's d)
Ground contact time (ms)	164 ± 12	161 ± 12	0.19
Flight time (ms)	**71 ± 9**	**55 ± 11**	**1.60****
Normalised step length	0.70 ± 0.03	0.72 ± 0.04	-0.30
Step Frequency (Hz)	**4.30 ± 0.25**	**4.66 ± 0.16**	**-1.71****
Trunk Angle Range (°)	8.6 ± 12.7	9.3 ± 4.8	-0.07
Normalised touchdown distance	**0.12 ± 0.03**	**0.01 ± 0.03**	**3.95*****
Normalised toe-off distance	**0.32 ± 0.02**	**0.47 ± 0.02**	**-7.03******

NOTE: variables calculated during the first 3 steps; elite sprinter data = 60 m final from 2018 IAAF World Indoor Championships; $p < 0.05$*, $p < 0.01$**, $p < 0.001$***

(A)

	Footballers (mean ± std)	Sprinters (mean ± std)	Effect Size (Cohen's D)
Ground contact time (ms)	**109 ± 8**	**93 ± 5**	**2.56*** **
Flight time (ms)	115 ± 7	116 ± 7	-0.18
Normalised step length	**1.12 ± 0.06**	**1.32 ± 0.03**	**-4.27*** **
Step Frequency (Hz)	**4.49 ± 0.16**	**4.80 ± 0.22**	**-1.63** **
Average Trunk Angle (°)	78.6 ± 3.1	78.1 ± 2.9	0.17
Normalised touchdown distance	**0.24 ± 0.03**	**0.21 ± 0.02**	**1.95** **
Normalised toe-off distance	**0.30 ± 0.02**	**0.34 ± 0.01**	**-2.19*** **

NOTE: variables calculated during 20-30 m split for football players; elite sprinter = 100 m final from 2017 IAAF World Championships; p < 0.05*, p < 0.01**, p < 0.001***

(B)

(A) depicts the acceleration phase and (B) the maximum velocity phase. Note that this table is adapted from [150].

During the initial acceleration phase a more forward-inclined orientation of the athlete can be observed compared to the late acceleration and maximum velocity phase [99]. The late acceleration phase ends when changes in trunk angle cease as the trunk becomes upright [99]. Segmental changes can provide an insight into how athletes adjust their technique to facilitate force production [99]. Furthermore, differences in kinematic variables such as shank angles at TD are specific to each phase of a sprint [151]. Experienced sprinters show changes in their shank angles during the acceleration phase, with an average of six to eight degrees per step [99,151,152]. This phase ends when the shank becomes perpendicular to the ground at TD. The increase in variables during the initial acceleration phase could lead to a decrease in the sprinter's ability to generate horizontal force during subsequent ground contacts. In other words, having a more perpendicular shank in the early stages of the sprint could limit the athlete's ability to generate as much forward motion [135]. It is common for the knee and hip joints to extend from TD onwards during both early and mid-acceleration, and for some athletes, the knee may start to flex just prior to TO [153-155]. During maximum velocity, the ankle and knee joint angles usually decrease for the first 60% of the stance phase, while the hip joint continues to extend throughout the entire phase, which is similar to its movement during acceleration [156]. The ankle goes through dorsiflexion followed by plantar flexion, with a net plantar flexor moment dominant throughout every stance phase of the sprint [135]. Bezodis, Trewartha and Salo [135] have shown that the ankle generates up to four times more energy than it absorbs during the first stance phase, compared to zero net energy generation during the mid-acceleration phase [154] and net energy absorption during the maximum velocity phase [156]. Research found that having a "stiffer" ankle while dorsiflexing during the early part of the first stance phase was positively related to higher horizontal COM velocities in a single sprinter [157]. Kugler and Janshen [134] suggested that a greater negative touchdown distance, i.e. planting the stance foot more posterior relative to the COM at TD, facilitated a forward leaning position and the generation of greater horizontal propulsive forces [124], which is especially important during acceleration. According to studies by Bezodis, Trewartha and Salo [135] and Debaere, Jonkers and Delecluse [122], knee joint mechanics play an important role in the first stance phase of sprinting. It is possible that the distance between the foot and the ground at TD may affect early acceleration performance through its impact on knee joint mechanics. While some have suggested that a larger negative touchdown distance is better for performance, this has only been based on observational differences between sprinters [124]. It is important to consider the possibility that there may be a limit to the benefits of increasing the negative touchdown distance. Elite sprinters land with their foot about 6 cm in front of the body's COM, whereas novice sprinters land with their foot about 12 cm in front [158]. The foot relative to the COM-position was more posterior (closer to the COM) for sprinters compared with rugby athletes, backs compared with forwards [159].

In summary, the acceleration and maximum velocity phases of sprinting have distinct kinematic determinants. In the acceleration phase of sprinting, kinematics often change significantly as the acceleration proceeds. The kinematics stay more constant during the maximum velocity phase, as athletes attempt to maintain their maximum velocity as much as they can.

2.3 RESISTANCE TRAINING, SPRINT PERFORMANCE/SPEED DEVELOPMENT & SPRINT SPECIFIC TRAINING

2.3.1 Prelude

As outlined previously, coaches work to increase both physical capacity and technical proficiency to improve SP. In the section above, I went into great length on kinematics and described how it may affect force output. The development of physical capacities as they relate to enhancing SP will now be covered in the following section. This is divided into two sections focusing on 1) the principle of specificity and 2) sprint performance and speed development. Additional relevant reviews, notable summary and commentary works are Young, Mc Lean, Ardagna and fitness [40],Young [106],Cross [160], Samozino*, et al.* [161], McMahon*, et al.* [162], Rumpf, Lockie, Cronin and Jalilvand [72],Cronin*, et al.* [163],Cronin and Sleivert [164],Randell*, et al.* [165],Contreras*, et al.* [166], Siff and Verkhoshansky [30],Verkhoshansky [31].

2.3.2 Overview

Resistance training is defined as any movement where the body is working against an external force that must be overcome in order to complete the movement [17,167]. It can improve muscular power, strength, and the rate of force development, resulting in better coordination between muscles and a lower risk of sports injuries [106], it further increases the muscles ability to produce force. Ultimately, it can enhance sprint performance [40,106,112,168]. At an elite level, training must be specific to each athlete based on their sport or playing position [43]. It is common practice depending on the goal of the sport, that different resistance training methods are applied, such as resistance training (machine or free weights), body weight and plyometric exercises, resistance band exercises and resisted sprinting [169].

2.3.3 Rate of force development

The maximal RFD characterises a range of underlying neuromuscular characteristics that facilitate the development of force quickly and therefore influences strength and power [170]. RFD is crucial in many sporting activities, such as sprinting or jumping in which force production times reported range from 100 to 300 ms [40,164,170]. Sprinters have between 50 to 250 ms of ground contact time [171], as a result, those who can exert more force during this period will likely run the fastest 10 m times [172]. Contact time during the acceleration phase of sprinting is <300 ms, and ~100 ms at top speed [173].

This has been validated by Weyand, Sternlight, Bellizzi and Wright [129], who discovered that the key to speed performance was the athlete's capacity to exert more force during the brief period of ground contact. Moreover, this is supported by data, demonstrating significant relationships between 10 m sprint time and peak RFD of professional rugby league players ($r = -0.54$) [172], and 5 and 20 m sprint time and RFD at 0-100 ms ($r = -0.63$, $r = -0.54$) [173]. Several authors have explained the main reason for this relationship [171,174]. Tillin, Jimenez-Reyes, Pain and Folland [174], found that explosive muscle contractions are crucial for sports like sprinting and jumping. In these types of movements, there is limited time for the muscles to generate force, so the RFD is one important factor of performance in explosive contractions [110]. As mentioned previously, this in turn would lead to an increase in the generated impulse or decrease in the time needed to obtain an equal impulse and subsequent acceleration of an athlete [175]. Heavy resistance and plyometric training can both create positive changes in motor unit recruitment and discharge rates, which are factors in RFD, according to a recent analysis by Aagaard, Simonsen, Andersen, Magnusson and Dyhre-Poulsen [171] that highlights neurological and muscular determinants of explosive strength. Additionally, quick ballistic contractions lead to positive modifications in motor neuron discharge rates, which raise the early onset of RFD [170].

2.3.4 **Power**

The outcome of a game is often influenced during the sprints, as well as when players are shooting or tackling. [176]. To overcome the body's inertia when accelerating from a stationary position or a moving start, higher levels of relative strength (strength divided by body weight) / high force generation capacity is needed. In order to develop sprint acceleration, resistance training methods are utilised [161,177-180] and many coaches focus on improving muscular power [22,164,181,182]. In order to have the greatest transfer to performance, it is important for strength and power training to be specific [183]. Power is defined as the amount of work done in a particular period of time, which is equal to the combination of force and velocity. Research has indicated that an increase in power results in an increase in SP. More specifically, incorporating weight and plyometric training into a workout routine has been shown to lead to a significant improvement of 6 to 10% in velocity over a distance of 5 to 20 metres [183,184].

2.3.5 **Force Velocity Relationship**

The capacity for work and power is dependent on the force-velocity (Fv) characteristics of the contributing musculature [185]. The relationship between these two factors is inverse in nature, whereby as velocity increases the capacity for muscle to produce force is decreased.

Maximum power (Pmax) can be reached under an optimal combination of force and velocity during a movement or contraction (Fopt and Vopt). For a strength and conditioning coach this means that Pmax may be improved by increasing the ability to develop, relative to the individual, high levels of force at low velocities (maximal strength) and/or lower levels of force at high velocities (velocity capabilities) or moderate force and velocities [22,163].

A major constraint of sprinting is time, this means that sprinters need to be able to generate forces as large as possible at high velocities. An issue for strength and conditioning coaches is to determine where to place the training “goal” within the continuum [186] (Figure 8). The following paragraph is going to focus on this.

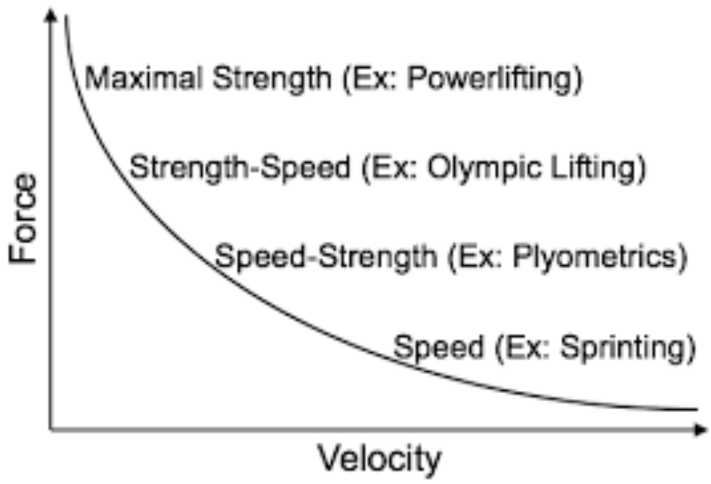

Figure 8 Force-velocity continuum.

Note, the curve represents the inverse relationship between force and velocity. On this continuum, maximal strength and maximal speed are located at opposite ends of the spectrum. The hybrids of these qualities, strength-speed and speed-strength, can be found in between. Power training can be conducted at any point along the curve. (Taken from Travis Pollen).

Force-velocity relationship allows reliable assessment of maximal power capabilities, an insight into an athlete's sprint mechanics during acceleration phase, and an athlete's propulsion capacities [187,188]. This allows practitioners and researchers to characterise the change in an athlete's maximal horizontal force and power production capabilities, when sprinting speed increases, and then directly determine an athlete's sprint acceleration performance [13,19,92]. The technical ability of force application during sprinting and its implication in sprinting performance has been well presented in detail previously. Therefore, the relationship provides an objective quantification of the Pmax an athlete can develop, the theoretical maximal horizontal GRF (F0) and the theoretical maximal velocity at which the athlete could run if there are no external constraints to overcome (V0)

[51,189]. The ratio between force and velocity corresponds to an athlete's Fv-profile (FVP). These different mechanical variables integrate an athlete's "physical" qualities (lower limb muscle force production capacities) [190]. The importance of having a velocity orientated force-velocity profile for sprint performance was highlighted by the constraint of sprinting. In the literature it is suggested that individualised sprint training should be based on an FVP, which means that athletes with force deficits should prioritise the development of horizontal strength (horizontal force; acceleration), while athletes with velocity deficits should perform more sprinting at maximal velocity [51].

2.3.6 Stretch shortening cycle

The stretch-shortening cycle (SSC) is a natural aspect of muscle function that is commonly observed in human movements. In sports, plyometric training is often utilised as a means of enhancing SSC performance [191]. Plyometric training consists of hops, jumps, and bounds. This form of training is utilised extensively by athletes involved in track and field, and other sports to improve skill execution and physical performance [191]. The successful integration of these exercises, however, may only be achieved with an understanding of the underpinning mechanics [192]. The SCC describes an eccentric phase or stretch followed by an isometric transitional period (amortisation phase), leading into an explosive concentric action [193]. In other words, a stretching of the muscle–tendon unit prior to a shortening. It has been observed that active stretching prior to a shortening contraction results in a significant increase in force, torque, mechanical work, and power during the shortening phase of the SSC when compared to a pure shortening contraction without active stretching [194,195]. When a muscle-tendon unit is stretched, mechanical work is absorbed by the muscle-tendon unit and can be transferred to positive energy during the following concentric contraction. The ability to generate maximal power is influenced by the type of muscle action involved and, in particular, the time available to develop force, storage and utilisation of elastic energy, interactions of contractile and elastic elements, potentiation of contractile and elastic filaments as well as stretch reflexes [196]. Those mechanisms underpin the SSC, however the two that have been researched the most are, 1) storage and release of elastic energy, and 2) muscle stretch reflexes which are both linked to the muscle tendon unit stiffness [197,198].

Storage and release of elastic energy: When we hop, jump, or run, our legs act like springs that compress on ground contact and release energy when pushed off [199]. The tendon is the main place where elastic energy is stored, and this energy is proportional to the force and deformation applied to it [200,201]. Previous research shows that elasticity is important for improving athletic performance, and can explain differences in jump types (20-30% difference seen between a countermovement jump and a squat jump) [200-202]. There is also a correlation (r = 0.785) between the tendon's ability to store energy and the performance of distance runners [203].

Muscle stretch reflexes: Stretch reflexes are important for regulating stiffness. Hoffer and Andreassen [204] showed that muscles with intact reflexes are stiffer than those without. This suggests that stretch reflexes contribute to muscle stiffness during the eccentric phase of SSC [205,206].

2.3.7 **The principle of specificity**

Training can be divided into non-sprint specific (e.g., resistance and plyometric training) and sprint-specific training. Non-specific is generally not specific to movement but is specific in terms of targeting the development of required physical capacities. It is suggest, in line with training specificity, that sprint-specific training provides greater benefits in speed/acceleration development compared to non-specific training [207].

The principle of specificity is the basis for designing a training program [208] and can be applied to all levels of athletes [106]. However, the level of specificity required appears to increase as the level of the athlete increases [209]. Training specificity is a concept that dictates that the greatest gains in performance are achieved when the training completed is closely linked to the performance [163,210]. Therefore, the more specific the training, the bigger the transfer of improvements from training, to the performance [211]. Training specificity is synonymous with the principle of dynamic correspondence (DC), which is a term used to describe an exercise or training programmes ability to directly affect the athletes sporting performance [30].

In other words, DC is the transferability of training to its ability to improve performance. According to this principle, several aspects must be considered when selecting exercises to improve transfer to performance. These include, movement similarity, amplitude/direction of movement, accentuated region of force production, dynamics of effort, rate and time of maximum force production and regime of muscular work [30].

2.3.7.1 Dynamic correspondence: Direction of joint movements

According to DC, the joint angular ranges used should be comparable to those used in athletic skill, and joint motions (such as flexion, extension, and abduction) are similar [212,213]. The forces acting on or expressed by the athlete should be taken into consideration relative to the local (athlete-fixed) coordinate system of the athlete, not the global frame, is a crucial presumption made while applying the criteria of DC. Numerous similarities of trunk, knee and hip angles are shared between squats and other weightlifting derivatives and the joint ROM that occur during sprinting movements [214,215]. Research comparing the effects of different squat ROM and SP found the largest significant improvements in sprint performance from quarter squats, followed by half squats and then full squat respectively (Figure 9) [215]. The quarter squat displays a range of motion at the knee and hip that is more similar, and thus more specific, to that observed in sprinting and therefore may partially explain why it appears to be more effective for improving SP in this context.

Group	Quarter Squat	HALF Squat	FULL Squat	VJ	40 sprint
QTR	0.12	0.06	0.02	0.15	–0.02
HALF	0.07	0.14	0.00	0.07	–0.01
FULL	0.00	0.05	0.17	0.01	0.00

VJ – vertical jump; 40 – 40 yard sprint

Group	Quarter 1RM	Half 1RM	Full 1RM	VJ	40 sprint
QTR	1.41	0.62	0.12	0.75	–0.58
HALF	0.88	1.76	0.02	0.48	–0.35
FULL	0.05	0.59	1.14	0.07	–0.10

ES – (post-pre)/pre-test SD

Figure 9 Percent changes in performance measures and effect size calculations based on squat depth. Taken from [215].

2.3.7.2 Dynamic correspondence: The principle of the accentuated region of force production

The concept of accentuated regions of force production pertains to the particularity of muscular exertion and, thus, the application of force during the duration of a movement. (positions in the movement where forces are the highest) [213]. It seems that exercises emphasising accentuated force have various strength and torque-angle curves depending on the length of the exercise. Specifically, long-length exercises have ascending strength curves and descending torque-angle curves, mid-length exercises have U-shaped strength curves and upside-down U-shaped torque-angle curves, and short-length exercises have descending strength curves and ascending torque-angle curves [216].

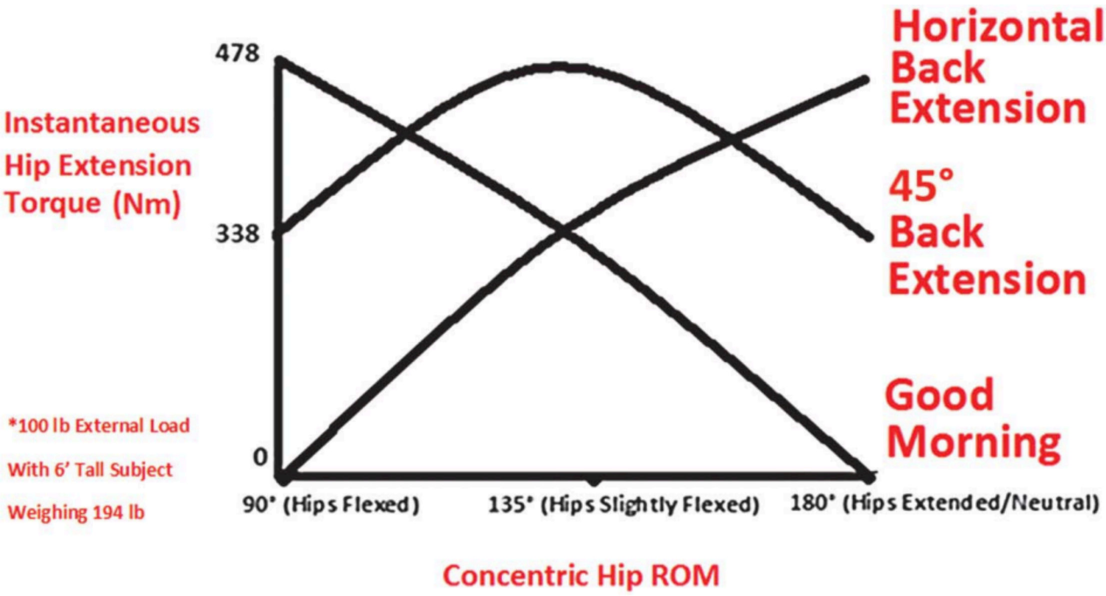

Figure 10 Hip extension torque

Graph illustrating instantaneous hip extension torque at selected ROM in three different hip extension exercises. Taken from: [216].

When aiming to improve performance in sports, it is recommended to choose exercises that mimic the hip torque curve (Figure 10) involved in the activity. For instance, the good morning exercise is effective for maximising hip torque in a flexed position, which is beneficial for the late swing phase of sprinting. On the other hand, the horizontal back extension is better suited for the stance phase of sprinting as it maximises hip torque in an extended position. For the acceleration phase of sprinting, the back extension is considered ideal due to its ability to maximise hip torque in the middle range of the hip flexion-extension axis, which is crucial for the first few seconds of a sprint [216].

During maximal speed sprinting, it has been observed that the glutes are at short lengths while the hamstrings are at long lengths upon ground contact. Gittoes and Wilson [217] found that the hip and knee angles during this stage of sprinting were around 150-175° and 155-145°, respectively. Strengthening these muscles at their corresponding lengths would be beneficial for maximising carryover, especially when considering that exercise has been noted to influence the optimal length of a muscle [218]. Nevertheless, there has been some research that opposes this viewpoint. According to Clark, *et al.* [219], bench press training at diverse ranges of motion and muscle lengths proved to be more advantageous than full range of motion bench, as it enhanced mid-range reactive strength and end-range force production during isokinetic testing without affecting initial-range performance.

2.3.7.3 Dynamic correspondence: The principle of dynamics of effort

The ability to apply or withstand varying magnitudes of force at different movement velocities is crucial for athletic performance. When it comes to training, it's important to consider the force-velocity characteristics of specific athletic movements [212]. Therefore, training efforts should take into account the force magnitudes, movement velocities, and contraction velocities associated with these movements. Research shows that heavy-load resistance training is better for maximal strength, but low-load high-velocity training may be necessary for improving high-velocity athletic performance in well-trained athletes. Combining high-load low-velocity and low-load high-velocity training seems to be the most effective strategy for improving performance in athletic movements. This is supported by research demonstrating both force and velocity specific adaptations in baseball players using either high-load or low-load resistance training [212].

2.3.7.4 Dynamic correspondence: The principle of time available

The principle refers to the time available to complete a key skill or athletic movement (being able to apply maximum force in less time). The capacity to maximise force generation during crucial time intervals determines success in various sports circumstances. Success in many sports scenarios is determined by the ability to maximise force production during critical time intervals. In such cases, performance improvement results from the ability to generate greater force within a certain time frame (i.e., increased rate of force development). Therefore, training should seek to improve rate of force development and use tasks that may have similar time constraints to sports specific movements [212]. Coaches should take into account the various factors that may lead to improvements in RFD. According to a recent review by Maffiuletti, Aagaard, Blazevich, Folland, Tillin and Duchateau [170], both heavy resistance and plyometric training can have positive effects on motor unit recruitment and discharge rates, which are important determinants of explosive strength (RFD). Furthermore, rapid ballistic contractions can also lead to favourable adaptations in motor neuron discharge rates, thereby contributing to an increase in the early rise of RFD.

It seems that heavy resistance training can effectively enhance RFD by promoting hypertrophy of type II muscle fibres and morphological changes of the entire muscle [220]. Moreover, the increase in tendon stiffness can also help with force transmission, resulting in greater RFD. Additionally, various training methods may impact adaptations in different tendons of the lower limb, such as the patellar and Achilles tendons, which can affect running or sprinting performance [221]. To make the most of the dynamic correspondence aspect, coaches need to understand how to scale the training process for long-term adaptations that support better results when transitioning to similar force production [212].

2.3.7.5 Dynamic correspondence: The principle regime of muscular work

The type of muscle movement depends on the type of muscle work, which can be categorised as eccentric, concentric, or isometric (task-specific strength in regard to the sport). SSC activities, which may or may not involve rhythmic, cyclical activity, are also part of the muscle work. In sports, the normal nature of athletic activities is only considered when taking into account the SSC, as concentric, isometric, and eccentric muscle action are rarely seen alone [212]. As a result of different type of strength training modalities, the use of concentric and eccentric actions can induce different changes.

There are unique factors and possible consequences that affect subsequent adaptation between concentric and eccentric actions [222]. For instance, eccentric contractions have been found to be more mechanically efficient and dissipate energy better than concentric contractions [205,223]. In addition, differences in structural adaptations have been observed between these two types of contractions. Muscle hypertrophy, which is linked to performance outcomes, seems to vary depending on the type of contraction. Eccentric training appears to have a greater impact on the distal portion of the muscle, while concentric training appears to affect the muscle belly more [224]. Moreover, eccentric training leads to longer fascicle length, while concentric training is more associated with increases in pennation angle and cross-sectional area [224,225]. These morphological changes can influence physical capabilities and should be taken into consideration when coaches design training programs. When considered separately, it seems that concentric actions are more sensitive to the specificity of kinetic and kinematic properties of contraction [222]. However, eccentric training has a broader effect on a range of force outputs and velocities, suggesting that differing adaptations occur between concentric and eccentric actions [226]. This situation is unique when considering SSC and complex athletic actions, and coaches should carefully consider the mechanisms involved in each type of contraction separately and in combination. Although most studies support sequential motor unit recruitment [227,228], there is evidence that eccentric actions can violate the size principle [228].

This means that while there may be clear and predictable activation patterns for concentric actions, something different may be happening eccentrically. When athletes perform both eccentric and concentric actions together, it can result in a complex sequence of neural control strategies [226]. This is further complicated by the fact that motor units involved in eccentric contraction have differing discharge rates and activation thresholds compared to those involved in concentric contraction [229].

2.3.8 Force-vector theory

The force-vector theory has also been proposed to guide coaches and researchers in selecting the most appropriate exercises and drills for improving each specific phase of sprinting similar to the principle of specificity. According to this theory, sports skills can be classified based on the direction of force expression relative to the global (world fixed) coordinate frame [230]. In this case sprint acceleration can be considered a horizontal activity, whereas maximum speed running is a more vertical activity, although it still has a horizontal component that facilities forward movement. Similarly, resistance training exercises would also be classified as horizontal or vertical on the same basis. The force-vector theory suggests that resistance exercises that target horizontal force development are more specific to horizontal skill performance, and exercises that target vertical force development are more specific to vertical skill performance [230]. In the literature there are two differing opinions about this theory. Loturco, Contreras, Kobal, Fernandes, Moura, Siqueira, Winckler, Suchomel and Pereira [109] claim that "*the force-vector theory is an emergent methodological approach, based on a solid and well-established mechanical foundation*". Fitzpatrick, Cimadoro and Cleather [230], on the other hand, contends that this idea really runs counter to the principle of dynamic correspondence, which is the most widely accepted measure of mechanical specificity employed in strength and conditioning [30]. As previously mentioned, the forces acting on or expressed by the athlete should be taken into consideration relative to the local coordinate system of the athlete, not the global frame. For instance, the GRF stated relative to the athlete are identical during acceleration and high-speed running. During acceleration, the force exerted in the horizontal direction in relation to the global frame is more powerful compared to when running at high speeds [128,129]. However, the explanation for this is that the athlete leans forward to exert more force in a horizontal direction (Figure 11). For example, Kugler and Janshen [134] discovered that there was a good correlation (r = 0.93) between the orientations of the GRF and the body at TO, indicating that the direction of force relative to the athlete is generally the same. The GRF is projected in a similar manner in both horizontal and vertical jumping; however, because the athlete leans forward more in horizontal jumping, the GRF is projected more horizontally in relation to the global frame [230]. Although the direction of the GRF relative to the athlete may differ greatly from that relative to the global frame, the criteria of DC are sometimes used to support the claim that an action like back squats is mechanically similar to an activity like acceleration or horizontal jumping [230]. This is so that the athlete's ability to convey force can be determined by the direction of force in relation to them. Therefore, the force-vector theory clearly contradicts the claim that squatting is less mechanically similar because of the different GRF orientation with respect to the global frame. Fitzpatrick, Cimadoro and Cleather [230], have stated that it is a common mistake to consider the direction of the GRFs in relation to the global frame. They argue that this misinterpretation arises from the fact that comparing two vectors in different coordinate frames that are rotated relative to each other is not a valid method. Therefore, it is incorrect to assume that the direction of two vectors is similar when evaluated in different coordinate systems.

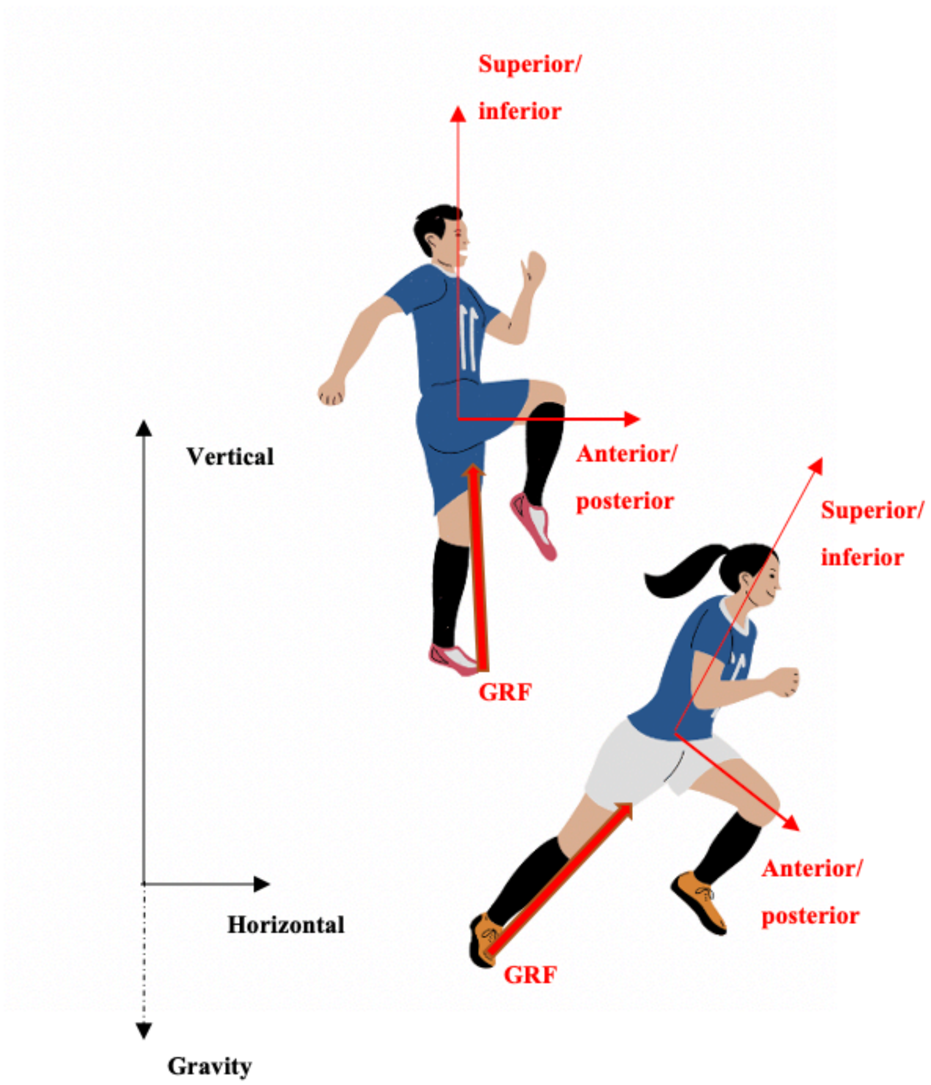

Figure 11 Relationship between global (world fixed—black axes) and local (athlete fixed—red axes) coordinate frames.

Note that: The athlete on the top experiences horizontal and vertical ground reaction forces relative to the global frame, as does the athlete on the bottom, who is rotated vertically. (A) An athlete accelerating experiences a ground reaction force (dark grey arrow) which has substantial horizontal and vertical components relative to the global frame. (B) If the athlete is rotated such that the local and global frames are aligned, it is apparent that the direction of the ground reaction force relative to the athlete is largely vertical [230].

This theory becomes interesting when trying to evaluate exercises like the hip thrust and if there are physical skills for which it might be an effective training tool. The effects of the hip thrust can range from an increase in gluteus maximus and hamstring size to an increase in strength and power [231], therefore research suggests the hip thrust results in training effects that are different to traditional approaches (i.e. squats) [231,232]. Contreras, Vigotsky, Schoenfeld, Beardsley, McMaster, Reyneke and Cronin [231] directly compared the squat and hip thrust in adolescent athletes and identified several important differences. The hip thrust was 'potentially more beneficial' than the squat for short sprint (0–20 m) speed, while the squat was superior for vertical, but not horizontal, jumping. Moreover, it has been demonstrated that the hip thrust activates more glute and hamstring muscles than the back squat [233]. Contreras, Vigotsky, Schoenfeld, Beardsley, McMaster, Reyneke and Cronin [231] refer to the force-vector theory to explain some of the differences found. Those who support the force-vector theory classify exercises inconsistently and demonstrate a fundamental misunderstanding of the mechanics [230]. Because the GRF is directed horizontally relative to the athlete, the hip thrust, for example, is categorised as a horizontal exercise (note that this is often described as acting antero-posteriorly; that is, using language that describes directions relative to the athlete). However, as previously mentioned, proponents of the force-vector theory take the direction of the GRF in relation to the global frame into account and would therefore consider the hip thrust an exercise that develops the capacity for vertical force production. The method by which a particular exercise is more specific is unclear, which is a last issue with the force-vector idea Fitzpatrick, Cimadoro and Cleather [230] raises. When considering the claim that "horizontal" exercises can improve an athlete's ability to direct force horizontally in relation to the global frame, how is this achieved without simply changing the athlete's orientation to the global frame? How can performing a hip thrust exercise with the knee bent at 90 degrees enhance an athlete's ability to control the GRF during closed kinetic chain leg extension, especially since this position is vastly different from the one used in their sport. It has been suggested that the force-vector theory and the mechanism behind the specificity of certain exercises is unclear, and instead alternative explanations have been proposed for the results seen in previous studies, in line with the principle of DC [230]. For instance, Bezodis*, et al.* [234],Bezodis*, et al.* [235] have demonstrated that, in contrast to the back squat, the amount of hip extensor moment necessary to accomplish a hip thrust increases as the hip nears full extension. Thus, in order to express force in the hip thrust, one must use a different range of motion than in the back squat. An exercise can be considered more mechanically specific when the force it generates aligns with the range of motion involved in the corresponding athletic skill, as determined by DC - the region of accentuated force generation. Research conducted by Bezodis, North and Razavet [234],Bezodis, Brazil, Palmer and Needham [235], suggests that the hip thrust exercise may exhibit a higher degree of specialisation for activities requiring significant force expression when the hip joint is near full extension. This is particularly relevant to movements like sprinting, which involve the triple extension of the hip, knee, and ankle joints. In the context of selecting resistance exercises for athletic training, it becomes crucial to identify how different exercises offer optimal transfer to enhance sport-specific performance. Considering the principle of specificity, there is a compelling rationale for including both the back squat and the hip thrust in exercise regimens. These exercises can be chosen based on their alignment with the specific force production requirements demanded by different aspects of athletic performance. This finding regarding the mechanical specificity of exercises like the back squat and hip thrust makes them a promising choice for correlation and predictive use in assessing changes in sprinting kinematics. Coaches and researchers can leverage these exercises, which closely replicate sprinting (force) patterns, to assess how an athlete's strength and performance in them may impact sprinting mechanics. This can facilitate the development of more precise training programs to enhance sprinting performance, rendering these exercises valuable for both assessment and prediction in sprinting kinematics.

To give a few more examples of exercises that relate to sprinting:

The good morning - peak force occurs in lengthened position when hips are at roughly 90 degrees [236]. This exercise has potential to transfer accelerating the leg towards the ground.

The horizontal hip extension - peak force occurs in shortened position when hips are fully extended [216]. This exercise has potential to increase force development when the foot hits the ground.

The 45° hip extension - peak force occurs half way between flexion and extension at a point when muscle is at mid length (during concentric and eccentric action) [237]. This exercise may transfer to acceleration mechanic when the body is in a similar position.

Previously it has been demonstrated that sprint and jump performances are correlated and jumping tests can predict sprint performance [41,165,176]. Therefore, In the following paragraph I will be focusing on different VJs, back squat and hip thrust, as a way of improving sprint performance.

2.3.8.1 Lower body strength & sprint performance

Field-based invasion team sport athletes are said to have high levels of muscular strength as a requirement for dealing with the intense neuromuscular demands of competitions [238,239]. For example, soccer players, must have enough muscular strength for speed development to evade opponents, perform high-intensity agility movements and change pace and/or direction [240]. Most resistance training programs will include squats to improve lower body strength, whether it is for male or female sprinters or field-based invasion team sport athletes

[24,25,29,176,184,232,241-245]. Traditionally, external load is applied while performing eccentric and concentric muscular motions across the whole range of motion [246].

Squats: Squatting primarily involves extension of the knee hip and ankle, which is a common pattern that contributes to performance in sprinting [173,247]. Several studies have analysed the relationships between maximum strength and sprint or jump performance [81,176,231,242,248-252], utilising various methods including back squat, deadlift, and hip thrust, with correlations ranging from r = 0.39 to r = 0.94 for 10m and r = 0.60 to r = 0.71 for 30/40 m/40 yard sprint time [81,184,249,253]. The high correlation reported between 1RM and sprint times (r = 0.94–0.71, p ≤ 0.01–0.001) by Wisløff, Castagna, Helgerud, Jones and Hoff [253] contrasts with other research that found moderate or non-existent relationships [107]. A 12-week resistance training program that involved back squats was used to enhance sprinting performance in rugby players [251]. The program resulted in improvements in 10 and 20 m sprint times that were comparable to those observed in a prior study on resistance training in adolescent athletes (1.1–6.2%) [250]. The improvements ranged from 1.6-2.5% for the 10m sprint and 0.5-1.7% for the 20 m sprint [251]. Moreover, McBride, Blow, Kirby, Haines, Dayne and Triplett [249] found a difference between weak and strong athletes. The stronger athletes – in squats - performed better sprint times in 10 and 40 yard compared to the weaker group. The ability to generate force, particularly through squats, can make the difference between weak and strong athletes in terms of sprint times. This refers back to what has been discussed about FV-characteristics. It may be that in scenarios where maximum strength training is effective the athletes have a force deficit and when not effective a velocity deficit.

Hip thrust: The barbell hip thrust is a weighted bridging exercise that is used to target the hip extension muscles, including the glutes and hamstrings [216]. The gluteal muscles help in pelvic control, hip external rotation, and hip extension [166]. It has been suggested that having hip extension is essential for enhancing lateral mobility, jumping, and sprinting speed [216,254,255]. Zweifel [256] and Contreras, Vigotsky, Schoenfeld, Beardsley, McMaster, Reyneke and Cronin [231] demonstrated that the hip thrust improved 10 m (- 1%) and 40 m (- 2%) sprint performance more effectively than a front and back squat. This might be due to the fact that the hip thrust is effective for sports that require horizontal force production because it is performed in a way that aligns with the body's force vectors [231] (Figure 12). Sprinting is a sport that relies heavily on horizontal force, speed, and impulse, making the hip thrust a valuable exercise for sprinters.

In summary, squats and hip thrusts are important for sprinting and overall athletic performance because they target essential muscle groups, improve explosive strength, replicate sprinting movements, enhance horizontal force production, and offer versatility in training. Incorporating these exercises into a well-rounded training regimen can contribute to improved sprinting performance.

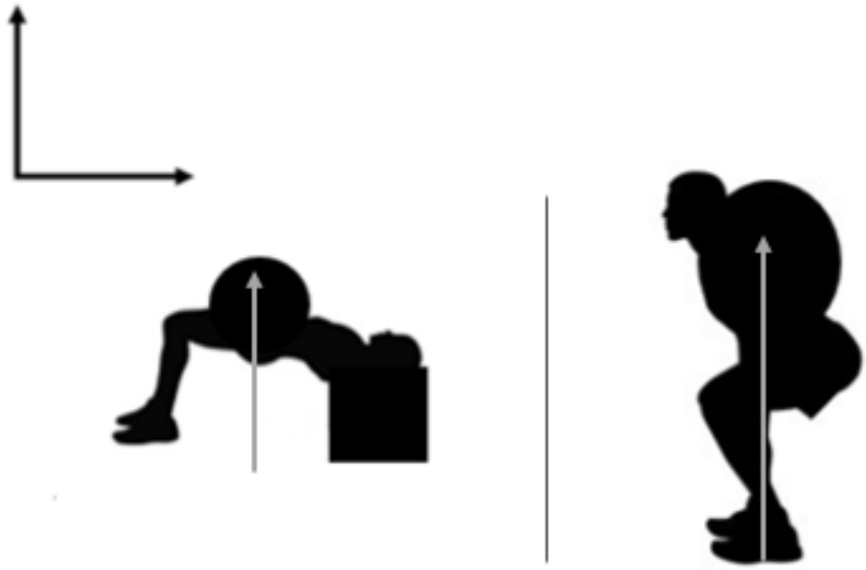

Figure 12 Typical postures during the barbell hip thrust and back squat.

Taken together, these findings suggest that muscular strength and improving strength in athletes with a deficit can improve sprint times in both track and field and field-based invasion team sports [176,184,257,258] and it has the capacity to improve power [259].

2.3.8.2 Lower body power and sprint performance

Jump performance has been associated with SP [109,164,258,260-262], which supports the theory that the ability to produce lower body power can influence sprint performance [176,253,263,264]. It has been widely reported that the CMJ and DJ are effective tools for detecting changes in performance during training [265]. They are often used as exercise and monitoring tools to assess neuromuscular adaptations resulting from acute and chronic training. Additionally, they have been used to evaluate an athlete's sprinting ability [261,262,266] and predict their performance [40,258,263,267]. Research has shown that there is a relationship between sprint performance and certain characteristics of vertical jumps, such as peak and mean power, force, and jump height [160].

Multiple studies demonstrate that increases in muscular power output have resulted in improvements in speed for field-based invasion team sport athletes [22,164,252,268-270]. In a study by López-Segovia, Dellal, Chamari and González-Badillo [268] disparities were observed between the athletes who generated the highest and lowest levels of power. Specifically, the athletes with greater power output achieved faster sprint times in comparison to those with lower power output. This study also reported a significant correlation ($r = -0.70$) between squats and 20 m sprint performance and less significant correlations ($r = -0.57$) with 10 m sprint performance. Another study showed significant correlations between sprint times and peak power in a loaded countermovement jump, and between the loaded countermovement jump and split times from 10 to 30 m sprint ($r = -0.56/-0.79$; $p \leq$

0.01/0.01) [270]. The results suggest that power produced with vertical jump is an important factor to explain sprint performance.

In summary, the choice of these exercises, (CMJ and DJ), is based on their established associations with sprint performance, particularly their ability to assess lower body power. These exercises have a track record of effectively detecting changes in performance during training, making them valuable tools for monitoring neuromuscular adaptations resulting from both acute and chronic training. Additionally, they have been used to evaluate an athlete's sprinting ability and predict their performance. Remarkably, these exercises have proven valuable not only for training but also for assessing and predicting their relationship with sprint performance.

2.3.9 **Optimal loading**

For coaches, determining “optimal” loading is useful for training implementation, comparative analysis and performance monitoring. It is recommended by Kawamori, *et al.* [271] that the optimal loads for each multi-joint exercise are determined based on an individual and exercise by exercise basis.

There is a large discrepancy in the optimal load reported for maximising power output in multi-joint exercises ranging from zero to 80% of 1RM. The highest mechanical power tends to be attained at higher percentages of 1RM in multi-joint movements compared to single joint exercises [196,271]. Using an athlete’s previous maximal ability to prescribe training loads can be problematic if the athlete’s 1RM changes as a consequence of training because the prescribed load may not match the % of 1RM intended for the particular training session [272]. A modern approach to resistance training called velocity-based training offers precise and objective prescription of resistance training intensities and volumes [272]. Using 3-5 data sets, a profile provides a more comprehensive understanding of an athlete's skill on a given exercise than a single 1RM back squat, which only evaluates an athlete's capacity to squat against maximal loads, or a single unresisted timed sprint at maximum velocity.

Load-Velocity Profiling: should be defined as a method that uses velocity to inform or enhance training practice. The use of velocity-based testing can be a helpful method for coaches to quickly assess an athlete's level of fitness and fatigue. This is especially useful when lifting a consistent weight, as changes in peak or average concentric velocities can indicate changes in the athlete's neuromuscular abilities [273]. Slower velocities may be a sign of tiredness, overexertion, or lack of training, while faster velocities could indicate improvements in neuromuscular capabilities or short-term performance enhancement [274]. It has been acknowledged in the past that giving athletes feedback during their training can increase their velocity and power outputs by up to 10% [273,275,276]. Additionally, when athletes of similar ability or position train together and observe each other's movements, it can lead to greater competition due to their competitive nature. Nevertheless, it's important to consider the intended goal of the exercise, as providing feedback may sometimes motivate athletes to prioritise speed over proper technique [272].

In the past load-velocity profiling also has been used to create individual profiles for athletes to estimate maximum power output. Figure 13 shows a load-velocity profile graph for a resisted sprint, with linear regression equation and R^2 value. Cross, Lahti, Brown, Chedati, Jimenez-Reyes, Samozino, Eriksrud and Morin [50] aimed to compare the effects on sprint performance and mechanical outputs of a resisted sprint training program centred on the individual Lopt for Pmax versus a control, lighter load associated with a decrement of 10% in maximal running velocity (L10). The athletes were individually assessed for horizontal force-velocity and load-velocity profiles using a battery of resisted sprints. A span of loading parameters was selected to provide a wide array of data for each athlete and to enable the accurate plotting of load-velocity relationships.

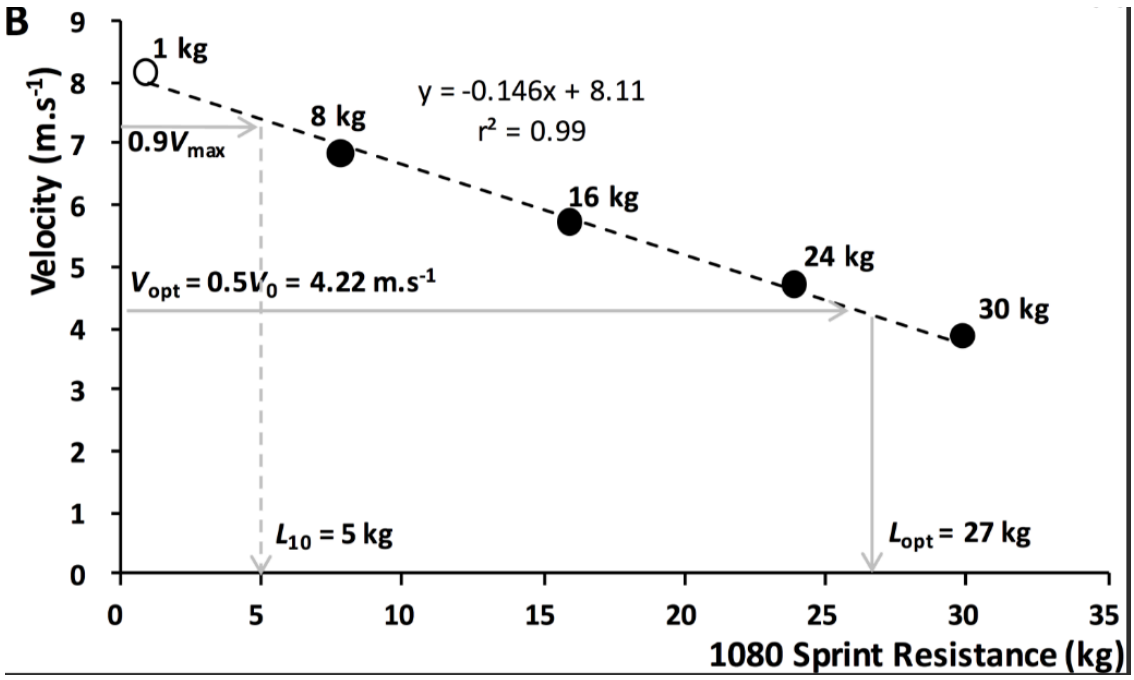

Figure 13 Illustration of computation of individual loading parameters from multiple resisted sprints combined into a load-velocity relationship.

Note that: Maximal velocity was averaged for the last 2 s of each sprint and plotted against load to obtain the linear load-velocity profile, from which optimal load (Lopt) and the load that induced a 10% decrease in maximal velocity (L10) were computed [50]. This illustration was taken from [50].

2.3.10 **Summary**

Different approaches have been implemented to increase speed, such as resistance training to increase strength. Some limitations appear to be based largely upon issues surrounding the mechanical specificity of resistance training exercises relative to the sprinting stride [277]. For example, high sprinting speeds require short CTs and many resistance training exercises require the application of force for durations in excess of those associated with sprinting. Moreover, another limitation of resistance training exercises is that they promote the application of large vertical forces through the acceleration of large external masses (i.e. back squat) and do not involve a mechanism whereby the leg is "punched" into the ground (the leg and the COM have largely the same vertical velocity at TD on contrast to the different velocities observed as part of the impact-limb deceleration mechanism when sprinting). The attainment of large vertical forces via the impact-limb deceleration mechanism appears to be a biomechanical solution to overcome the limitation associated with the inability of the stance leg extensor muscles to generate sufficient force during the brief ground contact phases associated with maximal sprinting speeds [277]. Therefore, incorporating specific sprint training along with other methods can improve speed and athletic performance. Training specificity aims to promote adaptations that directly benefit the sport. Specific sprint speed programs commonly used by strength coaches are overload or resisted training. Resisted sprints will be discussed in the following section.

2.4 RESISTED SPRINTS TO ENHANCE SPEED CAPABILITY

2.4.1 Prelude

With the objective of obtaining greater levels of specificity to enhance SP, resisted sprinting is commonly used [278]. The purpose of the following narrative review is to inform practitioners and researchers on the effectiveness of resisted sprint training (RST), loading parameters used, the methods of load prescription, and how these factors influence kinematics both acutely and following intervention periods. This review identifies the gaps and limitations in the literature, which sets the foundation and guides the research within this thesis. The following section is divided in acute studies and longitudinal/ intervention-based studies.

2.4.2 Overview

Resisted sprint methods involve sprinting against a force provided either by a sled that is towed, a pulley system, a weighted vest, a parachute, or sprinting up a hill [54]. The most commonly used and researched training method is resisted sled sprinting (Figure 14) [54]. RST protocols have become popular training regimes to improve sprint performance [32,33,36,73,143,279-286]. Although RST may provide movement similarity, it is unclear how factors like loading or population influence this, or how RST meets the other DC and specificity criteria mentioned above. The following discussion will examine RST through the lens of the previously outlined specificity criteria. However, before discussing these aspects it is important to review the literature on the effectiveness of RST as a performance enhancing training tool.

Figure 14 Sled sprinting

2.4.2.1 Overview over resisted sprint studies

To the authors knowledge four studies have examined the acute effects of RST on sprint performance, two studies investigating the influence of strength parameters on SP and 19 studies investigating the longitudinal effect of RST (Table 8; Table 9; Table 5). Interventions ranged from 4 to 10 weeks with loads ranging from 5 to 100%BM and 10 to 60%Vdec. The majority of research focuses on the acceleration phase [1,34,36,53,115,141,183,280,285,287-292] and only a few studies assess the effect on maximum velocity running [20,278,292,293].

Several systematic reviews (Table 10) have indicated that RST has shown positive effects on SP across various loading conditions (5–80%BM). In particular, it seems that RST improves acceleration significantly ($p = 0.0001$; effect size (ES) 0.61) [4,32]. However, it should be noted that not all reviews found a positive effect on maximum velocity performance ($p = 0.25$; ES 0.27). [32]. According to Petrakos, Morin and Egan [4] acceleration and maximum velocity adaptation depends on the weight of the sled. In their review light to moderate loading (<20%BM) increased the maximal velocity phase due to relatively lower horizontal force and higher velocity characteristics, but heavier-type sled load training improved the initial acceleration phase where strong horizontal forces are necessary. It was recommended that the RSS load be determined by the training objective (acceleration or maximal velocity), whether the athletes were in a strength/power phase, and/or the specific force-velocity demands of each athlete. Petrakos, Morin and Egan [4]'s overall guideline was that effective sled sprint training blocks should consist of 2-3 sessions per week of 5-35 m sprints, with a total distance of 60-340 m per session. This is similar to what was recommended by Alcaraz, Carlos-Vivas, Oponjuru and Martínez-Rodríguez [32] - a training frequency of 2–3 times per week, a volume of >160 m per session, and approximately 2680 m per week, for at least 6 weeks.

2.4.3 Different loading parameters and methods

The most cited method to prescribe load for resisted sprinting is percentage body mass (Table 4) [34,140-142,278,294-297]. However, working at a given %BM has many limitations [54]. With one major limitation being that it does not equate to the same loading zones for different people, (i.e. 50%BM for one person will cause a much larger Vdec than 50%BM for another). Furthermore, it does not account for the effects of changing friction coefficients and for force, power or sprint speed characteristics [54]. Thus, it is unlikely to provide a targeted or uniform training stimulus across athletes. Alternatively, a method that has been suggested by Cross, *et al.* [298] considers the linear relationship between load and decrement in maximal velocity. A load is prescribed in order to cause a reduction in maximum velocity relative to unresisted sprinting [33,280,281,284]. The Vdec approach is seen as a more appropriate way to prescribe loads in comparison to %BM, because findings from studies can be generalised to practice regardless of sled or changes in friction [299]. This method has been assessed through multiple and single sprint trial methods of sled load prescription with both methods proving to be effective in calculating the load that optimises power during RSS [37,300]. The recommendation by Cross, *et al.* [301] is it to use a combination of multiple-trial and single-trial methods. This study also demonstrated that a Vdec of 50% maximises power output during RSS and suggests athletes should train with loads that cause this reduction in velocity if the goal is to maximise power to improve sprint performance. While the load that optimises power output during RSS has been established for track and field and mixed code recreational athletes, other optimisation strategies are potentially interesting to achieve different training goals. Cross, Brughelli, Samozino, Brown and Morin [37] suggested different percentages of Vdec may represent training zones for either more speed or force orientated training. Early research on RST has reported that light load provides a stimulus while allow athletes to maintain kinematic characteristics similar to unloaded sprinting [149,280,302], and heavy load provides a different stimulus, by overloading force producing capabilities of the athletes [51]. These heavy loads alter the orientation of the force vector, requiring increased horizontal force that may transfer to free sprinting [51,54,298]. Instead of being thought of as a technical sprint exercise, RST under heavy loads should be considered as exercise to develop horizontal force generation through overload [207].

Table 4 Summary of the methods used to prescribe sled training loads to develop SP

Methods	Main characteristics	Limitations
Absolute (kg)	Simple to prescribe since it does not account for variability in athletes' performance (i.e., velocity and force production) and characteristics (i.e., BM, body composition, and anthropometrics).	The same absolute load applied for 2 athletes may provoke different adaptations, while also reducing sprint velocity (%) in a distinct manner. *Example: 3 × 20 m (15 kg)*
Relative (%BM)	Easy to use because, as it only considers athletes' BM, it simply requires weighing the athlete. It does not account for variability in athletes' performance (i.e., velocity and force production) and characteristics (i.e., body composition and anthropometrics).	The same relative load applied for 2 athletes of similar BM may lead to different adaptations and result in different reductions in sprint velocity (%). *Example: 3 × 20 m (15% BM)* *Loads used: from low (5% BM) to very heavy (>80% BM)*
Velocity decrement (%)	It considers the velocity loss of the athletes provoked by the applied load. Takes into account athletes' performance (i.e., velocity and force production) and characteristics (i.e., body composition and anthropometrics). It can be considered a more individualized approach.	It involves a thorough velocity loss assessment through an incremental loading sprint test (e.g., from 0% BM to 80% BM), which makes it hard to implement. Moreover, it requires expensive (e.g., timing gates, radar guns, laser, etc.) or time consuming (e.g., mobile apps and video analysis) technology. *Example: 3 × 20 m (15% V_{dec})* *Loads used: low (5% V_{dec}) to very heavy (> 50% V_{dec})*
Maximum resisted sled load test (MRSLT, %)	It provides a maximum load (100%) to be used by the athlete as a reference to prescribe sled training load; thus, it considers athletes' performance (i.e., velocity and force production) and characteristics (i.e., body composition and anthropometrics). It can be considered a more individualized approach.	It requires an extensive sprint assessment through an incremental loading sprint test following a strict protocol (e.g., from 15% BM until a load with which velocity at the 10–15 m interval is lower than 15–20 m). It is laborious to implement and requires expensive (e.g., timing gates, radar guns, laser, etc.) or time consuming (e.g., mobile apps and video-analysis) technology. *Example: 3 × 20 m (40% MRSLT).*

Note that this table is amended from Zabaloy, *et al.* [303]

Studies published before 2015 utilised lighter loads (<35%BM) assessing kinematic variables that found reductions in velocity SL, SF, FT, increases in CT, and changes in angular kinematics at different loads. Research previously recommended loading should not extend beyond approximately 13%BM or 10%Vdec to optimise the maintenance of kinematics while providing a resistive stimulus [149,280,302]. More recently, it has been suggested by Cahill, Cronin, Oliver, Clark, Lloyd and Cross [207], that prescribing a Vdec <10, <35% <50 or >65% may target high-speed (technical), speed–strength, power and strength–speed qualities which may provide important utility depending on where athletes display deficits. However, the topic of optimal load to improve sprint performance has multiple layers. For load prescription, it is also important for practitioners to understand the extent to which RST can impact kinematics for different sprint phases across different athletic populations, yet still improve SP. Although it is acknowledged that RST to be an effective training modality for improving SP, to date there still remains a lack of clarity around how loading acutely influences kinematics both during and following RST interventions [4,304,305].

2.4.4 RST modalities

RST encompasses various modalities designed to enhance sprinting performance [54,279,280,293,306-312]. Sleds, parachutes, weighted vest or mechanical systems are commonly used [4,32,284]. These devices are used to provide an external overload onto an athlete in an attempt to enhance their physical output and efficiency, while closely mimicking the movement of a sprint [4,312]. As mentioned previously, many devices have been shown to be valid and reliable [298,313] but practical issues with using these devices have been highlighted (i.e., transport, weight, friction or high costs) [314].

Sleds, when attached to an athlete via a harness, increase ground friction, demanding greater force output during sprints [314]. Moreover, the practicality of sleds can be influenced by factors like the size and weight of the sled and the space required for training. Sleds can be heavy and bulky, especially when loaded with weights. This can make them challenging to transport to the training location, particularly if athletes need to carry them to the track or field. It might require additional equipment, such as a cart or dolly, to transport heavy sleds efficiently. Parachutes, on the other hand, add air resistance [278]. An increasing number of coaches have employed isotonic sprint devices to provide an external resistance while sprinting, as these avoid these limitations. One notable isotonic device employed in RST is the Exer-Genie, a versatile device. The Exer-Genie provides resistance through a cord, offering a customisable method of adding resistance to sprinting [315].

2.4.5 **Reliability**

Reliability in RST is a pivotal consideration to ensure accurate and consistent training stimulus. Several studies have investigated the reliability of various RST devices and protocols, shedding light on the precision and reproducibility of measurements [37,316-319].

A study conducted by Cross [320], investigated friction and effective loading for sled sprinting, addressing a key concern in RST. Mean force data were analysed, with five trials performed for each condition to assess the reliability of measures. Variables were determined as reliable (ICC > 0.99, CV < 4.3%).

Similarly, the work of Pantoja, Carvalho, Ribas and Peyré-Tartaruga [319] focused on the effectiveness, power, and the force-velocity relationship during weighted sled towing, highlighting the significance of meticulous measurement by demonstrating reliable variables (ICC = 0.87–0.94). Moreover, Godwin, Matthews, Stanhope and Richards [316] made a notable contribution to this area by assessing the intrasession and intersession reliability of the Run RocketTM device for short sprint distances (5 and 15 m) under two mechanically braked resistance levels (R0 and R5). Their results demonstrated that the Run RocketTM displayed robust reliability, approaching nearly perfect levels within a single session and between sessions for each resistance level and sprint distance. The coefficient of variation (%CV) ranged from 2.4% to 5.8% across all trials, suggesting high levels of consistency. The intraclass correlation coefficient (ICC) values for both resistance levels and distances were very large and nearly perfect, ranging from 0.79 to 0.98. These findings underscored the Run RocketTM device's reliability, especially in recreationally trained participants. In addition to the Run RocketTM device, the 1080 Sprint device's reliability was investigated by Rakovic, Paulsen, Helland, Haugen and Eriksrud [317]. This study focused on within-session reliability and criterion validity for the 1080 Sprint device. The %CV for different sprint phases ranged from 0.82% to 2.56%, with standard error of measurement (SEM) values between 0.01 and 0.05. The ICC values were consistently high, ranging from

0.86 to 0.95. However, it's worth noting that biases were observed for specific sprint phases (t0-5 m and t0-30 m) when compared to post-processing timing gates. The biases were systematic, allowing for correction factors to be applied to ensure valid computations of sprint mechanical outputs. The Maximum Resisted Sled Load (MRSL) test is an innovative approach to determine the maximal sled load an athlete can handle while maintaining acceleration in a 20 metre sprint. Petrakos, *et al.* [321] sought to establish the reliability of the MRSL test. The results demonstrated that the MRSL test exhibited high reliability, with an ICC value of 0.95. This suggests that the test consistently provided similar results when repeated, indicating its stability and reproducibility. Furthermore, the within-subject variation, as indicated by the CV, was found to be 7.6%, which is relatively low, further emphasising the test's reliability. This high level of reliability is crucial for any performance test, as it ensures that the measurements taken with the MRSL test are consistent and dependable.

The aforementioned studies significantly contribute to the understanding of the reliability of these devices and tests in RST scenarios. Such findings are pivotal for coaches, athletes, and researchers, as they enable a more accurate and reproducible training stimulus and inform training protocols in sports and athletic development. This body of research reflects the ongoing efforts to standardise RST assessment procedures, enhancing the quality and reliability of data in this essential field.

2.4.6 Variables that impact kinematic characteristics

The assessment of physical capabilities during resisted sprints involves considering a range of variables, from the type and amount of resistance to the athlete's training background and sprinting conditions. These variables collectively impact kinematic characteristics, providing valuable insights into an athlete's performance and training needs. Some key variables that will be considered in this research include:

Load: The amount of resistance applied to the sprinter significantly impacts kinematic characteristics. Heavier loads can alter sprinting mechanics, for example affecting stride length, frequency, and posture. Heavier sled loads can lead to a decrease in stride length and frequency. Athletes must exert more force to move the sled, which can result in shorter, steps as they try to maintain their sprinting speed [149,280]. Moreover, athletes may lean forward more to counteract the resistance, leading also to changes in hip, knee, and ankle angles during the different phases of sprinting [284]. Finally, sprinting with heavier loads may prolong ground contact time during each step. Athletes may spend more time pushing against the ground to generate the force needed to overcome the resistance [328].

Training Status: Athletes with varying training backgrounds may respond differently to resisted sprinting. Elite sprinters and team sport athletes or very well trained athletes might maintain form better under resistance due to superior neuromuscular control, strength and power [246,322].

Sprint Phase: Kinematic changes can vary throughout different phases of the sprint, including acceleration and maximal velocity phases [32,99]. Athletes may adapt their technique to overcome resistance differently at different points in the sprint.

Type: Different types of resistance, such as sleds or parachutes, can influence kinematics differently. For instance, a sled primarily increases friction with the ground, impacting ground contact times (increase) and stride frequency (decrease) [54].

Sprint Distance: The length of the sprint can affect kinematics. Short-distance sprints may not exhibit significant changes in technique, while longer resisted sprints may lead to greater changes in technique as fatigue sets in [207].

Surface Conditions: The type of surface on which the sprint is performed can impact kinematic variables. Athletes may adapt their technique differently on a track, grass, or sand [32].

Recovery Time: The duration of recovery between resisted sprinting bouts can impact kinematics [280]. Fatigue may accumulate over multiple repetitions, altering technique [323].

2.4.7 Acute Studies

Researchers have examined the kinematics and kinetics of RST in some detail and consistently report reductions in flight time, step length and step frequency and increase in contact time as load increases. This is associated with an increase in trunk lean, greater hip and knee flexion as well as ankle dorsiflexion [1,2,36,54,149,278,282,284,288,304,324,325]. An overview of acute studies can be found in Table 7.

Kinematics: For example, loading (10–40%BM) results in decreased SL, swing phase duration, SF, FT, but increased CT, and trunk lean (the angle between the trunk and the vertical axis during sprint) [284] relative to unresisted sprinting. A greater reduction in SL as opposed to SF with increasing load has been reported [149,282,326], indicating that SL is compromised to a greater extent by RSS.

Cronin, Hansen, Kawamori and McNair [282] reported that sprint time increases in response to load (15%BM, 20%BM), with an increase of 7.5 to 19.8% resulting mainly from the decreased SL (from -5.2 to -16.5%) with small decreases in SF (from -2.7 to -6.1%). Findings of research on angular kinematics show an increase in hip flexion and trunk lean at TD compared to unresisted sprinting (9%BM to 32.2%BM), [1,115,149,278]. Also, the shank tends to be less upright at TD, facilitating a slightly shorter landing distance [278]. Leaning the body forward and shifting the athlete's COM forward can lead to a more efficient foot strike and reduce braking forces during running [282,327]. This position can be trained during RST.

The majority of the aforementioned studies have examined lighter RST loads (<40%BM, 30%Vdec), and more recent research has examined the effect of heavier loads (50 and 60%Vdec). Spatiotemporal variables changed significantly under these heavier load conditions, with increased contact time (60%Vdec: $p = 0.003$, $d = 2.10$), step frequency ($p = 0.004$, $d = -1.90$), and step length ($p=0.008$: $d = -1.58$). Touch down distance (60%Vdec: $p=0.003$, $d = 1.99$; 50%Vdec: $p=0.003$, $d = 3.50$) and COM angle at touchdown decreased (60%Vdec: $p=0.005$, $d = -2.30$, 50%Vdec: $p=0.005$, $d = -3.00$). The increase in trunk angle (forward lean) for heavier loading has shown to lead to an increase in horizontal force application and may have significant benefits for improving short-distance sprint performance, specifically the acceleration phase [36,51,328]. Additionally, the greater trunk lean may help decrease the braking forces associated with landing during acceleration [134,282]. Therefore, heavier loads may cause athletes to sequentially apply force in a position which better reflects the mechanical demands of the early acceleration phase, especially when considering the kinematics and dynamics of the first 3 steps.

It remains uncertain whether athletes from various sports, each with their own unique physiological characteristics, exhibit similar kinematics during the completion of RST at varying loads. Limited research has been conducted on multiple joint angles and loads during the acceleration and maximum velocity phase, or on comparing different sporting populations.

2.4.7.1 Differences in RST modalities

A study by Alcaraz, Palao, Elvira and Linthorne [278] provided a comprehensive analysis of the effects of three distinct resisted sprint devices (sled, parachute, and weight belt) on sprint kinematics. The findings of this investigation bear significant implications concerning the principle of specificity in training. All three devices - the weighted sled, parachute, and weight belt - induced a noteworthy reduction in average running velocity when compared to unloaded sprinting. This outcome aligns with the fundamental premise of these devices, which is to impose an overload on the athlete, consequently diminishing their running speed. Moreover, the observed reductions in in running velocity came from reductions to both stride frequency and stride length for all devices [278]. Of note, the study revealed that the three employed devices did not incite significant alterations in joint and segment angles within the upper and lower limbs. However, subtle modifications were detected in the trunk. Specifically, the weighted sled and parachute (similar loads) exhibited a tendency to augment the angle of trunk lean, with only the sled resulting in a statistically significant increase in this regard. This may be due to the variation in the direction of force application among the devices. Devices generating horizontal forces (e.g., sled and parachute) necessitated athletes to counteract these forces by assuming a forward-leaning posture. This was also confirmed by Cronin, Hansen, Kawamori and McNair [282]. The horizontal forces from these devices increased the time taken to perform leg movements during the ground contact phase of the stride, which led to a longer ground contact time and a reduced stride frequency. As a result, the athletes experienced changes in their stride characteristics due to the horizontal resistance. In contrast to horizontal force devices, the weight belt applies a vertical force to athletes. The weight belt's vertical force on the athlete lead to reductions in running speed, stride length, and stride frequency. When subjected to a higher vertical load, the athlete's response involves generating a greater vertical force during the ground contact phase to propel the body upward for the required flight phase of the stride. However, this increase in vertical force would likely come at the cost of a decrease in the athlete's horizontal force, resulting in reduced running speed, stride length, and stride frequency. This reduction would be akin to the impact described earlier regarding the horizontal force from a training device on the athlete. The effect on running technique with the weight belt was characterised only by relatively minimal changes in trunk lean.

Properly distributed weight (front and rear) helped balance the torques around the hips, thereby minimising significant alterations in trunk angle.

In summary, this underscores the importance of specificity in RST [278]. Different devices challenge athletes differently, and coaches should carefully select and monitor devices based on their training objectives and their impact on sprinting technique. For instance, during training sessions targeting the acceleration phase, the utilization of devices such as sleds and parachutes, which apply horizontal forces, results in an augmented angle of trunk lean. This alteration is conducive to the enhancement of horizontal force production [13]. Conversely, when focusing on training for the maximum velocity phase, characterized by the need for substantial vertical force production, the employment of a weight belt, which induces relatively minor adjustments in trunk lean, appears to be a more suitable choice.

2.4.8 **Interventions**

To the authors knowledge, in comparison to acute research on resisted sprint kinematics, only a hand full of intervention studies exist (n=7). Interventions have ranged from 4 to 9 weeks with loads used ranging between 2.5 to 60%BM and only one using a load of 7.5%Vdec (

Table 6). The aforementioned studies clearly demonstrate that load has a significant effect on acute kinematics during both acceleration and maximum velocity running relative to unresisted sprinting. It is important to point out that the length of the interventions are quite short and it is unclear how this may effect sprinting over one or multiple years of training. Longitudinal research also found loads of 50, 60%Vdec; 80%BM to be superior to loads of 5 to 40%Vdec in terms of improving sprint performance over distances ranging from 5 to 30m [20,33,34,51,279,280,284,329].

Sprint performance: An 8-week training protocol (16 sessions of 10x20 m sprints) with 16 male amateur soccer players was conducted with a sled load of 80%BM. Sled load increased maximal horizontal force production and mechanical effectiveness (i.e. more horizontally applied force. In addition, 5 m and 20 m SP improvements were moderate and small. This study highlights the usefulness of very-heavy sled (80%BM) training, which may suggest a value for practical improvement of mechanical effectiveness and maximal horizontal force capabilities in amateur soccer players [51]. However, it is important to mention that these results may not be applied to other sports.

Moreover, a 9-week training protocol was completed with sprint performance and force-velocity profiles compared before and after [284]. Out of the two recruited homogenous soccer teams one was used as a control group continuing training as normal with no systematic acceleration training while the intervention team was matched into two subgroups based on their sprint performance. Subgroup one trained with a resistance that induced a 60%Vdec from maximal velocity and subgroup two used a 50%Vdec. Both groups significantly improved 10–30 m split times ($p<0.05$, d = −1.25; −0.62). Furthermore, the 50%Vdec training group improved significantly more (lower split times) compared to the unresisted sprint training group in 0–10 m split-time ($p<0.05$, d = 1.03) [284]. Lahti, Huuhka, Romero, Bezodis, Morin and Häkkinen [284] concluded that with appropriate coaching, heavy resisted sprint training could be a tool to assist improvements in SP. The control group and the intervention groups were two separate teams with unavoidable differences in their training culture. Consequently, while the initial sprint performance was quite similar, variances in training and recovery methods could have influenced the results. Unfortunately, the researchers were unable to access a high-resolution slow-motion camera, which may have affected the reliability of a few variables. In line with previous studies on resisted sled training, this study utilised a single time point method (toe-off, touchdown). However, a more optimal approach would be to analyse waveforms, such as through the statistical parametric mapping method [284].

Kinematics: Recent research reported no changes in CT and joint kinematics across different phases of the sprint after a 4-week intervention with trained athletes (mostly sprinters, load of 7.5%Vdec) [330] and a 9-week training intervention in field sport athletes (50% and 60%Vdec) [284]. Without translating to unresisted running, the increase in CT in acute studies may show a favourable adaptation by enhancing RFD [284]. However, the literature has only assessed trunk lean, hip angle and spatiotemporal variables of team sport athletes and has yet to examine any other lower body joint angles. More longitudinal research is needed across different populations examining different joint angles with a greater variety of load, to get a clearer picture of a possible transfer effect into unresisted sprinting. Also, as mentioned previously, it is important for practitioners to understand the extent to which RST can impact kinematics for different sprint phases across different athletic populations, yet still improve SP. Do athletes with smaller kinematic differences see a larger transfer effect to SP? Also, the more specificity criteria RST meets with the transfer be greater? Thus, if something has movement and force vector specificity then it is likely to transfer better than something that only satisfies one of these aspects.

Kinetics: Investigations looking into the kinetic effects of a long-term training program used loads greater than 20%BM [33,331] and discovered that employing heavier sled weights (43-80%BM) resulted in a greater reduction in sprint times than using a lesser load (13%BM) or unresisted sprinting. It is interesting to note that Kawamori, Newton, Hori and Nosaka [33] is covered no appreciable variation in horizontal impulses between heavy and light loading groups from pre- to post training. However, the heavy group significantly decreased resultant and vertical impulses at 8 m from pre- to post training and such changes were significantly larger than those in the light group. On the other hand, Morin, Petrakos, Jiménez-Reyes, Brown, Samozino and Cross [331] found that a heavy RSS intervention led to an increase in horizontal force output. This is supported by Cottle, *et al.* [332] and Kawamori, Newton and Nosaka [36], who observed that sled pulls of 30% and 20%BM led to a large acute increase in horizontal impulses and propulsive GRF, in comparison to both unresisted and 10%BM loading, respectively. According to Newtonian mechanics, stronger propulsive impulses are necessary to overcome higher resistance. Longer CT and longer propulsive periods necessitate greater demands on force magnitude, which is essentially what is responsible for the rise in propulsive impulses.

Table 5 Summary of intervention studies in the area of RST performance

Interventions	Type of study / design	Authors	Subjects	Intervention duration		Load		Time / Velocity	Spatiotemporal Characteristics			
(Performance)					Vdec	%BM	total		CT	FT	SL	SF
The effect of resisted sprint training on speed and strength performance in male rugby players	Interv. (RS vs URS)	**Harrison & Bourke 2009**	Rugby, male, n=15, mean age 20.5	6 wks		13 %BM		sig.↑				
The longitudinal effects of resisted sprint training using weighted sleds vs. weighted vests	Interv. (Sled vs Vest)	**Clark et al 2010**	Lacrosse, male, n=20, mean age 19.8	7 wks		10 %BM Sled, 18.5 %BM vest		1.97%↑ URS /0.13%↑ Sled / 1.2%↑ Vest				
Effects of weighted sled towing with heavy versus light load on sprint acceleration ability	Interv. (High vs light load)	**Kawamori et al 2014**	Male, n=21, mean age 22.5	8 wks	10, 30 %Vdec			Heavy + Light sig.↑ for 10M , heavy for 5m				
Comparative effects of in-season full-back squat, resisted sprint training, and plyometric training on explosive performance in U-19 elite soccer players	Interv. (RS vs plyo)	**de Hoyo et al 2016**	u19 Soccer	8 wks								
The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and Australian football players	Interv.(RS vs URS vs control)	**Spinks et al 2007**	Soccer & Rugby, AFL, male, n=30, mean age 21.8	8 wks	10 %BM			sig.↑ 9% 5m, 6% 10m				
The effect of assisted and resisted sprint training on acceleration and velocity in Division IA female soccer athletes	Interv. (Effect of Assisted & RST on Acc & Vmax)	**Upton et al 2011**	Soccer, female, n=27, mean age 19.6	4 wks				Greatest sig.↑ in RST. group (No change in URS group)				
Effects of resisted sprint training on acceleration in professional rugby union players	Interv. (RSS vs URS on acc)	**West et al 2013**	Elite Rugby, male, n=20	6 wks		12.6 %BM		sig.↑ 2.3% / URS ↑for 10m , 2,58/ URS for 30m				

Very-heavy sled training for improving horizontal-force output in soccer players	Interv. (V Heavy Sled for ↑Horiz. Force output)	**Morin et al 2017**	Soccer Amateur, male, n=16	8 wks		80% Based off Vdec pilot data for Pmax		very-heavy sled-resisted sprint training increased maximal horizontal-force production compared with standard unresisted sprint training				
sprint ability in male soccer players	Interv. (Vest vs URS)	**Rey et al 2017**	Soccer Amateur, male, n=19, mean age 23.7	6 wks		18.9% +/- 2.1						
Mixed training methods: effects of combining resisted sprints or plyometrics with optimum power loads on sprint and agility performance in professional soccer ...	RST + Opt. P Load v vertical/horizontal Plyos + OPL- optimum power load	**Loturco et al 2017**	Soccer Elite, male, n=22, mean age 21.9	5 wks		20% / 12.5% / 5%						
Training at maximal power in resisted sprinting: Optimal load determination methodology and pilot results in team sport athletes	Interv. Optimal Power Load v 10% Vdec on performance	**Cross et al 2018**	Soccer & Rugby, male (n= 24) female (n=12), mean age 27.1	10 wks				2.28%↑5m, 2.11- 10m, 1.96- 20m				
Effects of resisted sprint training on sprinting ability and change of direction speed in professional soccer players	Interv. (Effect of RS vs URS on SP & COD ability)	**Gil et al 2018**	Soccer Elite, male, n=18	6wks	10%			URS 8%↑/RST 7%↑ - 5m, URS 5%↑/RST 5%↑ -10m, URS 4%↑/RST 4%↑ - 15m, URS 3%↑/RST 3%↑ - 20m, URS 2%↑/RST 3%↑ - 25m				
Changes in sprint performance and sagittal plane kinematics after heavy resisted sprint training in professional soccer players	Changes in SP & Kinematics after heavy RST	**Lahti et al 2019**	Soccer Elite, male, n=32, mean age 24.1	9 wks	50% & 60%			sig.↑ in both Sled groups for 5, 10,20,30m				
The effect of individualised sprint training in elite female team sport athletes: A pilot study	Interv. (Effect of Individualised Sprint training RS , assisted mixed, control	**Rakovic et al 2018**	Handball, female, n=17, mean age 23.3	8 wks	5, 8, 11kg resistance induced 11,18 & 25% Vdec							

Effect of traditional and resisted sprint training in highly trained female team handball players	Interv. (RS vs URS)	**Luteberget et al 2015**	Handball, female, n=18	10 wks		12.4 %BM		URS appears to be more effective than RST in enhancing 10-m-sprint time. Both groups showed similar effects in 30-m-sprint time				
Combined squat and light-load resisted sprint training for improving athletic performance	Interv.	**Pareja-Blanco 2021**	Physically active, male, n=91	10 wks		12.5% BM, 80%BM		↑				
Traditional versus resisted sprint training in highly-trained, female team handball players: Effects on performance and muscle architecture	Thesis/ Interv.	**Luteberget et al 2014**	n=18	9 wks		12.40%		↑				
Effects of unloaded sprint and heavy sled training on sprint performance in physically active women/ experimental and longitudinal	quantitative, experimental and longitudinal study was designed to compare the effect of 2 different loads (0% vs 40% BM) during sprint training on sprint performance	**Pareja-Blanco 2020**	Female, n=28	8 wks		0% vs 40% body mass / 20%, 40%, 60%, and 80% BM		↑				
Very Heavy Resisted Sprinting: A Better Way to Improve Acceleration?: Effects of a 4-Week Very Heavy Resisted Sprinting Intervention on Acceleration, Sprint and ...	Interv. (RST vs UST)	**Bremec et al 2018**	Youth soccer players, male, n=27, mean age 15.7	4 wks		25, 50, 75, 100%		↑ (-4.2% to -7.9% all split times)				

Table 6 Summary of intervention studies in the area of RST kinematics

Interventions	Type of study / design	Authors	Subjects	Intervention duration	Load			Time / Velocity	Spatiotemporal Characteristics				Joint angles			
Kinematics					Vdec	%BM	total		CT	FT	SL	SF	Hip	Knee	Ankle	Trunk
Kinematic, strength, and stiffness adaptations after a short-term sled towing training in athletes	Quasi-experimental, pretest/posttest randomised group design	**Alcaraz et al 2014**	National level athletes (24 sprinters, 2 long jumpers, and 4 decathletes), male (n= 20), (female n=10)	4 wks				improved performance						7.4% ↓ knee angle		sig.↑ 15.7% angle of trunk inclination
The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes	Interv. (free sprint training vs resistance training vs plyometric training vs RST on Acc kinematics)	**Lockie et al 2012**	Athletes, male, n=35, mean age 23.1	6 wks		12.6 %BM		sig.↑5 and 10m	sig.↑ for URS group		sig. ↑	sig.↓ except for sled group				
Kinematic, strength, and stiffness adaptations after a short-term sled towing training in athletes	Interv. (RSS vs URS)	**Alcaraz et al 2012**	Sprint Trained National Level, male (n=14) & female (n=8), mean age 21.2	4 wks	7.5 %Vdec			improved the velocity in the transition phase								
The effects of resisted sled-pulling sprint training on acceleration and maximum speed performance	Interv. (RS vs URS)	**Zafeiridis et al 2005**	Sutdents , male, n=22, mean age 20.1	8 wks			5kg	↑				↑ for acc				
The effect of resisted sprint training on maximum sprint kinetics and kinematics in youth	Interv. (RSS on the kinematics and kinetics of maximal sprint velocity)	**Rumpf et al 2015**	Children, n=32	6 wks		2.5, 5, 7.5 or 10%BM		↑ 5.99%				↑ 5.65%				
The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and Australian football players/ Intervention	Interv. (RSS on the acceleration performance and kinematics)	**Sprinks et al 2007**	Soccer, rugby union, or Australian football, n = 30					↑		no effect	no effect	no effect	no effect			

Table 7 Summary of acute studies in the area of RST kinematics

Acute Study	Type of study / design	Authors	Subjects		Load		Time / Velocity	Spatiotemporal Characteristics				Joint angles			
Kinematics				Vdec	%BM	total		CT	FT	SL	SF	Hip	Knee	Ankle	Trunk
Effects of weighted vests and sled towing on sprint kinematics	Comparison of sprint kinematics of URS vs RSS vs vest	**Cronin et al 2008**	Track & Rugby, n=20, mean age 19.9		15, 20 %BM		10-m times were significantly faster than in all the loaded conditions. Significantly slower 10-m sprint times for sled at 20%BM and 15%BM. The 30-m times became slower as load increased in both the vest and sled conditions.	↑	↓	↑	↓ 2.7–6.1%		Knee angles at TD were significantly greater (i.e. greater knee flexion) in both sled conditions than in both vest conditions		at foot strike and toe-off during sled towing with 15% and 20% of body mass were significantly greater than those at baseline and vest sprinting with 15% and 20%
Effects of resisted sled towing on sprint kinematics in field-sport athletes	Cross-sectional analysis of field sport athletes	**Lockie et al. (2003)**	Field sport athletes, male, n=23, mean age 23.1		12.6 %BM 32.2 %BM		↓ 8.7% ↓ 22.8%	↑ 10% ↑19-22%	↓20-25% ↓40-50%	↓10% ↓24%	↓ 6% ↓ 6%				↑
The effect of towing a range of relative resistances on sprint performance	Cross-sectional approach	**Murray et al. (2005)**	Rugby & soccer, male, n=33, mean age 21.1		10, 20, 30 %BM		↓ 9% ↓ 16% ↓ 23%			↓ 8% ↓ 8% ↓ 18%	0% ↓ 4% ↓ 6%				
Kinematic alterations due to different loading schemes in early acceleration sprint performance from starting blocks	Cross-sectional approach	**Maulder et al. (2008)**	Competitive track sprinters, male, n=10, mean age 20		10, 20 %BM		↓ 7% ↓ 12%	↑ 4-7% ↑11-13%	↓ 1-16% ↓12-20%	↓ 6-9% ↓11-12%	↓ 2-1% ↓ 4-3%				
Effects of three types of resisted sprint training devices on the kinematics of sprinting at maximum velocity	Quasi-experimental intrasubject cross-sectional design	**Alcaraz et al. (2008)**	Competitive sprints and long jump athletes, 11 male & 7 female, n=18, mean age 22		16 %BM		↓12-14%			↓ 8%	↓ 5%				

Acute Study	Type of study / design	Authors	Subjects		Load		Time / Velocity	Spatiotemporal Characteristics				Joint angles			
Kinematics				Vdec	%BM	total		CT	FT	SL	SF	Hip	Knee	Ankle	Trunk
Comparison of different sprint training sessions with assisted and resisted running: Effects on performance and kinematics in 20-m sprints	Counterbalanced crossover	**Van Den Tillaar & Von Heimburg 2017**	Handball, female, n=15				after one resisted run (from 3.59 to 3.54 s; 2% improvement)								
Interrelationships between different loads in resisted sprints, half-squat 1 RM and kinematic variables in trained athletes	Experimental design, analysing kinematics of acc	**Martinez et al. (2014)**	Competitive sprinters (n=7) and team sport athletes (n=14), male, mean age 18		5, 10, 15, 20, 25, 30 %BM		↓ 4% ↓ 7% ↓ 10% ↓.12% ↓ 14% ↓ 17%			↓ 2% ↓ 4% ↓ 6% ↓ 9% ↓ 10% ↓ 11%	↓ 2% ↓ 3% ↓ 4% ↓ 4% ↓ 5% ↓ 7%				
Effects of weighted sled towing on ground reaction force during the acceleration phase of sprint running	Experimental design analysing the effect of sled on ground reaction force during sprint	**Kawamori et al. (2014)**	Physically active collegiate team sport athletes, male, n=10, mean age 28		10, 30 %BM		↓ 6.9% ↓ 22.4%	↑ 2.9% ↑ 12.2%							
Determining the optimal load for resisted sprint training with sled towing	Cross-sectional analysis	**Alcaraz et al. (2009)**	Competitive track & field athletes, male, n=26, mean age 20		6 %BM 10 %BM 15 %BM		↓ 7% ↓ 10% ↓ 15%								
Comparison of step-by-step kinematics of resisted, assisted and unloaded 20-m sprint runs	Randomised counterbalanced design	**Van Den Tillaar et al 2018**	Handball athletes, female, n=37, mean age 17.8			5kg		↑	↓	↓	↑ for 3-4 steps				
Acute Study	Type of study / design	Authors	Subjects		Load		Time / Velocity	Spatiotemporal Characteristics				Joint angles			

Kinematics				Vdec	%BM	total		CT	FT	SL	SF	Hip	Knee	Ankle	Trunk
Effect of active resisted 30 m sprints upon step and joint kinematics and muscle activity in experienced male and female sprinters	Comparative, cross-sectional study with multiple groups and repeated measures	**Van Den Tillaar et al 2021**	Sprint athletes, male (n=14) female (n=14), mean age 27.6		10-40 %BM			↑	↓	↓	↓				
Comparison of Step-by-Step Kinematics of Elite Sprinters' Unresisted and Resisted 10-m Sprints Measured With Optojump or Musclelab		**Van Den Tillaar et al 2020**	Elite sprint athletes, n=6, mean age 30.0		10, 20 %BM										
Comparison of Step-by-Step Kinematics of Elite Sprinters' Unresisted and Resisted 10-m Sprints Measured With Optojump or Musclelab	repeated measures design (resisted and assisted conditions on running kinematics)	**Van Den Tillaar et al 2018**	Experienced sprinters, n=16 , mean age 26.4		10, 20 %BM		30m times were on average 12% slower than the normal sprints	↑	↓	↓	↓				
Acute Effects of Progressive Sled Loading on Resisted Sprint Performance and Kinematics.	cross-sectional exploratory study	**Pareja-Blanco 2020**	Rugby national team, n=10		0, 20, 40, 60, and 80%BM				↓	↓ (12.9% for 20% BM)					
Impact of Sled Loads on Performance and Kinematics of Elite Sprinters and Rugby Players	Comparative experimental study	**Pareja-Blanco 2022**	Elite male sprinters (n=8) & Rugby union players (n=10), mean age 23.3		0, 20 and 60%BM					↓ both groups with increasing load					
Muscle activity, leg stiffness, and kinematics during unresisted and	Comparative experimental study	**Zabaloy et al 2020**	Rugby players, male, n=12, mean age 23.5	0, 10, 30 and											

resisted sprinting conditions. (article was not acessable)				50% Vdec											
Effects of sled towing on peak force, the rate of force development and sprint performa nce during the acceleration phase	Quasi experimental cross-sectional design	**Martinez-Valencia et al 2015**	17 male & 6 female, mean age 17.9		10, 15, 20%BM		↑								

Table 8 Summary of acute studies in the area of RST performance

	Type of study / design	Authors	Subjects	Intervention duration		Load		Time / Velocity	Spatiotemporal Characteristics			
Performance					Vdec	%BM	total		CT	FT	SL	SF
Acute effects of sled towing on sprint time in male youth of different maturity status	Cross-sectional observational study with repeated measures	**Rumpf et al. (2014)**	Male children, n=35, mean age 13			2.5, 5, 7.5, 10 %BM			↓5- 4% ↓ 8- 7% ↓ 11- 7% ↓ 14- 9%			
Resisted sled training for young athletes: When to push and pull	Review	**Cahill et al 2020**										
Sled-pull load–velocity profiling and implications for sprint training prescription in young male athletes	Cross-sectional observational study with repeated measures	**Cahill et al 2019**	team sport college, n=70, mean age 16.7									
Effects of Different Loading Conditions During Resisted Sprint Training on Sprint Performance. Pretraining and post-training	Randomised controlled trial	**Rodríguez-Rosell et al 2020**	physically active, male, n=60			0, 20, 40, 60, and 80% of body mass			G80% worsened, G40% increased performance in unresisted and the rest of loading conditions. G0% and G60% increases in unresisted sprint performance.			

Table 9 Summary of acute studies in the area of RST and strength

	Type of study / design	Authors	Subjects	Intervention duration		Load	
Strength					Vdec	%BM	total
Do Faster, Stronger, and More Powerful Athletes Perform Better in Resisted Sprints?	Descriptive cross-sectional design	**Lizana et al 2020**	young physically active sport science students, n=70, male, mean age: 22.8			10, 30, and 50% body mass	
Relationships between resisted sprint performance and different strength and power measures in rugby players	Descriptive-correlational cross-sectional study	**Zabaloy et al 2020**	amateur rugby players, n=20, male				13.4kg

Table 10 Summary RST reviews

	Type of study / design	Authors	Subjects	Intervention duration		Load		Time / Velocity	Spatiotemporal Characteristics			
Reviews					Vdec	%BM	total		CT	FT	SL	SF
The effectiveness of resisted sled training (RST) for sprint performance : a systematic review and meta-analysis	Review - meta-analysis	**Alcaraz et al 2018**	Recreationally active individuals	4-10wks		5 to 80 %BM		Significant improvements between baseline and post-training in SP in the acceleration phase (effect size [ES] 0.61; p=0.0001; standardised mean difference [SMD] 0.57; 95% confidence interval [CI] −0.85 to −0.28) and full sprint (ES 0.36; p=0.009; SMD 0.38; 95% CI −0.67 to −0.10). Non-significant improvements between pre- and post-test in sprint time in the maxV phase (ES 0.27; p=0.25; SMD 0.18; 95% CI −0.49 to 0.13).				
Effect of different sprint training methods on sprint performance over various distances: a brief review	Review	**Rumpf et al. (2016)**	Active male individuals	6-8wks				Training effects of resisted sprinting across all distances were classified as large, with an average ES of 21.39. The greatest ES for resisted sprinting was observed for the 0–20 m distance, and resisted sprinting tended to show the greatest training effects of all specific sprint training methods.				
Resisted sled sprint training to improve sprint performance: a systematic review	Review	**Petrakos et al 2016**	Strength-trained or team sport individuals, sprint trained individuals		6-30 %Vdec	5-43 %BM	5 kg	(10 %BM or \10 %Vdec) loads provide 'small' decrements in acceleration (-1.5 %, ES = 0.50) to 'moderate' improvements in maximal sprint velocity (2.4 %, ES = 0.80). (10–19.9 %BM or 10–14.9 %Vdec) to ([30 %BM or [30 %Vdec) loads provide 'trivial' to 'extremely large' improvements in acceleration performance (0.5–9.1 %, ES = 0.14–4.00)				
Acute and longitudinal effects of weighted vest training on sprint-running performance: A systematic review	Review	**Macadam et al. 2022**	Active participants, athletes	8days-7wks, also acute studies		5%-40% BM		Vest loads (5–40% BM) were found to significantly increase acute over-ground times (10–50 m 4.1–16.9%, effect sizes [ES] = 0.93–3.11) through significantly decreased velocity (−2.2% to −17.3%, ES = −0.41 to −3.19), horizontal force (−5.9% to −22.1%, ES = −0.85 to −3.30), maximal power (−4.3% to −35.6%, ES = −0.32 to −3.44), and flight times (−8.3% to −14.6%, ES = −0.88 to −1.03), while increasing contact times (14.7–19.6%, ES = 1.80–3.17).	↑	↑	↓	

2.4.9 **Specificity of resisted sprinting**

The success of a sprint training program is founded on the principle of specificity [27]. To accomplish appropriate progressions, it is necessary that coaches gain an understanding of the joint angles amplitudes, accentuated region of force production, dynamics of effort, rate and time of maximum force production and regime of muscular work most used in their specific sport, and appropriately choose exercises that develop them [333]. Adequate loads are necessary to (re)produce the desired training stimulus without drastically altering sprinting kinematics and muscle activation patterns. RST is characterised as being 'sport specific' because it specifically develops strength and power qualities in the muscle groups used for sprinting. The 'most appropriate load' or 'optimal load' in RST is currently unknown [334]. In the literature, we can see two opposing viewpoints [303]. On the one hand, it has been proposed that loads corresponding to a 10%Vdec relative to unresisted sprint training would not imply significant changes in sprint mechanics, allowing athletes to more closely replicate conventional sprints [302,334]. On the other hand, the use of very heavy sled training is becoming more and more popular [50,284,298,328]. Depending on the load magnitude, resisted sprints may have different effects on sprinting kinetics and kinematics [149]. As previously mentioned, all loads (light and heavy) have a function but they target different capacities and therefore different aspects of specificity [115,303]. From a coaching standpoint the loading scheme utilised in RST may result in short-term and long-term adaptations that must be thoroughly understood for optimal application throughout the training season [303]. To correctly apply RST as a training method, we must first consider how important it is to be aware of the immediate effects produced by this method and, thus, understand its potential impact on the training session; second, we must be aware of the chronic adaptations that may occur in response to training because these changes will most likely affect athletic performance. For instance, when the primary goal is to replicate sprinting movements with a specific overload, without provoking large disruptions in the sprinting technique, it is crucial to use lighter loads (e.g., 10%Vdec). In contrast, when very heavy sled loads (e.g., 50%Vdec) are used, the changes in sprint mechanics are very noticeable, and as a result, they do not reflect the traditional sprint movement pattern, although they provide specific neuromuscular stimulus and evoke key adaptations for sprint performance [303].

The traditionally assessed kinematic variables in sprinting (CT, SL, SF, FT) progressively change with increasing load, when compared to unresisted sprinting. When sled loads are increased, it has been seen that sprint velocity, SL, FT, and SF decrease, CT increases, and joint kinematics change [1,141,149,282,335,336]. In amateur rugby players, Zabaloy, *et al.* [337] noticed a larger forward trunk lean when increasing loads from 0 to 50%Vdec, which further supports the idea that altering loads can result in significant changes to the conventional sprint method. Higher accelerations velocities are generated by more forward oriented forces [134] and the greater trunk lean may help decrease the braking forces associated with landing during acceleration [134,282]. Using heavier loads may extend the distance over which athletes can train acceleration mechanics while using RSS, offering an interesting perspective that may indicate a potential benefit of using heavier loads. However, when thinking of amplitude and direction of movement a distinction between the local and global frame of reference must be formed when analysing the direction of force application [230]. For instance, an athlete generates a significant amount of horizontal force [13] in relation to the global frame during the acceleration phase of a sprint, however, leaning forward causes the athlete's posture to change, creating a more horizontal force vector, which helps improve SP. As a result, with relation to the athlete, force is exerted along the body's longitudinal axis [230]. This becomes more interesting when looking at maxV, as there the orientation of the body should be vertical, but the orientation of the force needs to be perpendicular to the body. During maximum velocity sprinting, heavy RST can lead to a forward lean of the trunk, which inhibits the athlete's ability to maintain an upright position that is typically associated with achieving maximum velocity [338]. The overall GRF should be oriented more vertically than during acceleration, to overcome the effects of gravity and to maintain maximum velocity [124,129,338]. This does not mean that no horizontal force is applied, but vertical forces may play a more important role during this phase [129,338,339]. Therefore, when training the maxV phase careful consideration of the loads is important to not disrupt maxV mechanics.

It is important to note that lower leg stiffness has been associated with low elastic energy storage and reutilisation during SSC activities, which has a detrimental effect on sprint performance. Zabaloy, Carlos-Vivas, Freitas, Pareja-Blanco, Loturco, Comyns, Gálvez-González and Alcaraz [337] demonstrated an acute decrease in leg stiffness with increased sled loads in their research. Alcaraz, Elvira and Palao [330] observed no effect on leg stiffness after 4 weeks of light RST (7.5%Vdec). Despite the non-significant effect of time for vertical stiffness, a trend to signification (P = 0.081,1-b = 0.420, d = 0.422) was found for the unresisted group. When thinking of the principle of rate and time of maximum force production, a stiffer system could potentially have positive effects on running, such as an increased RFD at contact, leading to shorter contact time and higher peak force. As a result, controlling the reflexes that affect the stiffness of the tendo-muscular system is crucial for improving sprint performance. Bret*, et al.* [340] proposed that increased stiffness levels which are associated with a quicker release of elastic energy in situations where significant joint movement is not present are important for team sports. Athletes must exert maximum effort in response to changing game conditions, the ability to release elastic energy and execute explosive movements with minimal pre-stretch would be beneficial [341]. Since longer CT has been noted with increased sled loads [1,149,282,342], an excessive sled load may need too much amortisation time during the SSC [343], which would hinder the usage of the SSC. However, an increase in CT allows an athlete to produce the force required to overcome the overload, which can benefit when training the acceleration phase. Longer CT is the characteristic during this phase for unloaded sprinting, with larger propulsive and shorter braking phases during each ground contact[36,332]. This mechanical profile matches that of the heavier loaded resisted sprints and therefore displays specificity on multiple fronts.

Depending on the direction of the applied resistance resulting from the training exercise, RST is projected to increase the ability to create horizontal and vertical GRF when sprinting [278]. In response to this, it was proposed that, with continued use, the "cumulative effect" would favourably transfer to horizontal force output during ground contacts, boosting SL during unresisted sprinting [149,280]. Although unresisted sprints and RST are both targeting improved sprint performance, they are targeting different determinants of sprint performance and therefore the criteria for specificity are different. When compared to unresisted sprints, RST offers a particular method of overloading horizontal-force capacity [51], together with an increase in the trunk lean angle (which permits larger application of horizontal force) [4]. RST with 10, 15, and 20%Vdec loads alters the kinematics of the trunk, knee, and ankle joints in rugby players, allowing them to lower their COM and hence increase their ability to exert force in a horizontal direction during acceleration [344]. Rugby players at the highest levels [336] and amateurs both observed the same trends [345]. The idea that adaptations are load specific is supported by recent studies of Cahill, Oliver, Cronin, Clark, Cross and Lloyd [328] and Lahti, Huuhka, Romero, Bezodis, Morin and Häkkinen [284]. The main finding was that moderate to heavy loads resulted in increased sprint performance, particularly during the initial acceleration phase, when compared with unresisted or lighter loads. Loads of 50 and 60%Vdec improved significantly all 10–30m split times ($p < 0.05$, $d = -1.25; -0.62$) [284], and 75%Vdec was particularly effective at improving acceleration over 5, 10 and 20 m ($d = 0.40 – 1.04$, $p < 0.01$) [328]. RST may be a more specific training form that satisfies criteria based on movement velocity. Thinking of heavy or very heavy RST under the same reasoning, we should ask ourselves: should they be regarded as sprint efforts or even categorised as RST because they happen at extremely modest velocities and under very different muscular contraction conditions than conventional sprints [142,345]. With heavy loads athletes are not actually sprinting when FT is too low or even disappears, rather, they are marching since they have very little time to adjust their limbs for the ensuing contact [336]. Previous research reported little or no FT with sled loads producing >50%Vdec [345]. Supporting the concept of dynamics of effort, evidence demonstrates that heavy-load resistance training produces larger increases in maximal strength compared to low-load [346]. However, low-load higher velocity training may be necessary for improving high-velocity athletic performance, particularly among well-trained athletes [347,348]. Therefore a recent study by

Zabaloy, Freitas, Pareja-Blanco, Alcaraz and Loturco [303] proposed that when loads cause a < 30%Vdec, which mimics or at least reflects the conventional sprint method even under loaded conditions, RST should be performed with the aim of improving SP. On the other hand, heavy or very heavy loads with Vdec >30%, ought to be principally utilised to improve strength-related capacities for sprinting, rather than necessarily or directly related to conventional SP.

2.5 HOW COACHES PERCEIVE THE IMPACT OF RST ON KINEMATICS

As previously mentioned the use of resisted sprinting has gained popularity among coaches as a means to enhance sprint performance while maintaining specificity [319,349]. However, there is a significant amount of literature highlighting discrepancies in the recommended load, volume, intensity, and methodology for sled sprint training [350]. A recent review aimed to address these discrepancies by discussing various technologies and methodologies for assessing sled tow sprinting and providing practical considerations for coaches. The goal was to assist practitioners in utilising these training methods and assessing sprint performance. Research has shown that adding load to sprinting can cause immediate changes in movement patterns, but it remains unclear how coaches incorporate this information into their training programs [350].

Difficulties in bridging the gap between scientific findings and coaching practice have been identified, with coaches seeking practical conclusions while sport scientists focus on expanding general knowledge. Additionally, the dissemination of new information poses a challenge, as coaches tend to rely on informal communication methods rather than academic journals [351].

To date only one survey has explored how coaches incorporate resisted sprinting into their training programs, revealing a discrepancy between coaches' goals and their prescription of lighter loads for short sprints. This may not be sufficient to bring about the desired improvements in acceleration [47]. Hence, this thesis aims to investigate further the current practices of coaches in relation to RST. Moreover, it aims to obtain valuable perspectives on how coaches perceive the potential impact of RST on kinematics, gather information on their understanding of kinematics, and explore the different factors that influence their decision-making process when utilising resisted sprints as a training approach.

Gaps in the literature: To the authors knowledge, no studies have assessed multiple loads on multiple joint angles during both acceleration and maximum velocity phase running or compared different sporting populations [34,149,278,284,285,288,295,302,304,305,349,352-354]. Therefore, it is unclear if athletes from different sports with varying physiological characteristics display similar kinematics when completing RST at different loads. For example, it is plausible that sports that place a larger training emphasis on sprinting or strength training (sprinters vs. field-based invasion team sport athletes) may provide athletes with a greater ability to complete RST under heavier loads, without negatively impacting sprint kinematics. As a result, it might be possible that athletes with smaller kinematic differences may see a larger transfer effect. Furthermore, it is unclear if strength levels influence kinematics changes during RST. This thesis aims towards understanding these differences. Moreover, no attempts have been made to understand practitioners understanding of acute impact on kinematics and changes in kinematics. This is important as it is potentially going to impact whether a coach uses RST as a training modality and how.

Chapter Link

Based on the literature review it became evident that RST has significant implications for sprinting mechanics and performance. This led to the realisation that understanding coaches' perspectives and approaches to RST would be crucial in gaining a more comprehensive understanding of how RST is utilised in real-world training settings and how it aligns with the overall objectives of the thesis. The study was designed to build upon the discoveries from the literature and expand the scope of the research. By exploring coaches' perspectives and practices related to RST, the study aimed to gather valuable insights directly from coaches who prescribe and implement RST in their training programs. By incorporating coaches' input, the final study aimed to explore their comprehension of kinematics and how they perceive the potential impact of RST on sprinting mechanics. The study also intended to identify the factors that influence coaches' decisions in using resisted sprints as a training tool. This information would provide a more holistic understanding of the practical considerations and real-world implications of RST in athletic training. By combining scientific findings with practical insights from coaches, the final study aimed to contribute valuable knowledge to the field of sports science and enhance the efficacy of RST as a training method for enhancing sprint performance.

CHAPTER 3

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3 AN INVESTIGATION OF RESISTED SPRINT TRAINING PRACTICES OF COACHES AND THEIR PERCEPTION OF HOW RESISTED SPRINTING INFLUENCES KINEMATICS

3.1 INTRODUCTION

In recent times, there has been a significant increase in the popularity of specific sprint training methods, including the use of RST [12,32,278,285,295,302,328,355-360], [345,361,362]. Moreover, several systematic reviews have shown positive outcomes of RST on sprint performance under a variety of loading conditions [4,334]. Research has shown that when load is added to sprinting, it can cause immediate changes in kinematics [142,282], however there is currently no evidence to suggest that these changes transfer into unloaded running [49,280,281,284]. Despite this, it is important to note that the acute kinematic changes observed during RST can be either positive or negative and can vary depending on the phase of the sprint. Cronin, Hansen, Kawamori and McNair [282] found that sprint time increases when loads of 15 and 20%BM are added. This increase in sprint time is primarily due to a decrease in SL, with small decreases in SF. Other research has shown that there is an increase in hip flexion and trunk lean at touchdown when sprinting with a load [1,115,149,278]. The shank also tends to be less upright at touchdown, resulting in a slightly shorter landing distance [278]. Leaning the body forward and shifting the athlete's COM forward can lead to a more efficient foot strike and reduce braking forces during running [282,284]. This position can be trained during RST. Most studies have focused on lighter resisted sprint training loads, but recent research has also examined the effects of heavier loads. Under these heavier load conditions, spatiotemporal variables such as contact time, step frequency, and step length changed significantly [327]. The distance between the foot and the ground at touchdown and the angle of the COM at touchdown decreased. Research demonstrated that heavier sled loading leads to an increase in horizontal force capability and has significant benefits to improve short-distance sprint performance, specifically the acceleration phase [328]. It has been demonstrated that adjustments to different phases of the sprint and zones of training, including speed-strength, power, and strength-speed during ST, are influenced by the load placed on the sled. Furthermore, it is not clear if coaches/practitioners are aware of these changes, or if they are aware, how/if they use this information to guide training prescription. Previous research indicates that coaches may not fully understand the scientific literature available to them when it comes to sprinting techniques [3,363,364]. A recent survey aimed to explore how S&C coaches incorporate resisted sprinting in their training programs and found that the majority of S&C coaches followed the traditional recommendations of using lighter loads (< 20%BW) for both short and longer distance sprints. However, it is worth noting that there seems to be a contradiction between the coaches' goals and their prescribed load for short sprints. In particular, most coaches aimed to enhance speed-strength and power, yet less than 26% of them prescribed heavy enough loads to align with the current recommendations for achieving improvements in the application of horizontal force during the acceleration phase [47].

No studies have been conducted on coaches' understanding of changes in kinematics during or after resisted sprinting, their decision-making process on how to use this training method, and their perception of it. This survey aims to fill this gap in the literature by studying coaches' perspectives on these topics. The results of this study can provide valuable information on the practical use of resisted sprinting in coaching practice.

Firstly, understanding coaches' understanding of changes in kinematics during resisted sprinting can help them make more informed decisions when prescribing and implementing this training method. Coaches will have a clearer picture of how resistance affects athletes' movement patterns and can adjust training protocols accordingly.

Secondly, identifying the factors that influence coaches' decision-making on how to use resisted sprints provides valuable information for designing effective training programs. Coaches can consider factors such as availability, access, logistics, and practicality when selecting resistance modalities for their athletes. This knowledge can lead to more tailored and efficient training protocols.

Furthermore, by exploring coaches' perception of resisted sprinting as a training method, this study can shed light on any misconceptions or gaps in knowledge that coaches may have. Researchers and coaching professional bodies can use this information to develop educational programs and resources to bridge the gap between research and coaching practice. This can enhance the effectiveness and safety of resisted sprinting training.

Taking into consideration the aforementioned factors, the primary objective of this study was to explore the current practices of coaches in relation to RST. Additionally, it sought to gather insights on how coaches perceive RST's potential impact on kinematics, gather information on their comprehension of kinematics, and examine the various factors that shape their decision-making process when it comes to utilising resisted sprints as a training approach.

3.2 METHODS

3.2.1 Participants

A total of 52 participants comprising of coaches currently working in different sport settings such as track and field or field-based invasion team sports completed the online survey. Participants were recruited using a poster advertised on social media platforms Twitter and LinkedIn and directly through the research team's network of contacts. To increase visibility and utilise 'snowball sampling' [365,366], participants were encouraged to circulate the poster to their personal networks and peers. Inclusion criteria outlined that participants must be currently working in a sport setting and involved in speed development of athletes. To ensure that responses were collected from targeted populations, exclusion criteria (not currently coaching in a sport setting) was provided on the first page of the survey. Informed consent was sought from all coaches prior to completing the survey. The procedure was ethically approved by the Technological University of the Shannon Ethics Committee (20210609).

3.2.2 Survey Development

An initial survey was designed by a panel of three experts that had both practical and research experience in the topic area. To ensure the survey was an accurate resource and capable of fulfilling the aims of our brief, a validation process via the modified Delphi technique was undertaken [367]. This process required a panel of experts to volunteer to review and rate each question using Likert Scales (provided on an excel file by the principal investigator). Practitioners indicated on a 10- point Likert Scale how important they perceived each question, with '1' not important at all and '10' extremely important'. Experts were asked to add any further recommendations/changes to the questions, their wording, or the order of questions. This process was a three round review process with a one-week period allocated for each review round [367]. Within this window, once the practitioner had returned the excel file, the principal investigator made changes to the survey based on this collective feedback from all expert coaches and discussion with the supervisors. Then the updated version was returned for the next review. Once the survey was finalised (after all feedback was incorporated) it was sent out to the target population.

3.2.3 Survey Overview

This study used a web-based questionnaire (Microsoft forms) to survey information regarding coaches understanding of kinematics and investigate the factors which influence their decisions to use resisted sprints as a training method. The questionnaire included a mixture of open and closed questions which took approximately 20–30 minutes to complete (Supplementary Materials). Questions were framed around four areas including (1) Background information (2) Education & Qualification (3) Perception of RST kinematics and (4) Methodology. For fixed-question's, responses were provided on Likert Scales to determine perceived importance and extent of agreement. Practitioners indicated on a 5-point Likert Scale how important they perceived different variables, with '1' not important at all and '5' extremely important or indicated their confidence, with '1' no confidence at all and '5' high confidence. Participants also had the choice to indicate that they were not confidant or did not have an opinion (NA). The NA choice served as a filter in the prevention of inaccurate or erroneous responses [368].

Several multiple-choice questions were also included requiring either single or multi-response answers. Open- ended questions were used to further understand the coaches perceptions. All 52 participants completed the full survey which was necessary requirement to be included in this study. Participants had to complete a minimum of 80% of the survey to be included. The full survey is included in the Appendix D. Subsequently, a total of 52 responses were received for the survey and were included for the analyses.

3.2.4 **Statistical Analysis**

All data were collected using an online questionnaire. Data were then exported into Microsoft Excel and subsequently SPSS 24 (version 25, IBM, New York, USA) for further analysis. This observational study followed a descriptive, cross-sectional design, therefore quantitative data presentation is mostly descriptive in nature with frequency counts and percentages calculated. For descriptive purposes, means with standard deviations were reported for ordinal (Likert Scale) measurements and frequencies were used to describe categorical data. Chi squared tests for associations were run to identify any associations in frequency variables across the different coaching backgrounds, education levels, years of experience in coaching, sports and sources of information. Phi (φ) values of 0.1, 0.3 and 0.5 represented small, medium and large effect sizes respectively [369]. When more than 20% of expected counts were less than five, a Fisher's Exact test with Cramer's V (φ-c) was utilised. A thematic analysis approach was used to assess open-ended questions. This thematic analysis was conducted according to the 6-stage process outlined by Braun and Clarke [370] and previously used by surveys [371,372]. The 6 stages were as follows: (1) data familiarisation, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report. This thematic analysis allowed the identification of key topics and consistent patterns that were evident in various open-ended sections [370]. The lead researcher and supervisors of this study independently assessed the open-ended responses, and a consensus was reached on the themes and quotes used in the analysis [373].

3.3 RESULTS

3.3.1 Demographic Characteristics of the Coaches

25% of coaches had a bachelor's degree, 42% a master's and 27% were holding a PhD, while 6% did not have a degree. 29% of coaches earned a degree in Strength and Conditioning, 10% in Exercise Physiology and 42% in Sports Science, while 19% did a degree in a non-related field (Table 11). Of the total sample, 96% of coaches had a coaching qualification with 50% of the Coaches reported having a qualification in strength and conditioning. Athletic coaching qualifications included Athletics Ireland level 1 or international equivalent (14%), level 2 (6%), level 3 (10%) and level 5 (8%). 6% of the coaches had a qualification in GAA coaching, while 1% had one in soccer and 1% as a personal trainer. 60% of the coaches had coaching experience of 1-10 years and 40% up to 20 years, with 20, 26, and 33% coaches having coached athletes up to international, national, and regional levels, respectively, with 52% of them currently coaching in a full-time position.

Table 11 Coaches demographic characteristics.

	Proportion of Coaches (%)
What is your current occupational (coaching) status?	
Full-time paid work (30+ hours per week)	52
Part-time paid work (8-29 hours per week)	12
Part-time paid work (under 8hours per week)	13
Part-time unpaid work / intern	0
Consultant	10
Volunteer	8
Retired	0
Other	6
Number of years' experience coaching speed development?	
1 to 5	31
5 to 10	29
10 to 15	17
15-20	8
20+	15
What sport are you currently coaching in?	
Track and Field	46
Rugby	14
Baseball	2
Alpine Skiing	2
Football	14
None	4
Badminton	2
GAA	15
Basketball	2
What is the highest level of education you have completed?	
None	6
University Undergraduate Degree, BSc	25
University Postgraduate Degree, MSc (taught)	24
University Postgraduate Degree, PhD / Dr.	27
What is the related field/area of your education?	
Sports Science	42
Strength & Conditioning	29
Exercise Physiology	10
Other	19

3.3.2 Coaches' Views on RST

Of the 52 coaches, 41 (79%) used RST in the previous 24 months. The reasons for not using RST (21%) were, not being able to access the necessary equipment (64%), not enough time (18%), or not enough knowledge (18%).

Table 12 outlines the sources of information coaches used to aid in RST exercise prescription. The two most widely used sources of information were from Scientific Journals and Coaching Workshops.

The coaches' responses to the statement "Resisted sprint training is a useful training tool for improving unresisted sprint performance" can be found in Table 13 below. The findings show that there is a significant association between coaching qualification and the answers given to the aforementioned statement. It was observed that a significantly greater proportion of certified strength and conditioning coaches, in comparison to coaches holding other certifications (i.e. in track and field), expressed that RST is an effective training tool to enhance SP (52% vs. 47%; $\chi2[10]=34.245$; $\varphi\text{-c}=-0.6$; $p=0.000$). No other variable (years of experience, education or sport) demonstrated a significant association.

Table 12 Sources of information named by coaches.

	Proportion of coaches (%)
Scientific Journals	72
Coaching Journals	38
Social Media	46
Workshops	49
Other coaches	45
Other	3

Table 13 Coaches answers to the statement "Resisted sprint training is a useful training tool for improving unresisted sprint performance".

Based on your own experience: Resisted sprint training is a useful training tool for improving unresisted sprint performance.	Proportion of coaches (%)
strongly disagree	2
disagree	2
neutral	2
agree	40
strongly agree	52
N/A	2
Based on scientific literature: Resisted sprint training is a useful training tool for improving unresisted sprint performance.	
agree	52
strongly agree	45
N/A	3

3.3.3 Coaches perception of RST in comparison to other training tools

The majority of coaches (90%) viewed RST as equally effective when compared to other training tools such as resistance training, plyometric training, and unresisted sprinting. Coaches that did not think RST was as effective as other training modalities provided the following reasons.

"Depends on the athletes age and level."; *"It wouldn't be equally effective but can be useful in some cases. Would only prescribe if dealing with an experienced athlete in terms of their training age."*

3.3.4 Coaches confidence in their knowledge of RST

The majority of coaches indicated high to moderate confidence with their theoretical knowledge of RST, coaching of RST and training prescription (Table 14). Coaches who had high confidence in their theoretical knowledge of RST (48%) expressed that they used it to:

"Enhance force and technical efficiency, improve acceleration mechanics and sprint qualities, and develop their athletes."

There was no significant association between coaches theoretical knowledge of RST, coaching of RST and training prescription and the following variables – education, coaching certification, years of experience or source of information.

Table 14 Coaches confidence of their theoretical knowledge of RST, coaching RST during a session and prescribing RST in a program.

Using the options listed below please indicate how confident you are with:	Proportion of coaches (%)
Your theoretical knowledge of resisted sprint training	
not answered	21
no confidence	
small confidence	
moderate confidence	31
high confidence	48
Coaching resisted sprint training during training sessions	
not answered	21
no confidence	
small confidence	6
moderate confidence	28
high confidence	45
Prescribing resisted sprint training in training programmes	
not answered	21
no confidence	
small confidence	4
moderate confidence	29
high confidence	46

3.3.5 Coaches Prescription of RST and choice of modalities

When prescribing RST, 85% of the coaches indicated that the training prescription (resistance, repetitions and sets, distances, total volume), and training goal, are not the same for acceleration and maximum velocity development. The main reasons that coaches had for prescribing RST and the primary objectives when utilising it were to *"accelerate"* or *"enhance acceleration,"* as mentioned by 16 respondents (39%).

71% of the coaches prescribe RST for initial and late acceleration phase development, 13% for the transition phase and only 5% for maximum velocity phase. Statistics on how coaches prescribe RST are detailed in Table 15.

For the aforementioned variables there was no significant association with education, certification or source of information.

Table 15 RST phase prescription.

	Proportion of Coaches (%)
Initial acceleration	42
Late acceleration	29
Transition	13
Max Velocity	5
All	11

The modalities coaches reported to use can be seen in Table 16, with 45% of the coaches using a resistance device such as a sled. 88% of the coaches indicated that they were implementing RST as both a technical and a physical stimulus (Table 16). Most coaches prefer using either a %Vdec or a %BM approach for prescribing resistance, with 26% and 19% respectively, with some coaches indicating to use multiple modalities (i.e., sled and Exer-Genie) (Table 16). For the aforementioned variables there was no significant association with education, certification or source of information.

The thematic analysis applied to the coaches' responses on their rationale for choosing multiple modalities resulted in five major themes. The first theme that arose was about availability, access, and logistics. Group members mentioned having easy access to the equipment. The second theme, practicality, was about group members choosing the most practical options. The third theme, Athlete, focused on considering the athlete's age and level. The last two themes, price and phases, involved group members considering the sprint phases or the price of the equipment. Three major themes (Goal of session; Effect on technique and Athlete) were identified for what coaches considered most important when choosing the RST modality. These are outlined in Table 17 along with exemplar responses for each theme. Moreover, the thematic analysis applied to the coaches' responses on their rationale for choosing one load prescription strategy over the other resulted in three major themes. The first theme that arose was about easiness. Group members mentioned %BM as a straightforward method. The second theme, based on literature, was about group members choosing %BM based on what they have read in the literature. The third theme, knowledge, focused on group members understanding of the loading strategies. The theme of individualisation revolved around group members selecting %Vdec, with the aim of tailoring the load for each athlete and sprint phase more effectively. Each theme is outlined in Table 18 along with exemplar responses. 6% of coaches stated they prescribe the same load for the whole group and do not specify loads to each individual athlete. Their reason was that: *"It is a very homogenous group. Additionally, lack of equipment and time availability. If more time, equipment, more of a heterogeneous group I would look to individualise this, as I have done previously."*

Table 16 RST prescription.

	Proportion of coaches (%)
What resisted sprinting modalities do you use?	
Aerodynamic (e.g., parachutes)	7
Motorised/robotic (e.g., 1080 Sprint, Dynaspeed MuscleLab)	11
Pulley (e.g., Exer-Genie)	21
Sliding (e.g., sled, tire pulls)	45
Other	16
Do you implement resistance sprinting as a technical and/or physical stimulus?	
Technical	5
Physical	7
Both	88
I have not considered this before	
What strategy do you use to prescribe resisted sprinting load?	
Percentage of body-mass (%BM)	26
Percentage velocity decrement (%Vdec)	19
Percentage of maximum resisted sled load (Can be used with other measurable resisted sprint methods e.g. Run Rocket or Exer-Genie)	1
Absolute load	4
Degree of hill incline	10
No strategy	3
Other	8

Table 17 Reasons for choosing multiple modalities.

Theme	Example Responses	Number of responses (n)
Availability, Access & Logistics	"I have access to a variety of hills in my location and understand how to integrate them into my program. They don't require set-up and I can coach the desired responses from them. I have also used bullies and sleds though I have found that athletes often struggle to adapt to external loading which is not the case with hills."	12
Practicality	"If I have a small group, I am more likely to use sleds. If I am dealing with larger groups, I am more likely to use manual resistance."	3
Athlete	"Depending on the age and level of the athlete. Sleds for younger or lower development level athletes and pulley type for more advanced athletes to work on early acceleration technique or they're force velocity profile."	3
Price	"Price and availability "	2
Phases	"Based on sprint phase"	2
Goal of session	"Goal of the session based on time of year and objectives for the meso cycle do training. For example, in the past during fall training with sprinters I usually did lighter and longer late stage acceleration/transition work where resistances were at 1-5kg on the 1080 and we tracked peak and avg velocities at given resistances. Later in the week we would do heavy and short resisted sprints usually 10m and up to 16-20kg resistance tracking peak power output. Sometimes even going up to 21-25kg."	16
Effect on technique	"I'm always trying to develop and stabilise technique, so the prescription is dialled in to develop the quality without disrupting technique."	14
Athlete	"Individual needing based on evaluation"	2

Table 18 Reasons for selecting %BM over %Vdec and reasons for selecting the %Vdec over %BM.

Note that reasons for selecting %BM over %Vdec are presented in the upper half of the table (light grey shading) and reasons for selecting the %Vdec over %BM are presented blow.

Theme	Example Responses	Number of responses (n)
Easiness	"Percent BM is a pretty straight forward tool to implement with a large group of athletes. I would say that %Vdec is the best solution if you have the time or resources."	8
Based on literature	"Scientific journals, practical work and experience, ease of calculations when doing it with multiple athletes."	2
Knowledge	"Percent BM is a pretty straight forward tool to implement if you don't understand %Vdec."	2
Individualisation	"Progress training and individualise training in an effective way." "It has the ability to individualise the loading regime, in contrast to other forms."	9
Based on literature	"Seems more appropriate based on literature." "Research from Morin, Samozino, Cross, Cahill, etc."	6

3.3.6 **Factors Considered by coaches before selecting a Resistance**

Factors coaches consider to be important before selecting load are detailed in the table below with 56% of coaches reporting to find it extremely important to consider or identify the sprint phase for improvement. 88% of coaches indicated that acute changes in technique during RST influence training prescription, and 95% indicated that long-term changes to sprinting technique are an important factor to consider before selecting a load (Table 19).

Table 19 Coaches rating of factors to consider before selecting a resisted sprinting load/resistance.

		Proportion of coaches (%)
Sprint phase identified for improvement e.g. acceleration or maximum velocity		
	extremely important	56
	very important	37
	moderately important	7
	slightly important	
	not important	
	I have not considered this factor before	
Different positional sprint demands (Team sports)		
	extremely important	15
	very important	37
	moderately important	15
	slightly important	12
	not important	7
	I have not considered this factor before	15
Athlete's force-velocity characteristics		
	extremely important	44
	very important	32
	moderately important	12
	slightly important	5
	not important	2
	I have not considered this factor before	5
Athlete's training age		
	extremely important	32
	very important	27
	moderately important	27
	slightly important	12
	not important	2
	I have not considered this factor before	
Athlete's speed capabilities		
	extremely important	20
	very important	37
	moderately important	37
	slightly important	2
	not important	5
	I have not considered this factor before	
Athlete's level of experience with resisted sprints		
	extremely important	20
	very important	42
	moderately important	27
	slightly important	10
	not important	2
	I have not considered this factor before	

		Proportion of coaches (%)
Athlete's strength capabilities		
	extremely important	20
	very important	44
	moderately important	22
	slightly important	7
	not important	7
	I have not considered this factor before	
Training surface		
	extremely important	24
	very important	39
	moderately important	17
	slightly important	10
	not important	7
	I have not considered this factor before	2
Number of days pre/post competition		
	extremely important	32
	very important	44
	moderately important	15
	slightly important	7
	not important	2
	I have not considered this factor before	
Resisted sprinting modality		
	extremely important	22
	very important	46
	moderately important	15
	slightly important	7
	not important	7
	I have not considered this factor before	2
Acute change in technique		
	extremely important	29
	very important	34
	moderately important	20
	slightly important	5
	not important	10
	I have not considered this factor before	2
Long-term technique changes in unresisted sprinting		
	extremely important	29
	very important	51
	moderately important	10
	slightly important	5
	not important	5
	I have not considered this factor before	

3.3.7 **Coaches Perceptions of URS technique characteristics**

Frequency analysis indicated that 95% (acceleration phase) and 66% (maxV phase) of coaches perceived the same technique characteristics for RST important as for URS and 5% (acceleration phase) and 34% (maxV phase) did not.

Thematic analysis identified two main themes when coaches described good unresisted sprinting technique, 1) Mechanics and 2) spatio-temporal variables. They are characterised by group members indicating that they focus on mechanics (positions, joint angles, segment angles) for good sprinting technique or more on spatio-temporal variables. Moreover, the thematic analysis applied to the coaches' responses on their rationale for not considering the same technique characteristics important for maxV resulted in two major themes 'mechanics' and 'not using RST'. Not using RST, arose from the opinion of group members that they do not use RST for maxV so they had different considerations concerning unresisted sprinting. All themes are outlined in Table 20 along with exemplar responses for each theme.

Table 20 Table presenting a) coaches responses of their understanding of good unresisted sprinting technique for acceleration and maximum velocity phase (light grey shading), and b) coaches were asked to give more detail on their reasons of why they did not consider the same technique characteristics important.

Theme	Example Responses	Number of responses (n)
Mechanics	"Acceleration: Explode out, drive the lead leg/arm, stay low, drive the legs. Max velocity: I don't really focus on this phase but I would look at trunk position." "Positioning is more important than posture in sprinting and sports in general… Proper foot strike is at the core of what I am attempting to effect. "	39
Spatio-temporal variables	"Angles of attack, excursion angles during ground support, contact times, flight times, rate of stride rate change, stride rate, stride length.....same for both questions....."	9
Mechanics	"Because the sled in the fly phase changes biomechanics of the run. I would think that unresisted max velocity sprinting would be more about bounding and less about pulling. I think this would have a great effect on the trunk position and contact time." "Hard to maintain good mechanics whilst doing so. As max v is predominantly vertical forces, I'm not so sure resisted would be a good idea." "I currently think resisted sprints with my current tools could create poor mechanics for upright max velocity sprinting."	7
Not using RST	"I don't use it for Vmax." "Not using it."	3

3.3.8 **Coaches Perceptions of changes in technique during RST**

Frequency analysis revealed that 73% of the coaches reported that RST changes acute sprinting technique compared to unresisted sprinting during the acceleration and maxV phase, with coaches indicating that CT, FT, SL, SF and joint angles are affected. 17% of the coaches reported that it did not change and 10% stated to not have had considered this before. Additionally, coaches (73%) expressed that various RST modalities have a distinct impact on technique. However, a small proportion of coaches (15%) did not concur with this statement, and there were also some coaches (12%) who had not previously considered this aspect. Coaches education, certification, years of coaching experience or source of information seemed not to demonstrate any significant association with their perceptions of changes in acute sprinting technique.

66% of the coaches reported that a change in acute technique has an influence on how they prescribe resistance. The following Table 21 shows those coaches responses to what they would do in this case where they felt technique was affected by RST. Moreover, 14.6% of the coaches agreed with the following statement. 'Changes in technique during resisted sprint training negatively impact unresisted sprint performance.' 42% of the coaches indicated to disagree, while 24% strongly disagreed and 17% stated to be neutral.

Table 21 Coaches actions to acute change in technique during RST.

Note that 'make resistance heavier' and 'make resistance harder' are separated based on different modalities.

	Proportion of coaches (%)	
	Acc	maxV
Stop using it	2	9
Adjust the resistance	15	11
Make load heavier	2	0
Make load lighter	11	11
Resistance easier	7	7
Resistance harder	0	0
Give them time to adjust to the training modality	21	15
Allow time to adjust to resistance	15	9
Change modality	4	3
Change attachment point	2	1
Provide verbal feedback on technique	22	17
Other	13	12

According to the responses of 73% of the coaches, it has been observed in their experience that RST induces long-term changes to unresisted sprint technique during the acceleration phase. Additionally, 46% of the coaches believed that this also occurs during maxV running. Furthermore, they indicated that CT, FT, SL, SF, and joint angles would be influenced during both the acceleration and maxV phases, as shown in Table 22. Coaches education, certification, years of coaching experience or source of information seemed not to demonstrate any significant association with their perceptions of changes in long-term sprinting technique.

Table 22 Coaches understanding of which spatio-temporal variables are affected by RST acutely and long-term.

		Acute		Long-term	
		Acc	maxV	Acc	maxV
		Proportion of coaches (%)			
Contact time	majorly affected	67	55	22	24
	minorly affected	7	10	24	18
	affected	20	25	38	37
	not affected	5	10	16	21
Flight time	majorly affected	56	50	17	16
	minorly affected	22	15	28	21
	affected	17	23	42	42
	not affected	5	12	14	21
Step length	majorly affected	51	55	27	18
	minorly affected	20	15	22	13
	affected	29	28	46	50
	not affected	0	2	5	18
Step frequency	majorly affected	46	40	11	18
	minorly affected	24	20	22	21
	affected	20	30	41	42
	not affected	10	10	27	18
Joint angle	majorly affected	31	20	26	18
	minorly affected	29	30	16	18
	affected	24	40	53	40
	not affected	15	10	5	24

In addition, coaches (49%) reported to believe that various RS modalities have varying impacts on technique over the long term. However, 27% of the coaches disagreed with this statement, while 24% had not previously taken this into account. Furthermore, 44% of the coaches indicated that a change in long-term technique affects their approach to prescribing resistance during the acceleration and maxV phase. Coaches responses to what they would do in this case are summarised in Table 23.

Table 23 Coaches actions to long-term change in technique during RST.

	Proportion of coaches (%)	
	Acc	**maxV**
Stop using it	2	9
Adjust the resistance	19	15
Make load heavier	4	3
Make load lighter	11	7
Resistance easier	7	6
Resistance harder	2	1
Give them time to adjust to the training modality	20	17
Allow time to adjust to resistance	9	9
Change modality	4	5
Change attachment point	5	5
Provide verbal feedback on technique	19	14
Other	11	12

3.3.9 How changes in technique are being monitored

Frequency analysis revealed that 63% of coaches reported to monitor technique changes during resisted sprinting and 71% for unresisted sprinting. Table 24 details what variables coaches monitor during RST and URS.

The thematic analysis applied to the coaches' responses on how to monitor changes in technique during unresisted and resisted sprinting resulted in three major themes outlined in Table 25 along with exemplar responses for each theme. The first theme, camera, was about group members choosing different types of cameras (i.e. IPhone, high speed camera) for monitoring sprinting technique. The second theme, eye, focused on group members responses indicating that they would watch the athlete to try and see changes in technique. The last theme, technology & software, combines group members answers including monitoring technology like timing gates or radar guns.

Table 24 Variables that coaches monitor during URS and RST.

	Proportion of coaches (%)	
	unresisted	resisted
Sprint time	22	11
Contact time	18	3
Flight time	13	1
Step frequency	16	2
Joint angles	22	9
Segment angles	13	5
I have not considered any of these variables before	0	0
Other	2	10

Table 25 How coaches monitor changes in technique during RS and for URS.

Theme	Example Responses	Number of responses (n)
Camera	"Video camera and Kinovea" "High speed camera" "HSC with app"	24
Eye	"Just watching " "My eye" "Coaches eye"	9
Technology + Software	"Timing gates and Radar" "Muscle lab DynaSpeed/IMU and LaserSpeed/IMU for kinematics" "Optojump"	7

3.4 DISCUSSION

This study sought to conduct a comprehensive survey of coaches' current resisted sprint training practices and coaches perception of how RST alters kinematics. Currently there is a lack of clarity around how coaches implement RST, what drives their decision making with regard to implementation, how they perceive RST to influence kinematics during RST, and how this subsequently affects unresisted sprinting. To the author's knowledge this is the first study to investigate this.

The coaches who participated in this study were highly qualified, with a significant portion (36%) holding a level 2 coaching qualification or higher and 50% holding an S&C accreditation (i.e. NSCA; CSCS). Additionally, 40% of coaches met the criteria for being considered expert coaches based on previous research (i.e. having over 10 years of coaching experience), and 21% had experience coaching international-level athletes.

A majority (92%) of coaches surveyed expressed their belief that RST is beneficial for enhancing sprint performance. Additionally, a notably higher percentage of certified S&C coaches, compared to other certified coaches, appeared to concur that RST serves as a valuable training tool (52% vs. 47%; $\chi2[10]=34.245$; φ-c=-0.6; p=0.000). This association between coaches beliefs and their coaching qualification demonstrated a large effect, in contrast to education or source of information, that did not have any association with coaches beliefs. This finding aligns with previous research as according to Williams, Baghurst and Cahill [47], a significant 82% of the

S&C coaches surveyed expressed strong agreement regarding the usefulness of RST in enhancing SP. It is worth noting that this outcome is not unexpected, given the numerous studies that have highlighted the advantages of RST for SP [280,306,374]. Recently, heavy resisted sled training (50 and 60%Vdec), was used to explore the impact on SP, kinetics, sagittal plane kinematics, and spatiotemporal parameters in professional male soccer players over a nine-week period compared to traditional training [284]. The findings of this investigation demonstrated that both sled-based training groups resulted in significant improvements in 5, 10, 20, and 30 m SP, as well as enhancements in mechanical efficiency, peak power, and peak force, which were not observed in the traditional training group [284].

The 48% of coaches who had high confidence in their theoretical knowledge of RST reported that their main reasons for using RST were to 1) improve force development and technical efficiency, and 2) improve acceleration mechanics and horizontal force production qualities. This is in agreement with research indicating that by overloading the sprint movement, resisted sprinting essentially increases the amount of force required to both accelerate away from a stationary position and to maintain maximal sprinting speed [4].

Scientific or Coaching Journals were the most commonly stated source of information (90%) that coaches used to source their information around RST, which may indicate that coaches are using an evidence-based approach when prescribing RST training. Most coaches expressed a strong to moderate level of confidence in their theoretical knowledge of RST, coaching RST, and training prescription.

Additionally, the source of information regarding RST did not impact the level of confidence in coaches. Whether they obtain information from social media, fellow coaches, or scientific literature, their confidence remained the same. However, 10% of coaches reported that they do not read scientific literature around RST (i.e. using social media) and chose not to explain why they prescribe RST. This is much lower to what was reported in research by Healy, Kenny and Harrison [46], where coaches stated to source information from other coaches (79%). However, it was noted in this current study that the background information pertaining to coaches' education, experience, or coaching certification did not seem to have a significant association on coaches' confidence in their understanding of RST or their perspectives, thoughts, or alternative viewpoints, with the exception of S&C coaches who demonstrated a stronger inclination towards agreeing that RST is advantageous for improving SP.

A majority of the coaches (71%) stated that they would recommend prescribing RST for both initial and late acceleration. Additionally, 85% of coaches acknowledged that the desired outcomes and training components for RST might vary when prescribing it for acceleration and maximum velocity. Only 6% of coaches indicated that they prescribe the same load for the whole group and did not specify loads to each individual athlete or sprint phase. This finding contradicts the study conducted by Williams, Baghurst and Cahill [47], which indicated that coaches would prescribe the same load for both phases (up to 20%BM). Coaches (n = 62) in this study further indicated that loads of 0-20%BW were chosen to improve short-distance sprint performance. Fewer coaches used loads between 20-40%BW (n = 37). Approximately

24% (n = 27) of coaches used loads between 40-60%BW, and a slightly higher percentage of coaches (n = 29) used loads between 60-80%BW. A smaller percentage of coaches (n = 24) used loads over 80%BW This implies that coaches in the current study may possess a more comprehensive knowledge of how to prescribe RST in order to enhance speed and power. However, the coaches participating in Williams, Baghurst and Cahill [47] survey were S&C coaches and around 50% of the coaches had 10+ years of experience and worked primarily with Division 1 college football. In comparison to coaches in this current study where only about 40% had +10 years of coaching experience in speed development. Williams, Baghurst and Cahill [47] did not specify if coaching experience was specified on sprint or speed development. Some scientific practice in coaching for resisted sprinting would involve considering the following key points:

Variation in Prescription: Coaches may consider prescribing resisted sprint training for both initial and late acceleration phases. They should recognise that the desired outcomes and training components of RST may differ when targeting acceleration and maximum velocity. Prescribing the same load for all athletes without individual specifications should be avoided.

Kinematic Changes: Coaches should be aware that loading in RST leads to specific kinematic changes compared to unresisted sprinting. These changes include decreased SL, swing phase duration, SF, FT, but increased CT and trunk lean [149,282,326]. Understanding these kinematic alterations can guide the design and implementation of RST to enhance sprint performance.

Loading: Research suggests that heavier loads in RST (50-60%Vdec) may result in more significant spatiotemporal changes, including increased CT, SF, SL, and reduced touch-down distance and COM angle at touchdown [327]. These changes can lead to improved horizontal force application, reduced braking forces, and enhanced acceleration performance [36,51,328]. Coaches should consider incorporating heavier loads in RST protocols when aiming to target these benefits.

Kinetics and Impulses: RST with heavier sled loads (>20%BM) has been associated with greater reductions in sprint times and changes in kinetic parameters. Heavier loads have shown to decrease resultant and vertical impulses while increasing horizontal force output and propulsive GRF [133]. Coaches should consider these kinetic effects when designing RST programs to enhance sprint performance.

Consider Force Magnitude: Coaches should understand that longer CT and longer propulsive periods require greater force magnitude to overcome higher resistance. This underscores the importance of developing force production capabilities in athletes during RST to improve their ability to generate propulsive forces.

Transfer to Unresisted Sprinting: Long-term training interventions using RST have shown limited changes in CT and joint kinematics across different phases of sprinting [284,330]. However, more longitudinal research is needed to investigate the transfer effects of RST on various joint angles and different athletic populations.

The findings of the thematic analysis presented in Table 17 indicate that coaches choose the RST modality based on either the session goal or its potential impact on an athlete's technique. Moreover, a majority of coaches (90%) expressed their intention to incorporate RST as a means of both technical and physical stimulation. To accomplish this, coaches reported primarily utilising the %BM and %Vdec methods (19% and 26%). Coaches who select %BM over %Vdec do this mainly based on ease of use, information they gathered from literature and a lack of knowledge about %Vdec. The decision to choose %Vdec over %BM was based on factors such as personalisation and insights gathered from various sources of literature. Even though a high number of coaches (70%) reported to source their information regarding RST from scientific literature, the number of coaches who use %Vdec is not very high (26%), leading to the question if coaches either misinterpret the literature, intentionally ignore it based on ease of load prescription or because a lot of the literature in the field used a %BM approach to load prescription [4,297,319,375,376]. Early research prescribed RST loads based on %BM in an attempt to individualise loads, however research clearly has demonstrated that loadings based on body mass do not account for individual variations in strength, power, or technical ability and friction [377].

Among researchers, there is an ongoing and extensive debate concerning the most effective load to be used in training. This debate is fuelled by the fact that there are various methods of loading, including %BM, %Vdec, and absolute loads [12,378]. The discrepancies observed in the literature regarding the optimal load can be attributed, in part, to differences in the methodology of loading prescription and the equipment utilised for both imposing the overload on athletes and measuring the relevant variables being analysed. These measurement tools include timing gates, radar systems, and force plates [2,12,378]. Moreover, the inclusion of athlete variations and the influence of surface frictions adds further complexity to this matter [12,378]. To date, guidelines for practitioners and coaches regarding the most appropriate technology and methodologies for athlete testing and monitoring remain unclear [350], which may add to the problem of misconception.

The majority of coaches (73%) expressed a belief that RST leads to acute technique changes in the acceleration and maxV phase. Studies have shown that increases in sled load are associated with linear decreases in both SL and sprint time [2]. This finding aligns with previous research that found significant increases in CT and decreases in SL (which is desired) when using a 30%BM resistance compared to sprinting without resistance or with a 10%BM resistance [36]. However, it is important to note that changes in SF may vary among athletes, as some studies have found no significant change in mean SF with increased load [2,326]. The use of heavier sled loads for acute sprinting improvements has been debated, as the associated decreases in SL, are by some researchers considered as non-ideal and non-specific for sprinting [2]. However, the decrease in SL is caused by the horizontal overload, which is necessary to increase force production and therefore likely not a problem. That is specific to the goal of increasing horizontal force. This debate might be reflected in the results of the current study, with a 66% of coaches stating that acute kinematic changes influenced their load prescription. Some coaches (26%) reported adjusting the resistance (make the resistance lighter) in response to kinematic changes. A small percentage of coaches (9%) indicated that they would stop using RST altogether in the maxV phase if technique changes occurred. Additionally, coaches believed that RST had an impact on long-term acceleration and maximum velocity unresisted sprinting technique (73% and 46% respectively), and 44% of coaches acknowledged that those changes in unresisted sprint technique (that were perceived as negative changes) would influence their load prescription. Education, coaching background or certification did not appear to have any association with these findings. However, it is important to acknowledge that in sports other than track and field, the focus may be on overall improvements in speed rather than subtle kinematic changes. Therefore, incorporating resisted sprinting can overload SL and potentially enhance overall performance [2]. On the opposing end of the debate research is suggesting the use of heavier loads to induce improvements in short distance sprint performance [280,288,308], as changes in kinematics observed during RST can be advantageous, depending on the specific phase and objective. For example, the use of heavy loaded RST (<20%BM) [37] has been shown to result in an enhancement in horizontal-force production [331]. It is plausible to consider that assuming a more horizontal posture during the acceleration phase may contribute to this effect. When considering RST as a means of increasing movement specific horizontal force, power, and effectiveness, it is possible that much heavier loads could potentially provide an effective training stimulus [37,50,51,319,324,379,380]. According to Zabaloy, Freitas, Pareja-Blanco, Alcaraz and Loturco [303] there is a lack of definitive evidence to support the superiority of heavy or very heavy sled training over sled training when it comes to low-to-moderate sled loads in any of the sprint phases, particularly in team sport athletes. In addition, a substantial amount of evidence suggests that caution should be exercised when using heavy or very heavy loads (i.e., more than 30%Vdec or exceeding 50%BM) due to the evident mechanical, technical, and physiological changes that occur in various sprint-related factors throughout different phases of sprint running [303].

The concerns of coaches regarding changes in sprint kinematics were also evident in their approach to monitoring techniques. A majority of coaches (63%) reported using technology-based equipment to monitor kinematic changes during RST. Video analysis was the most popular resource used, with 46% of coaches using it. The second most common option was coaches observing, chosen by 17% of coaches. 13% of coaches used speed gates and other forms of technology. This finding is consistent with recent literature, which has also highlighted the use of technology-based equipment by Brazilian Olympic sprint and jump coaches (79%), specifically video analysis software, to monitor their athletes [381]. The significance of monitoring technique during RST has been confirmed by Bolger, Lyons, Harrison and Kenny [277], with all coaches expressing its importance, and the majority of them favouring the utilisation of video analysis for this objective. It is worth mentioning, though, that this investigation by Bolger, Lyons, Harrison and Kenny [277] solely consisted of 7 participants, all of whom were highly skilled sprint coaches. Conversely, the sample of our current study encompasses coaches with different levels of expertise, including coaching different sports and having varying years of experience in coaching speed development.

3.5 CONCLUSION

It was observed that coaches considered RST to be a valuable training tool for enhancing sprint performance, based on both their personal experience and scientific literature. However, we observed the following: (1) coaches tend to prefer %BM over %Vdec when selecting RST, primarily due to its ease, existing literature, and lack of familiarity with %Vdec. (2) Coaches typically select RST methods based on their availability, accessibility, logistics, and practicality, rather than solely relying on scientific evidence. In this study, coaches demonstrated an awareness of technique changes during and after resisted sprint training. However, there appears to be a discrepancy between scientific literature and their understanding and therefore the practical application. A significant portion (73%) of coaches acknowledged that RST can cause acute changes in technique during the acceleration and maximum velocity phases, with 66% of them adjusting the training load by making it lighter or reducing the resistance accordingly. Furthermore, a small percentage (14.6%) of coaches indicated that changes in technique could negatively impact unresisted sprint performance, currently unclear in the literature [284].

Implications of this survey are summarised within the following key points:

1. Education on Load Selection: As coaches tend to prefer using %BM over %Vdec when prescribing RST, implications involve educating coaches about the advantages and considerations of using %Vdec. Providing more information and guidance on

load selection methods can help coaches make informed decisions and potentially optimise the effectiveness of RST.

2. Practical Considerations in RST Methods: The survey shows that coaches typically select RST methods based on availability, accessibility, logistics, and practicality, rather than solely relying on scientific evidence. This implies that there is a discrepancy between scientific literature and practical application in terms of RST methods. Implications involve providing coaches with evidence-based guidelines on selecting RST methods that align with both practical considerations and scientific principles.
3. Awareness of Technique Changes: The survey demonstrates that coaches are aware of technique changes during and after RST. The literature provides different perspectives on the impact of kinematic changes observed during RST, with some researchers considering them non-ideal for sprinting while others suggest their potential advantages for specific phases and objectives. The implication is that coaches need to consider the context of their sport, performance goals, and the specific phase of sprinting when assessing the impact of kinematic changes and adjusting load prescriptions accordingly.
4. Use of Heavier Loads for Specific Phases and Objectives: The literature supports the use of heavier loads in RST to induce improvements in short-distance sprint performance, particularly for enhancing horizontal-force production. The survey shows that coaches adjust the training load in response to kinematic changes and acknowledge the impact of RST on acceleration and maximum velocity (un)resisted

sprinting technique. The implication is that coaches can consider incorporating heavier loads in RST for specific phases and objectives, while being cautious about the potential mechanical, technical, and physiological changes associated with heavy or very heavy loads.

5. Consideration of Context and Sport-Specific Needs: It is important to acknowledge that different sports may have varying performance goals and priorities. While there may be debates regarding the ideal resistance and kinematic changes in RST, implications involve considering the specific needs and objectives of different sports when designing RST programs. This includes evaluating the overall improvements in speed and considering the potential benefits of incorporating heavier loads for specific phases or objectives, such as enhancing horizontal force production.
6. Further Research on Optimal Load Prescription: More research is needed to determine the optimal load prescription strategies for RST across different populations and training goals. This includes investigating the effects of different load intensities, exploring the long-term effects of RST on sprint technique and performance, and evaluating the mechanical, technical, and physiological changes associated with various load levels. This knowledge can provide evidence-based guidelines for coaches to enhance the effectiveness of RST.
7. Bridging the Gap between Science and Practice: The survey highlights that coaches often prioritise practicality and accessibility over scientific evidence when selecting RST methods. Future implications involve bridging the gap between scientific literature and practical application, encouraging coaches to consider both factors

when designing RST programs. This can be achieved through coach education programs, knowledge dissemination, and collaboration between researchers and practitioners.

It is crucial for coaching organisations and research institutions to take the lead in bridging the gap between researchers and coaches, in order to minimise the resulting discrepancies and provide coaches with the necessary tools to overcome these challenges.

Chapter Link

The second study aligns with the overarching objectives of the thesis by assessing the reliability of an isotonic sprint device and its potential as a training tool for enhancing sprint performance. It addresses the objectives of the thesis by enhancing our comprehension of kinematic features during resisted sprinting and evaluating the practical implementation of resisted sprint training. Additionally, it offers valuable insights into the practical application of resisted sprint training and highlights the important considerations to keep in mind when incorporating isotonic resistance devices into training programs. This information is intended to assist coaches and athletes in making informed decisions regarding the usage of isotonic resistance devices in sprint training, taking into account the associated considerations and limitations.

CHAPTER 4

4 RELIABILITY OF AN ISOTONIC SPRINT DEVICE

4.1 INTRODUCTION

Resisted sprint training is one of the most effective and popular methods to develop speed, with the most popular methods being, towing a sled, parachute or using mechanical systems [4,32,284]. These devices are used to provide an external overload onto an athlete in an attempt to enhance their physical output and efficiency, while closely mimicking the movement of a sprint [4,312]. Many devices have been shown to be valid and reliable [298,313] but practical issues with using these devices have been highlighted (i.e., transport, weight, friction or high costs) [314]. As a result, an increasing number of coaches have employed isotonic sprint devices to provide an external resistance while sprinting. These devices have demonstrated the ability to improve sprint performance [288], with a four-week training intervention demonstrating improvements in 5 m (7.9% decrease in time), 10 m (5.7%), 20 m (4.2%) and 30 m (3.7%) sprint times in youth soccer players [288]. The Exer-Genie (EG) is a commercially available resisted sprint device providing variable isotonic resistance from 1-500 units of resistance (oz). It can be used in a similar fashion as a sled to provide horizontal resistance during sprinting. Using this isotonic device in a training program may provide enough stimulus to increase the horizontal GRF overtime and subsequent SP [36]. Unlike sleds, which have friction limitations, the EG can be utilised on any type of surface without any constraints. However, it is currently unclear if such a device provides a velocity decrement that is reliable. The authors are not aware of any intrasession or intersession reliability data for the EG. It is important to establish the reliability of any equipment before using it for research or clinical purposes. Reliability is determined by the degree of correlation and agreement between measurements [382]. Thus, in case of the EG we want to know if it provides external load in a reliable manner because the magnitude of load dictates adaptation [383,384], and therefore it is crucial to understand if this load prescription is reliable within and between sessions [382]. Therefore, in order to use the EG as a potential method for enhancing sprinting performance, it is necessary to assess its reliability. The main purpose of this study was to examine the reliability of an isotonic sprint device at 5, 10, 15 & 20 m at three different resistance levels.

4.2 METHODS

4.2.1 Participants

A total of 13 female (4) and male (9) participants (age, 21 ± 1.61 years; height (cm), 178.08 ± 2.88cm; weight (kg), 84.27 ± 10.87 kg) completed the following experimental protocol. Participants were recruited if they (a) had experience with resistance and sprint training (minimum of 18 months), (b) were currently strength training, (c) were currently participating in competitive sprinting, or team sport and (d) were injury free for a minimum of 6 months. These criteria were chosen to improve ecological validity, reduce the chance of injury, and to prevent delayed onset muscle soreness. Written informed consent was received from all athletes prior to participation. The study was approved by the Technological University of the Shannon Ethics Committee (approval code: 20200308), and all procedures were completed in accordance with the declaration of Helsinki.

4.2.2 Experimental Protocol

The present work consisted of a test-retest experimental design with two independent testing and one initial familiarisation session spread across three days. Sessions were separated by five to seven days and were scheduled for the afternoon (2 h maximum), as participants had to attend college. The study involved participants completing 18 sprints (20 m) on an indoor sprint track (Mondo, Sportflex Super X 720 K39, Italy). Participants were attached to a resistance device (Exer-Genie, Thousand Oaks, CA USA), with the resistance levels varying between

2, 5, and 8 oz in a random order over two main testing days. The selection of these loads aimed to represent a range of light, medium, and heavy resistance. This study only indirectly measured the reliability of the load prescription via sprint time (sprint time is an indicator of the resistance and reliability, as it is influenced by the resistance). Sprint time was assessed using photocell timing gates (Brower Timing Systems, 2016, Draper, UT USA), which were set up at 5 m intervals (0-5, 5-10, 10-15, 15-20). The Brower Timing System was selected for testing, as it has previously demonstrated to have good reliability and validity [385]. The within-session and between-session relative reliability (comparison of the three sprints of one session; comparison of the average of the three sprints across days) of the variable sprint time, for each split, was assessed by the intraclass correlation coefficients and their 95% confidence intervals (Figure 15). Participants were asked to refrain from physical performance two days before all testing sessions to ensure an equal state of physical fitness.

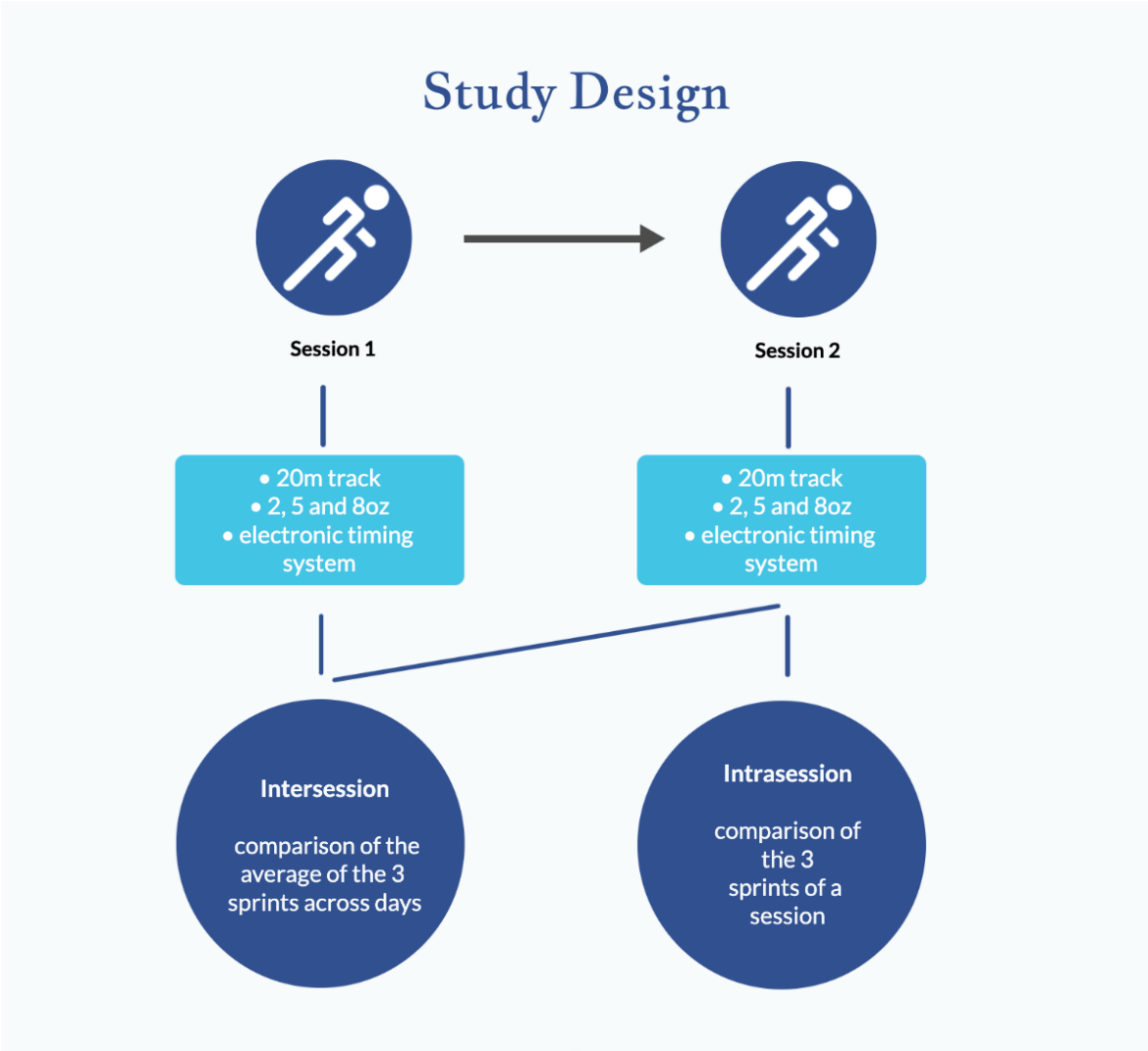

Figure 15 Overview of the study design.

Note that the intrasession reliability was tested on day two.

4.2.3 **Procedures**

The resisted sprints were completed using the Exer-Genie speed trainer (Thousand Oaks, California U.S.A). The EG was set up in five steps.

Step 1: The anchor was secured around a fixed point (railing around the track)

Step 2: The harness was secured on the rope of the EG

Step: 3 The rope was walked out parallel to the sprinting track in a straight line

Step 4: The resistance on the EG was adjusted

Step 5: The participant was strapped in the harness of the EG

For the sprint testing sessions, the first 20 m of a pre-marked 60 m indoor track was used. The beginning and the end of those 20 m were marked by cones. Photoelectric timing gates (Microgate, Bolzano, Italy) were placed at both the start and finish line and at 5 m intervals to record split times [386,387].

At the beginning of every session, all participants completed a standardised 15-minute warm-up using the RAMP protocol, and finished with sprints that increased in intensity, as in Jeffreys [388]. Participants were then provided with a further 5-minutes to complete additional self-selected warm-up exercises. Once the warm-up was completed, participants performed three sprints at each resistance (2, 5 and 8 oz - nine sprints in total-per day). A minimum 5-minute rest period was provided in between each sprint [389].

At the start of each trial the device was attached to the participant by a waist harness which connected on to the rope with a length of 36 m via a safety clip. The device itself was attached to the railing of the sprint track via an anchor strap (91.44 cm) and safety clip (waist height) (Figure 16). The attachment of to the device was checked after each trial. A minimum of 5-minutes recovery was provided between each of the trials. To increase consistency between participants, participants followed these instructions for the testing:

- Participant started precisely 0.3 m behind the first set of timing gates [390].

- Participants used the same front foot for each trial.
- A two-point standing position was used at the start and participants started their sprints of their own volition.
- Participants were instructed to run maximally through the final 20 m timing gate, with cones placed beyond this to encourage this.
- Participants were verbally encouraged to run as fast as possible through the 20m timing gate, and only decelerate after this.
- Participants were checked to wear the same footwear and clothing for all testing sessions.

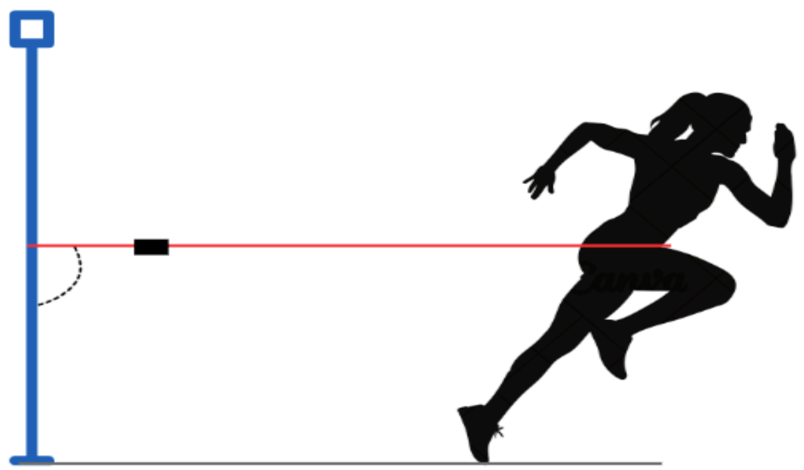

Figure 16 Exer-Genie attachment via a hip harness.

Data Analyses

All reliability comparisons were conducted for the test day and retest day. Initially, all data (dependant variable: sprint time in seconds (5, 10, 15 & 20 m) at all resistance levels) were incorporated into a spreadsheet (Microsoft Excel software Corp., Seattle, WA, USA). Normality was checked with the Shapiro-Wilk test before analysis. Test-retest absolute reliability was measured by the standard error of measurement (SEM), expressed in relative terms through the coefficient of variation (CoV, %). SEM was calculated from repeated measures ANOVA as the root mean square of mean square error ($\sqrt{MS_E}$) [391,392]. In the field of sport science, it has been suggested that CoV ($\frac{SEM}{Mean} \times 100$) values lower than 10% are acceptable [393]. The within-session (ICC2,5) and between-session (ICC2,1) relative reliability of split times (comparison of the three sprints captured during the second session; comparison of the average of the three sprints across testing days) was assessed by the intraclass correlation coefficients and their 95% confidence intervals (95%CI) using JAMOVI version 1.6.23.0 (Jamovi, Amsterdam, NL) with the SimplyAgree Module [394]. Relative reliability was interpreted based on the lower bound confidence intervals (ICC; poor <0.39, fair 0.40-0.69, good 0.70–0.89, and excellent >0.90) [395].

4.3 RESULTS

$ICC_{2,5}$ estimates, and their 95% CI were calculated based on a mean-rating, with 3 sprints captured during the second session across 13 participants. The descriptive data are displayed in Table 27. The within-session reliability measurements for the split times were fair to good (ICC ≥ 0.76, lower bound 95% CI ≥ 0.44) as demonstrated in Table 27. The absolute reliability values (SEM: 0.02 – 0.09; CoV: 3.13 – 7.10%) confirm an acceptable reproducibility over three trials for the majority of split times. $ICC_{2,1}$ estimates, and their 95% CI were calculated based on a single-rating, across two test days across 13 participants. The between-session reliability measurements for sprint time were less reliable, demonstrating poor reliability (ICC ≥ 0.63, lower bound 95% CI ≥ 0.02) with relatively low absolute SEM and CoV.

Table 26 Descriptive measures of the days and of the split times [s].

	Session 1			Session 2		
Split Distance	**2 oz (Mean ± SD)**	**5 oz (Mean ± SD)**	**8 oz (Mean ± SD)**	**2 oz (Mean ± SD)**	**5 oz (Mean ± SD)**	**8 oz (Mean ± SD)**
Split 1 (5 m)	1.26 ± 0.10	1.24 ± 0.09	1.34 ± 0.12	1.33 ± 0.12	1.37 ± 0.11	1.40 ± 0.12
Split 2 (10 m)	0.86 ± 0.08	0.86 ± 0.08	0.97 ± 0.10	0.94 ± 0.09	0.86 ± 0.07	1.01 ± 0.14
Split 3 (15 m)	0.77 ± 0.07	0.79 ± 0.06	0.87 ± 0.07	0.81 ± 0.06	0.79 ± 0.06	0.92 ± 0.16
Split 4 (20 m)	0.70 ± 0.07	0.71 ± 0.06	0.81 ± 0.09	0.75 ± 0.05	0.82 ± 0.05	0.86 ± 0.16

Table 27 Within and between-session relative (ICC with 95% CI) and absolute (SEM and CoV) reliability of the split times [s].

		Between-Session				Within-Session			
		ICC2,1	(95%CI)	SEM	CoV (%)	ICC2,5	(95%CI)	SEM	CoV (%)
2 oz	5 m	0.56	(0.15 - 0.81)	0.07	4.15	0.84	(0.68 - 0.92)	0.05	3.13
	10 m	0.50	(0.10 - 0.78)	0.05	4.59	0.81	(0.64 - 0.91)	0.04	4.00
	15 m	0.56	(0.15 - 0.80)	0.05	5.08	0.89	(0.78 - 0.95)	0.03	3.34
	20 m	0.60	(0.21 - 0.81)	0.05	5.48	0.36	(0.08 - 0.65)	0.09	10.87
5 oz	5 m	0.58	(0.19 - 0.81)	0.08	4.68	0.76	(0.56 - 0.89)	0.06	3.79
	1 0m	0.63	(0.25 - 0.84)	0.06	5.11	0.79	(0.61 - 0.91)	0.06	5.16
	15 m	0.62	(0.25 - 0.83)	0.06	5.24	0.67	(0.44 - 0.85)	0.07	6.89
	20 m	0.46	(0.02 - 0.76)	0.07	7.06	0.87	(0.74 - 0.94)	0.04	4.55
8 oz	5 m	0.21	(-0.21 - 0.59)	0.17	9.93	0.76	(0.56 - 0.89)	0.12	7.10
	10 m	0.25	(-0.23 - 0.63)	0.10	8.38	0.86	(0.72 - 0.94)	0.06	4.50
	15 m	0.22	(-0.26 - 0.61)	0.11	10.34	0.89	(0.78 - 0.95)	0.05	4.47
	20 m	0.13	(-0.34 - 0.55)	0.11	12.02	0.91	(0.82 - 0.96)	0.05	4.65

4.4 DISCUSSION

To the best of the authors' knowledge, this was the first study to assess the reliability of an isotonic sprint device for short sprint distances (20 m) at three resistance levels (2, 5 & 8 oz) in invasion-based team-sport athletes. The majority of split times demonstrated acceptable reliability within and between sessions, apart from within-session for 2 oz at 20 m and between-session for 8 oz at 15 and 20 m. Within-session relative reliability for sprint time was more varied demonstrating fair to good reliability, with one exception at 2 oz for 20 m where reliability was poor. Between-session reliability measurements for sprint time were less reliable, demonstrating poor reliability (8 oz), indicating that measurements were poorly representative and stable over time.

In comparison the split times reported by Godwin, Matthews, Stanhope and Richards [316] demonstrated much greater reliability (within-between session relative reliability - CoV: 2.4-5.8%, ICC2,5: 0.79-0.98; CoV: 2.0-4.1%, ICC2,1: 0.87-0.97) compared to the present study. They examined the reliability of the RunRocket in recreationally trained individuals for two resistance settings (level 0 & 5). Rakovic, Paulsen, Helland, Haugen and Eriksrud [317] reported higher within session reliability for the 1080 Sprint device, CoV ranged from 0.82 to 2.56%, ICC ranged from 0.81 to 0.95, while SEM ranged from 0.01 to 0.05, depending on distance and phase of sprint. However, compared to the present study Rakovic, Paulsen, Helland, Haugen and Eriksrud [317] reported reliability based on ICC and did not interpret reliability based on the lower bound confidence intervals as suggested by Koo and Li [395].

The within-subject variation is greater than previously reported for unloaded 10 m sprint time (CoV = 1.9%) [396]. Another previous study has investigated the reliability of 10 m sprint time with RSS loads of 10 and 20%BM, reporting a CoV of 1.7–5.8% [1]. Athletes in the current study, compared with Maulder, Bradshaw and Keogh [1] and Meylan, McMaster, Cronin, Mohammad, Rogers and DeKlerk [396] sprinted over longer distances (up to 20 m). The resistance experienced in this current study was comparatively greater over the longer distance, potentially leading to increased fatigue and explaining the observed within-subject variation when compared to [1]. However, to date we do not know how different resistance settings on the EG translate into Vdec or %BM. It is possible that the relatively smaller sample size used in the present study may have contributed to the high within-subject variation observed in physical performance parameters. This is consistent with previous research findings which suggest that larger sample sizes tend to decrease variability [397].

The above-mentioned studies yielded reliable results ranging from satisfactory to excellent. However, there are many advantages to using the isotonic sprint device and several reasons why the Exer-Genie has become popular in recent years. It is a lightweight and portable piece of exercise equipment, which is especially useful when fields are far away, and heavy resistance is not practical to carry (i.e. sled and weights). In addition, the isotonic sprint device offers various resistance options that are beneficial for sprinting, which are convenient to adjust quickly, allowing users to switch between resistance settings within seconds [398,399]. When used for group training, the device can be attached to goal posts or fences to accommodate multiple athletes at once [400]. However, it is worth noting that finding an anchor point to use the device may pose a challenge if one is not readily available at the training facility, which never poses a problem with a sled. The EG is a versatile tool that can be used on any surface. Although mechanical systems like the dynaSpeed and 1080 Sprint also have no surface friction issues, they may not be as affordable as the EG.

Sleds used for RST can face challenges related to the friction between the sled and the surface [320,401-403]. These challenges can complicate load selection for the training. For example, different training surfaces, such as grass, turf, or pavement, can have varying levels of friction [401]. The coefficient of friction between the sled and the surface determines how much resistance is experienced during sprinting. It becomes difficult to accurately predict and control the amount of friction, making load selection challenging. Moreover, friction between the sled and the surface can vary throughout a sprint [404,405]. As an athlete accelerates, the frictional force may change, leading to inconsistent resistance during the sprint. This inconsistency can make it challenging to select an appropriate load for training, as the resistance may not be consistent across the entire sprint distance. Factors such as foot strike, body angle, and SL can affect how the sled interacts with the surface. As athletes modify their technique during sprinting, the frictional forces and resulting resistance can change, further complicating load selection. Finally, the design and construction of the sled itself can contribute to challenges related to friction and load selection [406]. Sleds may have different types of runners or skids, which interact with the surface. The material, shape, and condition of these components can influence the friction and resistance experienced during training. Inaccurate or inconsistent sled design and construction can make it difficult to standardise the load selection process. However, there is a lack of clarity around how much resistance the EG is actually providing. Given the linear relationship between load and decrement in maximal velocity [12], the Vdec approach has been suggested as an appropriate way to prescribe resistive sprint loads [407]. Individual load–velocity profiles allow coaches to prescribed individual training by identifying the load for each individual that causes a given decrement in velocity. This provides practitioners with a simple method to standardise the training stimulus across individuals, with different training goals expressed relative to Vdec [12]. Various percentages of Vdec indicate training zones that are suitable for either speed or force-oriented training [12]. Therefore, it would make sense to prescribe load for isotonic sprint devices in a similar manner after an acceptable reproducibility of the resistance settings (2 & 5 oz) has been demonstrated, future research should investigate how the different resistance settings equate to Vdec.

Limitations

The study examines the reliability of an isotonic sprint device among a particular group of team sport athletes. However, different populations may exhibit variations in physiological characteristics such as muscle fibre composition, body composition, aerobic capacity, anaerobic threshold, and muscle strength. These differences can affect how individuals respond to training or performance measurements. For example, the reliability of an isotonic sprint device may vary between team sport athletes and endurance runners due to differences in their physiological profiles. Moreover, sex can also play a role in the reliability of performance measurements. There may be differences between males and females in terms of muscle mass, hormone levels, and biomechanics. This can influence the reliability of performance measurements between sexes. Considering these factors, it is crucial to interpret research findings within the context of the specific population studied. Extrapolating the results of a study conducted on team sport athletes to other groups, such as endurance runners or individuals with different physiological characteristics, may not accurately reflect the reliability or applicability of the findings in those populations. To ensure the relevance of research, it is important to conduct studies that include diverse populations and consider the specific physiological characteristics and demands of each group.

Due to the nature of the loads used in this study (2, 5, and 8 oz), the chosen loading protocols resulted in different percentages of Vdec for each participant. Consequently, it is unclear what impact these protocols have on velocity. Since this was not the main focus of the study, it would be beneficial for future research to quantify the effect of EG resistance on velocity in order to develop a training program based on Vdec. Additionally, it would have been beneficial to include an unresisted condition in this study. The unresisted condition could have helped to identify measurement errors or variations in the testing procedure itself. (If there is a significant difference between repeated measurements in the unresisted condition, it may indicate issues with the timing system, the track surface, or other factors that could affect the reliability of the measurements.)

Finally, it is important to note that this study indirectly assessed the reliability of the load prescription via time which has its limitations. While split times can provide insights into performance, they do not directly measure the resistance applied by the device. This indirect measurement approach may not capture the full extent of variations or inconsistencies in the resistance levels. The reliability of split time measurements may be influenced by various factors other than the resistance levels. For example, athlete fatigue, technique variations, or environmental conditions could impact sprint performance and introduce additional variability in split times. Therefore, it becomes challenging to attribute the observed variations solely to the reliability of the prescribed resistance levels.

4.5 IMPLICATIONS AND CONCLUSION

The implications of the study assessing the reliability of an isotonic sprint device for short sprint distances (20 m) at three resistance levels (2, 5, and 8 oz) in field-based invasion team-sport athletes are as follows:

Appropriate resistance levels: The study found that the majority of split times demonstrated acceptable reliability within and between sessions. This suggests that the selected resistance levels of 5 oz for within-session measurements and 2 & 8 oz for between-session measurements were generally appropriate for assessing sprint performance in the given population.

Within-session reliability: The within-session relative reliability for sprint time was varied, ranging from fair to good, indicating that the device generally produced consistent results within a single session. However, there was an exception at 2 oz for 20 m where the reliability was poor. This suggests that the device may not be reliable for measuring sprint times at 20 m with a resistance level of 2 oz within a single session.

Between-session reliability: The between-session reliability measurements for sprint time were less reliable overall, demonstrating poor reliability. Specifically, the measurements were poorly representative and stable over time for the 8 oz resistance level. This implies that the device may not be suitable for accurately tracking changes in SP over multiple sessions at 15 m and 20 m with 8 oz of resistance.

Practical implications: The findings have practical implications for researchers, coaches, and athletes using the EG. If the load is not consistent then coaches cannot be confident in how much load is being applied, how heavy this is for the athlete, and how much work they have completed. Thus, influencing the coaches capacity to programme and periodise effectively. Therefore, coaches should be cautious when interpreting and comparing sprint time results obtained from this device, particularly when using the 8 oz resistance level between sessions and the 2 oz resistance level within a session at 20 m. Other methods may need to be considered for more reliable and consistent measurements in these specific scenarios.

Further research: The study highlights the need for further research to explore alternative protocols that can improve the reliability of sprint time measurements, especially at specific distances and resistance levels where the current device showed poor reliability. Additionally, investigating potential factors influencing the device's performance, such as athlete characteristics or technique, could provide insights into improving its reliability.

Overall, while the majority of split times demonstrated acceptable reliability within and between sessions for the isotonic sprint device, caution should be exercised when interpreting results at specific distances and resistance levels. Further research is necessary to enhance the reliability of measurements and identify factors that influence the device's performance in athletes.

Chapter Link

The transition from the exploration of reliability in resisted sprinting to the investigation of acute kinematic changes in this research narrative marks a pivotal juncture in our pursuit of comprehending the multifaceted nature of RST. The previous chapter, which delved into the measurement reliability of a resisted sprint device. It also established the premise that accurate and dependable data are vital for understanding the training implications of RST. Building upon this foundational understanding, this chapter embarks on an exploration of acute kinematic changes during RST, providing a more nuanced view of how resisted sprinting influences kinematics of athletes. While the preceding chapter emphasised the methodological aspect, this chapter immerses us in the dynamic world of sprinting mechanics and investigates how these mechanics are altered under the influence of external resistance. Furthermore, this chapter serves as a continuum of the investigation initiated in the earlier sections of the thesis. It leverages the insights garnered regarding the reliability of measurement and extends them into the practical realm by applying these measurement techniques to assess acute kinematic alterations. Through this interconnected approach, I aim to draw comprehensive conclusions regarding the practical implications of RST on athletes' kinematic profiles and, by extension, their sprinting performance. Ultimately, this chapter builds upon the foundational understanding of RST's biomechanical effects, bringing us one step closer to discerning its true potential as a training tool for enhancing sprint performance.

CHAPTER 5

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5 RESISTED SLED SPRINT KINEMATICS: THE ACUTE EFFECT OF LOAD AND SPORTING POPULATION

Osterwald, K. M., Kelly, D. T., Comyns, T. M., & Catháin, C. Ó. (2021). Resisted sled sprint kinematics: the acute effect of load and sporting population. Sports, 9(10), 137.

5.1 INTRODUCTION

Sprinting is a powerful action where the muscles of the lower limbs produce high amounts of vertical and horizontal net force with each step [13]. Research indicates that the body is oriented with a large degree of forward inclination during the acceleration phase but becomes more upright as velocity increases and as athletes progress through a sprint [124,408]. Recent literature has established that acceleration and maximal velocity SP are related to the technical ability to apply resultant ground reaction forces in a more horizontal direction [92]. Thus, faster athletes have a constant forward orientation, not only through acceleration but also in the maximum velocity phase [13,92].

When attempting to improve SP, an increase in the ability to produce force and power, and/or improved technical execution is targeted [4]. Resistance training is a way of improving muscular power [24,25,29,106] and exercises such as squats, power cleans and deadlifts make up the base of most of the strength and conditioning programs for athletes to develop speed and power [24,25,29]. However, given that movement similarity is a key component of the principle of specificity [210], it may be logical to assume that the addition of external load during a sprint may more closely mimic the action of sprinting while targeting increased force and power output due to the additional resistance. Resisted sled sprinting has become a common sprint training method utilised by many sports teams and athletes [4,288], and its popularity is reflected in its inclusion in several recent publications

[4,32,34,149,278,280,282,284,285,291,295,296,301,302,305,319,325,345,349,353,357,409-414].

In addition, multiple systematic reviews have demonstrated positive effects of RST on SP across multiple loading conditions [4,334]. More specifically, RST appears to significantly improve acceleration [4] (effect size (ES) 0.61) [334], but not maximum velocity performance ($p > 0.05$, ES 0.27) [334]. However, to date there remains a lack of clarity around how loading influences kinematics during resisted sprinting, which, as stated, is important as movement similarity is a key component of specificity [334].

A number of studies have assessed kinematics and demonstrated that loading (10-40%BM) resulted in decreased step length, swing phase duration, step frequency, but increased contact time (CT), trunk lean and knee flexion [288,295,304]. To date, only one study has assessed multiple loading strategies (light to heavy) on the same participants, across different phases of a sprint. However, this study only assessed trunk lean and did not examine any lower body joint angles [337]. This is important as it may influence how resisted sprinting is prescribed when targeting improvements in either acceleration or maximum velocity performance.

Furthermore studies have not compared different sporting populations, and it is therefore unclear if athletes from different sports with varying physiological characteristics display similar kinematics when completing RST at different loads [2,34,149,278,284,285,288,295,302,304,305,349,352,354]. For example, it is plausible that sports that place a larger training emphasis on sprinting (Sprinters Vs. Team sport athletes) may provide athletes with a greater ability to complete RST under heavier loads, without negatively impacting sprint kinematics. However, this is currently unknown.

The results of this study will provide coaches with important information that may influence how RSS is employed as a training tool to improve SP for acceleration and maximal velocity running and how prescription may change based on sporting population. With this in mind, the aim of this study was to examine the kinematic characteristics of RSS under different loading conditions and compare how these loads influence kinematics in sprint athletes and invasion team sport athletes.

5.2 METHODS

5.2.1 Participants

Thirty healthy participants (sprint athletes (n=10), female (n=4), male (n=6); team sport athletes (n=20), Gaelic football (n=19), Soccer (n=1), female (n=3), male (n=17), 21.4 ± 3.3 years, 185.8 ± 8.2 m, 85.2 ± 11.8 kg) volunteered and provided written informed consent. Participants were recruited if they (a) had experience with resistance and sprint training (minimum of 18 months), (b) were currently strength training (three times a week), (c) were currently participating in competitive sprinting or team sport and (d) were injury free for a minimum for 6 months. These criteria were chosen in order to reduce the chances of a possible injury and to prevent delayed onset muscle soreness which might be caused by the dynamic nature of the testing protocols, as well as to improve ecological validity. The study was approved by the Athlone Institute of Technology Ethics Committee (20180206), and all procedures were completed in accordance with the declaration of Helsinki.

5.2.2 Experimental Approach to the Problem

This study assessed the kinematics of sprint and team sport athletes during RSS at multiple loads (unloaded, 10, 20, and 30%Vdec) using a between-within repeated measures design. Athletes completed 2 testing days that included a familiarisation day and an experimental day, which were separated by a minimum of 48 hours.

On both days participants completed 40 m sprints (12 each) on an indoor running track at each of the above listed loading conditions. Kinematics were only assessed during experimental measures.

5.2.3 Procedures

The following set-up was employed during both familiarisation and experimental trials. Timing gates (Brower Timing Systems, 2016, Draper, UT USA) were placed at 5 m intervals over a 40 m distance on an indoor running track (Mondo, Sportflex Super X 720 K39, Italy). The Brower Timing System was selected for testing, as it has previously demonstrated to have good reliability and validity [385]. As the athlete accelerated and moved forward, they passed through the gates. When the athlete's body (hip) crossed through this zone, they interrupted the infrared single beams, briefly blocking the light from reaching the sensor on the opposite side. This interruption was detected by the gate's sensors. The moment the athlete's movement triggered the beams was precisely recorded as the starting time for their race or performance [385]. For resisted runs, a weighted sled was attached to each participant by a 3.6 m cord and waist harness to minimise lateral displacements during sprinting van den [294]. On each day, prior to the commencement of trials participants completed a standardised 15- minute warm up using the RAMP protocol, and finished with sprints that increased in intensity, as in Jeffreys [388].

Participants were then provided with a further 5-minutes to complete additional self-selected warm-up exercises. The warm-up included:

R – 400 m jog on the indoor track,

A - Squats, lunges, split squats, arms swings, A - skips,

M - World's greatest stretch, bretzel stretch, leg kicks, calf pump and stretch,

P - 3 sub max runs at 75%, 85% and 90% [388].

Familiarisation: Participants performed three 40 m sprints at each loading condition (unloaded, 10, 20 and 30% Vdec) in a randomised order. A minimum 5-minute rest period was provided in between each sprint [290]. The method for calculating the load-velocity relationship established by Lockie, Murphy and Spinks [149] was employed to estimate loading during familiarisation trials. However, data generated from these trials was then used to adjust loadings by creating an individual linear regression equation for each participant that indicated the required load to reach the planned Vdec (10%, 20% and 30%Vdec) [329]. Participants wore athletic training shoes (no spikes, boots, or cleats) to ensure the consistency of the measurements when comparing different types of athletes.

Experimental trials: Participants performed three 40 m sprints under each loading condition. Multiple trials help improve the reliability and accuracy of the data collected. A single trial might be influenced by various factors, including random variations and external influences (e.g., wind, surface conditions) [415]. Averaging the results from multiple trials reduces the impact of these variables. While fatigue is a consideration, conducting three trials for each condition is a standard practice to enhance data reliability. A minimum 5-minute rest period was provided in between each sprint [389]. Participants conducted 12 sprints in total: three with a load of 10% velocity decrement, three with a load of 20 % velocity decrement, three with a load of 30% velocity decrement and three unloaded sprints. The athletes started with unresisted sprints and then completed the remaining loads in a randomised order. In addition to the set-up described above, sprints during experimental trials were recorded for examination on two different high-speed cameras (HSC). The experimental set-up can be seen below in Figure 17. The HSC were placed at nine metres from the middle of the athlete's lane and the optical axis of the HSC was perpendicular to the direction of running. The HSC (Sony RX10 III, IPhone 7) were set at a height of 0.85 metres and mounted on a rigid tripod, and the frame rate was set at 250 Hz [1,416]. Each of the two cameras had a field of view of 5 m. The first camera captured the first 5 m (0-5 m), which was considered as the early acceleration phase and the second camera captured 5 m between 25-30 m, which was considered as the maximum velocity phase [289,295]. Sprinters build up momentum as they accelerate. The athletes had to continue sprinting beyond the data collection zone (up to 40 m) to maintain their momentum and ensure they were running at their maximal speed when they crossed the finish line. This can provide more accurate data on an athlete's maximum speed. To make video analysis easier, markers (zinc oxide tape) were placed on the right-hand side of the participants’ body. Landmarks were established through palpation and exact locations can be seen in

Table 28 below [281]. A metre stick was placed in the field of view of each camera, for scaling purposes [417]. Timing gates at 5 m intervals (nine sets) allow coaches and researchers to obtain a detailed velocity profile of the sprint. To precisely measure how an athlete's speed changes throughout the 40 m sprint, providing insights into acceleration and maximum speed, the timing gates were placed in 5 m intervals.

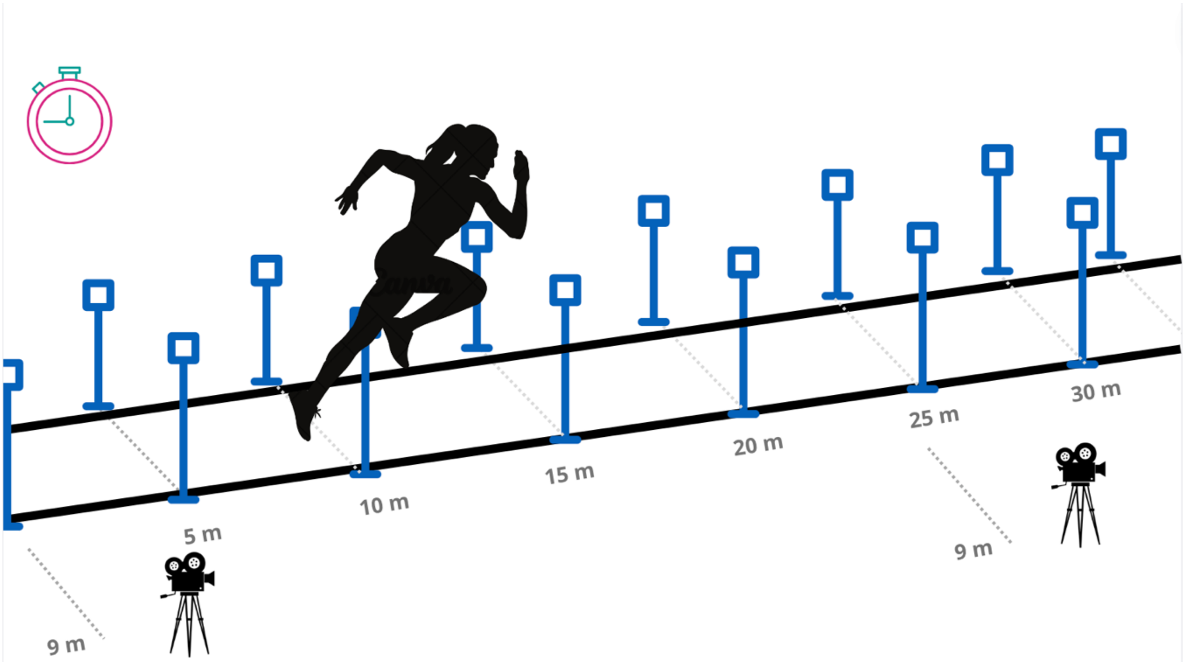

Figure 17 Experimental Set-up.

Table 28 Marker placement landmark description.

Landmark	Description
Shoulder	Acromion process
Hip	Greater trochanter, located at the proximal, lateral part of the shaft of the femur
Knee	Lateral condyle, at the superior end of the tibia
Ankle	Lateral malleolus, at the low end of the fibula
Toe	Fifth metatarsal bone / transmetatarsal joint at the distal outer edges of the foot (on the shoe)

High-Speed-Video Analysis: The video footage collected from the two HSC was captured, and a kinematic analysis was completed with Dartfish Software (Fribourg, Switzerland). The tools incorporated into Dartfish high speed video analysis software facilitate the slowing down and magnification of video images in order to calculate joint angles. Joint (trunk, hip, knee, and ankle) angle variables were calculated for the first two contacts of the right foot during the acceleration phase and one (first right foot contact) during the maximum velocity phase of each trial [64]. One step for the maxV phase was deemed sufficient, as kinematics are more consistent due to the athlete sprinting at constant velocity [30]. Hip angle is neutral when thigh and trunk are aligned vertically. When the hip angle is getting bigger it is the action of extension, when it getting smaller it is the action of flexion. For the knee joint, 'neutral' can be defined as the position where the thigh and lower leg are in alignment, forming a straight line. When the knee angle increases, it indicates the action of knee extension, where the leg is straightening. Conversely, when the knee angle decreases, it signifies knee flexion, indicating that the leg is bending. Regarding the ankle joint, 'neutral' can be defined as the position where the foot is neither pointed downward (plantarflexion) nor upward (dorsiflexion). At this neutral position, the ankle angle is considered to be 90 degrees. When the ankle angle increases, it signifies plantarflexion. Conversely, when the ankle angle decreases, it represents dorsiflexion. (A decrease in angle refers to the angle becoming smaller and an increase as becoming bigger.) All angles were measured at toe-off (TO), first frame in the video where foot had left the ground and touch-down (TD), first frame in the video where foot had contact with the ground [329]. TO and TD were selected as a reflection of what is happening during the force producing component of each stride. Ground contact time is defined as the time between initial ground contact and toe-off and in Dartfish the time of the event of TO was subtracted from the time of the event of TD to calculate CT. Range of motion (ROM) for all loading conditions was calculated from the angles measured at TD and TO as follows. $Percentage\ Change = \frac{(TO-TD)}{|TD|} * 100$. Percentage change equals the change in value $(\mathrm{TO} - \mathrm{TD})$ divided by the absolute value of the original value (TD), multiplied by 100. Joint angle definitions in the sagittal plane are shown in Figure 18.

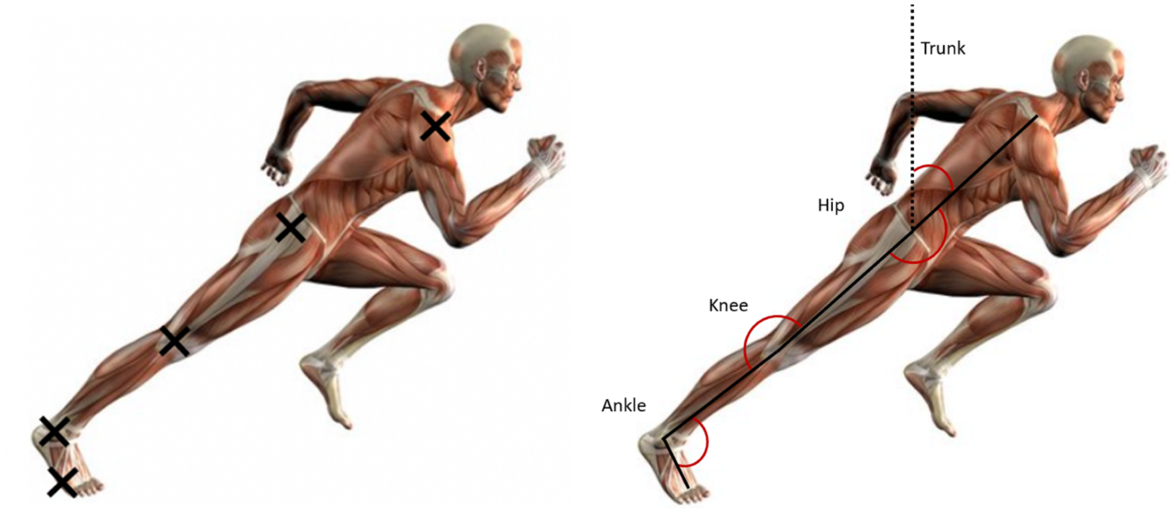

Figure 18 Marker placement.

Note that: Used to define segments and simplify Dartfish analysis and joint angle definition in the sagittal plane (Partly amended from FisioSport Pavona [418].

5.2.4 **Statistical Analysis**

All data are reported as mean values with standard deviation. Normality of data was determined using the Shapiro-Wilk test. Multiple between-within mixed-model ANOVAs were performed to examine differences for joint angles and CTs between groups (field sport athletes vs. sprint athletes) and within groups (unloaded, 10%Vdec, 20%Vdec and 30%Vdec). Two-way ANOVAs were performed to examine differences in joint angles between acceleration and maximum velocity phase. Mauchley's test was used to examine sphericity. In cases where the assumption of sphericity was violated, a Greenhouse-Geisser correction was employed. Homogeneity of variance was examined using Levene's test. Post-hoc testing using Bonferroni was used to identify where differences lay. Effect size (ES) values, partial eta squared (η2p), were also calculated. Threshold values for ES statistics were small (0. 01), medium (0. 06), and large effects (0. 14) [419]. The level of significance was set at as p = 0.05. Statistical calculations were performed using IBM SPSS 20.0 (Chicago, IL, USA) and MATLAB (R2018a, MathWorks, MA, USA). Intra-tester and inter-trial (between sprints) reliability for joint angles was assessed by intraclass correlation coefficient (ICC), coefficient of variation (CV%), and typical error (TE) with 95% confidence intervals, using Hopkins spreadsheet [301]. Four trials were tested and retested for intra-tester reliability.

5.3 RESULTS

All results for CT and joint angles for early acceleration and maximum velocity can be found in Table 29 Ground contact times [s] between groups. The Shapiro-Wilk test revealed that all data was normally distributed for the acceleration and maximum velocity phases. No significant group*load interactions were identified for any variables, and therefore only main effects for load and group are reported below.

5.3.1 Reliability

For within session (between sprints), ICC with 95% confidence intervals and CV% showed excellent reliability for all kinematic variables (0.96 – 1.00, CV%: 1.78 – 3.39). Intra-tester reliability (the same sprint was analysed twice) also displayed excellent reliability for all variables (0.96 – 1.00, CV%: 0.63 – 2.99).

5.3.2 Contact Times

Contact time displayed no significant difference between groups for both the acceleration and maximum velocity phase ($p > 0.05$). However, there was a significant main effect of load during the acceleration phase for step 1 and 2 ($F(3,84) = 28.540$, $p<0.05$, $\eta p2 = .505$); ($F(3, 84) = 74.935$, $p<0.05$, $\eta p2 = .728$), and during maximum velocity ($F(3, 63) = 9.228$, $p<0.05$, $\eta p2 = .278$). Post-hoc analysis indicated significant differences between unloaded and 10%Vdec, unloaded and 20%Vdec and unloaded and 30%Vdec (average increase, .016s - .046s, $p<0.05$, 95% CI [-.022

to -.010], [-.031 to -.020] and [-.056 to -.035]) during the acceleration phase, and between unloaded and 30%Vdec during maximum velocity (average increase .039s, p<0.05, 95% CI [-.072 to -.006]) Table 3.

Table 29 Ground contact times [s] between groups.

		First Ground Contact		Second Ground Contact		MaxV Ground Contact	
Load	Group	Mean	SD	Mean	SD	Mean	SD
0%	Sprint	0.178	0.018	0.147	0.010	0.111	0.009
	Team	0.202	0.027	0.163	0.015	0.136	0.064
	Total	0.194	0.027	0.158	0.016	0.128	0.054
10%	Sprint	0.198	0.017	0.164	0.011	0.121	0.008
	Team	0.220	0.027	0.178	0.019	0.129	0.014
	Total	0.212*	0.026	0.173*	0.018	0.126	0.013
20%	Sprint	0.221	0.038	0.173	0.014	0.135	0.012
	Team	0.233	0.037	0.188	0.021	0.147	0.016
	Total	0.229*	0.037	0.183*	0.020	0.143	0.015
30%	Sprint	0.223	0.023	0.202	0.024	0.160	0.018
	Team	0.248	0.046	0.200	0.028	0.164	0.023
	Total	0.240*	0.041	0.201*	0.026	0.163	0.021*

* p<0.05 significant difference compared to 0%Vdec (unloaded). Note that mean ± SD reported.

5.3.3 Joint Angles

There was no significant main effect of group for any joint angles examined (Table 30).

Acceleration Phase Step 1: Increased load resulted in an increase in knee flexion, with differences occurring between unloaded and 10%Vdec (average decrease 3.8 degrees, p<0.05, 95% CI [.481 to 7.249]), between unloaded and 20%Vdec (average decrease 7.1 degrees, p<0.05, 95% CI [4.052 to 10.338]) and between unloaded and

30%Vdec (average decrease 10.4 degrees, p<0.05, 95% CI [6.159 to 14.766]). No other significant differences were observed for step 1.

Acceleration Phase Step 2: A similar pattern was displayed for hip angle at TO, with differences observed between unloaded and 20%Vdec (decreased by 5.8 degrees, p<0.05, 95% CI [1.392 to 10.263]) and between unloaded and 30%Vdec (decreased by 7 degrees, p<0.05, 95% CI [2.239 to 11.876]). Besides hip angle, loading increased knee flexion at TD with a significant difference between unloaded and 10%Vdec (average decrease 3.4 degrees, p<0.05, 95% CI [.297 to 6.528]), between unloaded and 20%Vdec (average decrease 7.6 degrees, p<0.05, 95% CI [3.155 to 12.225]), between unloaded and 30%Vdec (average decrease 10.7 degrees, p<0.05, 95% CI [6.843 to 14.612]), and between 10% and 20%Vdec (average decrease 4.2 degrees, p<0.05, 95% CI [.804 to 7.751]). Loading increased ankle dorsiflexion at TD with differences between unloaded and 10%Vdec (average decrease 5.3 degrees, p<0.05, 95% CI [.578 to 10.037]).

Similarly, trunk lean increased at TD&TO with differences observed between unloaded and 10%Vdec (average increase 4.3 degrees, p<0.05, 95% CI [-7.828 to -.817]), between unloaded and 20%Vdec (average increase 7.8 degrees, p<0.05, 95% CI [-13.223 to -2.502]) and between unloaded and 30%Vdec (average increase 6.7 degrees, p<0.05, 95% CI [-10.392 to -3.103]). Differences occurred at TO for trunk lean between unloaded and 10%Vdec (average increase 4.2 degrees, p<0.05, 95% CI [-7.860 to -.690]), between unloaded and 20%Vdec (average increase 6.7 degrees, p<0.05, 95% CI [-9.989 to -3.466]), between unloaded and 30%Vdec (average increase 7.2 degrees, p<0.05, 95% CI [-10.105 to -4.385]), and between 10% and 20%Vdec (average increase 2.4 degrees, p<0.05, 95% CI [-4.808 to -.097]).

MaxV: Statistical analysis revealed a significant main effect of load on trunk lean at TD and TO. Differences at TD occurred between unloaded and 20%Vdec (average increase 6 degrees, p<0.05, 95% CI [-11.800 to -.236]), between unloaded and 30%Vdec (average increase 12.4 degrees, p<0.05, 95% CI [-18.745 to -6.684]) and between 10% and 30%Vdec (average increase 10.5 degrees, p<0.05, 95% CI [-16.855 to -4.183]). At TO differences were observed between unloaded and 20%Vdec (average increase 9.5 degrees, (p < 0.05, 95% CI [-13.665 to -5.484]), between unloaded and 30%Vdec (increase 14.4 degrees, p<0.05, 95% CI [-20.117 to -8.733]), between 10% and 20%Vdec (average increase 6 degrees, p<0.05, 95% CI [-11.862 to -.047]), between 10% and 30%Vdec (average increase 10.8 degrees, p<0.05, 95% CI [-18.238 to -3.373]), and between 20% and 30%Vdec (average increase 4.8 degrees, p<0.05, 95% CI [-9.501 to -.201]).

5.3.4 Range of Motion

A between-within mixed-model ANOVA was performed to examine differences in range of motion for different loading conditions.

Acceleration Phase Step 1: There was a significant main effect of load ($F(3, 84) = 6.243$, $p = .002$, $\eta p2 = .419$) and group ($F(1, 28) = 9.134$, $p = .005$, $\eta p2 = .246$) for knee ROM, with the sprint group displaying a larger ROM by an average of 10.1%. Furthermore, post-hoc analysis revealed a significant difference in ROM between unloaded and 20%Vdec (increase: 4.8%, $p < 0.05$, 95% CI [-9.340 to -.285]) and unloaded and 30%Vdec (increase: 6.8%, $p < 0.05$, 95% CI [-11.847 to -1.868]) for the whole group.

Acceleration Phase Step 2: There was a significant main effect of load for knee ROM ($F(3, 84) = 13.985$, $p = .000$, $\eta p2 = .617$) and group ($F(1, 28) = 12.058$, $p = .002$, $\eta p2 = .301$), with the sprint group demonstrating a larger ROM by an average of 8.2%. Pairwise comparison revealed a significant difference in ROM between unloaded and 10%Vdec (increase: 4.4%, $p < 0.05$, 95% CI [-8.233 to -.658]), unloaded and 20%Vdec (increase: 8.4%, $p < 0.05$, 95% CI [-12.560 to -4.245]), unloaded and 30%Vdec (increase: 10.9%, $p < 0.05$, 95% CI [-16.054 to -5.782) and similarly, between 10% and 30%Vdec (increase: 6.4%, $p < 0.05$, 95% CI [.658 to 8.233) for the whole group. In addition, there was a significant main effect of load ($F(3, 84) = 4.377$, $p = .013$, $\eta p2 = .336$) but not for group ($F(1, 28) =.541$, $p = .468$, $\eta p2 = .019$) for ankle ROM. Pairwise comparison revealed a significant difference in ROM between unloaded and 10%Vdec (increase: 9%, $p < 0.05$, 95% CI [-15.942 to -2.101]) only.

MaxV: There was a significant main effect of load ($F(3, 63) = 4.377$, $p = .002$, $\eta p2 = .537$) but not group ($F(1, 21) = 2.530$, $p = .127$, $\eta p2 = .108$) for knee ROM. Pairwise comparison revealed a significant difference in ROM between unloaded and 30%Vdec (increase: 10.4%, $p < 0.05$, 95% CI [-16.839 to -4.016]). Furthermore, there was a significant main effect of load for ankle ROM ($F(3, 63) = 4.597$, $p = .014$, $\eta p2 = .421$) but not group ($F(1, 21) = .334$, $p = .\ 570$, $\eta p2 = .016$). Pairwise comparison revealed a difference in ROM between unloaded and 30%Vdec (increase: 10.8%, $p < 0.05$, 95% CI [-23.804 to 2.105]). No other variables reached significance ($p > 0.05$). During maxV there were no group differences.

Finally, hip ROM was not impacted by any of the loads for both acceleration and maximum velocity phases.

Table 30 Mean ± SD kinematic variables for acceleration phase steps 1 (S1) and 2 (S2) and maxV phase for all athletes.

Acceleration phase Step 1								
	Hip		Knee		Ankle		Trunk	
Load	**TD**	**TO**	**TD**	**TO**	**TD**	**TO**	**TD**	**TO**
0%	101.7 (± 9.46)	177.2 (±7.34)	112.3 (±7.89)	146.7 (±9.55)	102.5 (±8.74)	136.9 (±9.66)	48.2 (±19.34)	45.7 (±19.40)
10%	97.6 (±10.84)	170.9 (±14.09)	108.4 (±8.46)*	144.1 (±21.78)	101.2 (±8.43)	135.2 (±9.10)	51.7 (±14.81)	46.8 (±6.51)
20%	98.4 (±11.58)	171.3 (±7.13)	105.1 (±8.27)*	146.3 (±9.91)	99.1 (±19.75)	136.3 (±9.84)	49.1 (±7.34)	47.8 (±5.90)
30%	99.9 (±11.69)	170.1 (±8.80)	101.8 (±7.39)*	144.7 (±10.29)	98.6 (±19.08)	135.2 (±9.24)	48.6 (±8.15)	46.9 (±5.18)
Load	p = .166, ηp2 = .058	p = .145, ηp2 = .084	p<0.05, ηp2 = .464	p = .553 ηp2 = .015	p = .724, ηp2 = .015	p = .513, ηp2 = .027	p = .629, ηp2 = .015	p = .578, ηp2 = .008
Group	p = .385,ηp2 = .072	p = .055, ηp2 = .049	p = .545, ηp2 = .013	p = .058, ηp2 = .122	p = .133, ηp2 = .079	p = .750, ηp2 = .004	p = .872, ηp2 = .001	p = .688, ηp2 = .006
Acceleration phase Step 2								
0%	113.5 (±9.15)	177.0 (±7.34)	121.6 (±6.55)	150.8 (±7.29)	104.9 (±7.80)	132.1 (±6.87)	34.3 (±7.16)	33.0 (±5.90)
10%	108.3 (±10.58)	169.8 (±14.09)	118.2 (±6.73)*	151.6 (±7.58)	99.6 (±7.89)*	133.4 (±6.94)	38.7 (±7.61)*	37.3 (±6.71)*
20%	108.1 (±9.24)	170.8 (±7.13)*	113.4 (±7.87)*^	150.2 (±8.55)	102.9 (±8.18)	135.3 (±6.93)	42.2 (±12.31)*	39.7 (±5.61)*^
30%	107.0 (±10.27)	169.5 (±8.8)*	110.9 (±6.19)*	148.5 (±7.72)	101.6 (±7.43)	132.7 (±6.49)	41.0 (±7.49)*	40.2 (±5.39)*
Load	p<0.05, ηp2 = .188	p<0.05, ηp2 = .130	p<0.05, ηp2 = .492	p = .116, ηp2 = .068	p<0.05, ηp2 = .119	p = .066, ηp2 = .082	p<0.05, ηp2 = .277	p<0.05, ηp2 = .430
Group	p = .282, ηp2 = .041	p = .118, ηp2 = .085	p = .223, ηp2 = .050	p = .055, ηp2 = .149	p = .324, ηp2 = .035	p = .339, ηp2 = .033	p = .296, ηp2 =.0.39	p = .226, ηp2 = .044
Maximum velocity phase								
0%	120.3 (±35.68)	133.4 (±88.86)	121.5 (±45.89)	139.1 (±39.63)	83.7 (±51.32)	106.1 (±50.47)	10.6 (±4.87)	9.9 (±5.52)
10%	110.6 (±50.03)	164.9 (±72.75)	138.6 (±39.63)	134.3 (±53.00)	70.4 (52.51)	125.9 (±25.80)	12.8 (±6.76)	13.5 (±6.97)
20%	109.3 (±45.32)	179.9 (±52.07)	128.6 (±35.96)	135.1 (±47.42)	58.5 (±50.39)	117.2 (±41.51)	16.6 (±8.33)*	19.5 (±6.00)*^
30%	99.8 (±51.92)	152.9 (±70.99)	112.2 (±40.53)	147.0 (±29.17)	62.2 (±48.34)	108.7 (±51.63)	23.3 (±9.95)*^	24.3 (±8.66)*^~
Load	p = .572, ηp2 = .031	p = .464, ηp2 = .089	p = .109, ηp2 = .096	p = .700, ηp2 = .018	p = .302, ηp2 = .056	p = .469, ηp2 = .039	p<0.05, ηp2 = .409	p<0.05, ηp2 = .529
Group	p = .865, ηp2 = .001	p = .380, ηp2 = .396	p = .144, ηp2 =.099	p = .200, ηp2 = .077	p = .699, ηp2 = .007	p = .339, ηp2 = .044	p = .794, ηp2 = .003	p = .138, ηp2 = .107

TO = Toe-off, TD = Touchdown, ηp2: Effect size (Small: 0.2 – 0.59, Moderate: 0.60 – 1.19, Large 1.19 >), * = p < 0.05 significant difference to unloaded (0%Vdec), ^ = p < 0.05 significant difference to 10%Vdec, ~ = p < 0.05 significant difference to 20%Vdec

5.4 DISCUSSION

RSS is often prescribed for team sport athletes and sprint athletes [4,34,51,280,285,294] in an effort to improve sprinting performance [280] as it is believed to increase lower-limb power and strength, potentially in a more specific manner than traditional resistance training [4,34,282,352]. Despite this, some concerns with regard to the transfer of RSS training to sprinting performance have been highlighted [280,302,349], due to how RSS may alter kinematics during acceleration and maximum velocity running. However, to date there remains a lack of clarity around what way loading influences kinematics during RSS.

To the authors' knowledge, this is the first study to investigate the effect of multiple loads (unloaded, 10, 20 and 30%Vdec) on kinematics and compare how this effect varies in different sporting populations. Our results confirm that load has a significant effect on kinematics during both acceleration and maximum velocity running and that team sport athletes and sprint athletes, respond to RSS in a very similar manner, with only minor differences between groups.

5.4.1 Contact Time

Contact time is crucial in sprinting as it is the only time an athlete has the ability to apply force [98]. RSS has been used to help increase the application of muscular force, especially at the hip, knee, and ankle in trained athletes [149,280,342]. Previous research demonstrates [149,282,326] that CT increases with the addition of load in resisted sprints, with increases of 17 -22 % reported at loads ranging from 12.6 - 32.2%BM during acceleration [149,282] and increases of 19-26% during maxV with similar ranging loads [282,326]. The current study supports these findings and demonstrated an increase in CT with increasing load, however this response was not consistent for acceleration and maximum velocity (Table 29).

During acceleration CT significantly changed at all loads relative to unloaded (9.3%-27.2% increase), however during maxV the only significant change occurred between 30%Vdec and unloaded (27.3 % increase). The increase in CT during acceleration may be a result of the athlete requiring more time to create momentum and produce force, in order to overcome the higher resistance, and would perhaps be appropriate for the development of hip extension power [280,298]. For example, when squatting at heavier loads research indicates that there is a reduction in movement velocity, increasing the time to produce force, which in turn increases power output at lighter loads [252].

Although this increase in CT appears consistent across the literature [1,149,282,294,324,420], only a handful studies have examined the change in CT in unloaded sprinting after an RSS intervention. Alcaraz, Elvira and Palao [330] and Lahti, Huuhka, Romero, Bezodis, Morin and Häkkinen [284] reported no significant changes in CT for sprint acceleration and maxV after a 4-week intervention with trained athletes (mostly sprinters, load of 7.5%Vdec) and a 9-week training intervention in field sport athletes (50 and 60%Vdec) [284]. Therefore, although RSS increases CT, previous research indicates that this does not appear to transfer to unloaded sprinting [334] and may facilitate a positive adaptation by improving rate of force development [284].

5.4.2 Trunk Lean

Our research expands on previous findings [149,279] and indicates that the degree of trunk lean varies with the addition of lighter and heavier loads and can be described as follows: during the acceleration phase there was no change in trunk lean for the initial step, however, trunk angles were significantly greater (greater degree of trunk lean) at all loads at TD and TO during the second step in comparison to unloaded sprinting, with values ranging from 31 degrees in unloaded sprinting to 47 degrees at 30%Vdec. This is in agreement with previous literature [149,282] that has demonstrated an increase in trunk lean across various loading conditions (12.6%BM, to 32.2%BM; 2.5kg to 10kg) at TD and TO by 8% to 69%. Higher accelerations velocities are generated by more forward oriented forces [134] and the greater trunk lean at TD during RSS may help decrease the braking forces associated with landing during acceleration [134,282]. Kunz and Kaufmann [421] investigated the relationship between kinematics and sprinting performance and demonstrated that the forward inclined trunk was an important factor for sprinting performance, as it is a key structure involved in locomotion [422]. Furthermore, the orientation of the maximum force vector strongly correlates with the forward lean of the body at TO (r = 0.93) [134]. Therefore, although the addition of load appears to alter kinematics relative to unloaded sprinting, the increased trunk lean observed, may consequently train athletes to orient their trunk in a position that may facilitate application of force in a more horizontal direction. However, without a measurement of force we cannot confirm this relationship.

This pattern was also observed during maximum velocity with trunk lean significantly increasing at both 20%Vdec and 30%Vdec at TD, and TO, relative to unloaded sprinting and to 10%Vdec. Therefore, athletes were not achieving an upright running position but remained in a more forward oriented position. This may be problematic during maximum velocity running, as the greater trunk lean associated with the heavier loads may disrupt optimal vertical force application. During maximum velocity running the body should be relatively upright [338], with the overall GRF oriented more vertically, to overcome the effects of gravity and to maintain maximum velocity [124,129,338]. This does not mean that no horizontal force is applied, but vertical forces may play a more important role [129,338,339]. A recent systematic literature review [32] recommends that there is no optimal load for RST, but that the load should be adapted according to the desired objective. Our findings support existing research [4,34] that recommends that lighter loads (> 12.5%BM) should be used when implementing RSS methods to train maxV, in order to train the athletes force producing capacity while maintaining maxV mechanics.

More specifically, our findings indicate that a load of 10%Vdec allows athletes to maintain mechanics similar to unresisted running, while loads heavier than this may compromise maxV kinematics. On the other hand, using higher loads may extend the distance over which athletes can train acceleration mechanics while using RSS; offering an interesting perspective that may indicate a potential benefit of using heavier loads. However, given the acute nature of the current study, further research is required to assess if this change in trunk lean associated with heavier loads has a negative transfer to trunk lean during unloaded sprinting and should also assess the extent to which loading may extend the time an athlete spends in acceleration mechanics. To date only a few studies assessed this, reporting mixed results [280,284]. Spinks, Murphy, Spinks and Lockie [280] demonstrated that RSS using loads of 10%Vdec over a period of 8 weeks improved sprint performance for unloaded sprinting and associated this with the increased trunk lean (18.2%). More recently no transfer impact on unloaded sprinting kinematics after 9-weeks RSS training with loads of 50%Vdec and 60%Vdec was reported, suggesting that very heavy sled loads provide an overload that is efficient in assisting increases in SP for acceleration and maximum velocity phase (5-30 m) without violating kinematics [284]. However, this study only included trunk and hip angles and therefore, future research should include multiple joint and segment angles and a variety of different loads.

5.4.3 Hip Angle

During step 2 of the acceleration phase loads of 20 and 30%Vdec (TO: 170; 169 degrees) resulted in a significant increase in hip flexion relative to unloaded sprinting at TO. There are two possible explanations for the observed reduction in hip extension at TO observed under loaded conditions. Firstly, the athletes might not be strong enough to get through a full ROM with the addition of load [326] and a weakness in the hip abductor muscle typically appears when an athlete is leaning forward with minimal hip extension [423]. It is logical to assume that overtime training may allow the athlete to adapt to the additional load, develop stronger hip extensors, and subsequently facilitate hip extension more similar to that observed in unloaded sprinting. However, to our knowledge this has not yet been investigated. Given that hip extension provides the most significant propulsive forces during sprinting [424-426], this may offer a positive training adaptation. Alternatively, it is possible that athletes were rushing during the acceleration phase in an attempt to run as fast as possible instead of focusing on pushing the ground away (and achieving full extension) during the movement. However, this is unknown and further research is required to determine this.

5.4.4 Knee Angle

During the acceleration phase, knee angles were significantly smaller (less extension) for RSS at all loads at TD in comparison to unloaded sprinting. No significant differences were displayed at TO, with mean knee extension values ranging from 145.4 degrees for unloaded sprinting to 143.4 for 30%Vdec. Knee angle for unloaded sprinting at TO was already close to full extension and similar to previous literature in elite sprinters (142 degrees to 160 degrees) [148]. Findings of this study are in line with previous results from an investigation of RSS [282], even though different loads were used (15%BM and 20%BM). Cronin, Hansen, Kawamori and McNair [282] reported less extension at TD and no change in extension at TO and suggested that during RSS propulsive forces may act through a greater range, and therefore may comprise a greater proportion of the stance phase. The increase in knee flexion at TD observed with increased load may place the athlete in a position where the shank is in a more horizontal position, potentially allowing athletes to apply force in a more horizontal direction. The ability to apply force more horizontally into the ground is a performance determining factor in acceleration performance [13]. In contrast, Lockie, Murphy and Spinks [149] reported an increase in knee extension (32%BM), with mean values of 156.4 degrees (32%BM) and 148.0 degrees (unloaded). The authors suggested that this increase in knee extension may indicate that the athlete was attempting to gain an increase in propulsive force through a more vigorous extension of the shank segment [149]. However, these values were measured at maximum extension and not TO. The results of our ROM analysis indicated that athletes went through greater knee ROM when loaded. Increased ROM at the knee may increase the time to develop force and therefore increase impulse during sprinting. Furthermore, sprinters demonstrated greater ROM than team sport athletes. This may indicate that sprint athletes may have stronger hip extensors allowing them to go through a larger ROM or may be more technically proficient. However, this is uncertain as kinetics were not analysed in the current study and therefore warrants further investigation.

Limitations

As with all investigations, this study should be appreciated considering its limitations. The study sample size was small to moderate, and therefore the findings may not be fully reflective of the population the sample was taken from. The majority of studies including ours look at single time points (TD, TO), however, discrete point analysis may result in loss of important information during other parts of the movement [427-429]. A more ideal approach is likely the analysis of waveforms, such as the statistical parametric mapping method, but was beyond the scope of this project [430]. Moreover, this study only investigated the acute changes in kinematics of RSS, and it is therefore difficult to extrapolate this information into a longitudinal outcome regarding the enhancement of sports-specific performance. Moreover, due to a limited field of view the measurement of variables during acceleration was only possible for the first two steps. The measurement of variables for example, at the first two steps only, may present a disadvantage, as load-specific changes in kinematics may be present throughout the whole acceleration phase. A step-by-step analysis would elucidate the different phases and changes in kinematics during the sprint

[141]. Despite our best attempts at reducing fatigue via appropriate resting periods, it is possible that this still played a role [294]. Sled loads however, were performed in randomised order; therefore, all conditions have been similarly affected by this fact. Furthermore, it is important to note potential issues with the reliability of the timing gates used for data collection should be considered. The variations in single beam timing gates reliability could have introduced some degree of measurement error into the results. The choice between single-beam and double-beam timing gates can impact the reliability of timing results. In situations where precise timing is critical, double-beam gates are preferred due to their higher accuracy. However, the Brower Timing System was selected for testing, as it has previously demonstrated to have good reliability and validity [370]. Finally, for the interpretation of the results, it is important to consider the potential for type 1 (false positive) and type 2 (false negative) errors. While measures were taken to reduce these errors, such as using appropriate statistical tests and sample sizes, the inherent variability in human performance and measurement techniques may introduce some degree of uncertainty.

5.5 CONCLUSION

Despite these limitations this study is novel and has added to the existing body of knowledge, advanced research on RSS and has important practical implications to be considered. This study investigated the effect of RSS on sprint kinematics under various loading conditions similar to previous research, however the examination of multiple joint angles, across different phases of a sprint, the number of loads and the comparison on how these loads influence kinematics in sprint athletes and invasion team sports athletes is novel. The results of this study provide coaches with important information that may influence how RSS is employed as a training tool to improve SP for acceleration and maximal velocity running and how prescription may change based on sporting population.

In conclusion, this study showed that RSS resulted in acute changes in sprint kinematics during sprint acceleration and maxV phases, yet in a distinctive manner when using different loads. Furthermore, this study indicated that both sprint and team sport athletes respond to RSS in a very similar manner. ROM however increased with increasing load to a greater extent for sprint athletes potentially enabling them to create more propulsive forces, which may be due to stronger hip extensors. The utilisation of any sled load would appear to ensure that acceleration kinematics at step one were not adversely affected, however our data indicates that the addition of load alters technique at step two of acceleration and during maxV. Whether or not these changes may adversely affect performance is unclear given the acute nature of the current study. It is possible though that further training under loaded conditions may allow athletes to reach kinematics more similar to unloaded sprinting. It is also possible that the observed change in kinematics, with the addition of load, may positively influence sprinting technique, e.g., a better trunk lean. Although, the heavier loads did not allow the athletes to reach mechanics that are reflective of maxV, the increase in trunk lean, enabled them to place themselves in an optimal position to maximise propulsive forces, thus, potentially extending the distance over which it is possible to train acceleration. For training maxV loads up to 10%Vdec may be appropriate if coaches and athletes are looking to provide an overload without altering trunk kinematics. Although we have not reported acute kinematic changes, a long-term investigation should include multiple joint and segment angles and a variety of different loads to further investigate the impact on kinematics.

Chapter Link

The last study complements the findings of the previous study, enhancing the overall objectives of the thesis by delving deeper into the effects of resisted sprinting on kinematic characteristics and its potential as a valuable training tool for enhancing sprint performance. The initial study examined the immediate kinematic impacts of various sled load conditions on sprinters and field-based invasion team sport athletes and discovered noteworthy alterations in hip, knee, ankle, and trunk angles during both the early acceleration and maximum velocity stages of the sprint. These alterations were found to be influenced by the size of the load, highlighting the significance of taking into account the sprint phase and load when incorporating resisted sprint training. These findings lead to the development of the research question for study two to further explore the effects of RST on kinematic characteristics and the factors that influence these changes, thereby complementing the findings of the first study. Both studies were completed in conjunction with each other. As to date it is uncertain whether athletes with fewer kinematic disruptions experience a more substantial transfer to unloaded sprinting. Therefore, this study represents an initial step in understanding whether an athlete's strength characteristics influence the extent of kinematic disruptions observed during resisted sprinting. Collectively, these studies provide a comprehensive understanding of resisted sprinting as a training tool, specifically addressing the objectives of the thesis and offering valuable insights into the potential advantages it holds for athletes in enhancing their sprint performance.

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CHAPTER 6

6 DO STRENGTH CHARACTERISTICS IMPACT RESISTED SLED SPRINT KINEMATICS?

6.1 INTRODUCTION

The ability to sprint is fundamental to excelling in track and field as well as various team sports like soccer, rugby, football, or basketball [71-74]. Therefore, selecting appropriate training techniques to enhance sprinting capability holds significant value in training programs. It has been acknowledged that having sufficient strength, both in absolute terms and in relation to body mass, is crucial for achieving success in team sports such as rugby [431]. Multiple studies have shown that there is a correlation between strength, sprint and jump performance [176,432], suggesting that athletes who are stronger tend to perform better in sprints [109,176,249,253,433-435]. Engaging in resistance training alone may not guarantee the best results in terms of muscle strength and performance. Instead, the extent of personal effort and the systematic organisation of the training stimulus are what truly determine the outcomes of resistance training. As a result, it is important to customise resistance-training programs to suit individual goals in order to maximise the desired outcomes [436]. This may involve incorporating different types of resistance training, such as using machines or free weights, performing body weight exercises, engaging in plyometrics, utilising resistance bands, or even incorporating resistance during sprinting [169].

Resisted sprint methods are a form of sprint-specific training, which consist of sprinting while facing resistance from various sources such as a sled, pulley system, weighted vest, parachute, or uphill sprinting [54]. Among these, the most extensively researched and commonly utilised technique is resisted sled sprinting [54]. RST protocols have gained popularity as effective training programs for enhancing SP [33,51,329] and are known to produce greater muscular activation and increase force output when compared to unloaded sprinting [329,330,437]. To date, research has demonstrated that resisted sprints are effective for improving SP across multiple loading conditions (5–80%BM) [4,32]. More specifically, RST appears to improve acceleration (p = 0.0001; effect size (ES) 0.61) performance [4,32], with more recent research demonstrating benefits of very heavy loads for acceleration (50% and 60%Vdec) [284]. The observed increases in SP following resisted sprinting may be explained by increases in an athlete's ability to produce horizontal and vertical forces [36,51,92,438].

Studies have also assessed the acute kinematics of RST and demonstrated that loading (10–40% BM) acutely results in decreased step length, step frequency, swing phase duration, increased contact time, trunk lean [284] and knee flexion relative to unloaded sprinting [288,304,325,338,439]. This impact on kinematics appears to become larger with increasing load, which based on the theory of dynamic correspondence may impact transfer from RST to unloaded sprinting. Recently it has been shown that differences in speed, strength, and power abilities could explain the individual responses during RSS, since faster, stronger, and more powerful athletes require heavier sled loads to experience similar Vdec [360]. Even though RSS appears to improve sprint performance even in the presence of acute kinematic disruption [284,330], it is unclear if those athletes who display less kinematic disruption see a greater transfer to unloaded sprinting. Therefore, this study is an initial step to firstly elucidate if strength characteristics influence the degree of kinematic disruption observed in during resisted sprinting. The results of this study may provide coaches with important information that may influence how RSS is employed as a training tool to improve SP and how prescription may change based on strength level. Therefore, the main purpose of this research was to examine the relationship between change in kinematics (relative to unloaded sprinting) during RSS at various loads and strength, jump and SP measures of Irish sprint and field-based invasion team sport athletes.

6.2 METHODS

6.2.1 Participants

Thirty healthy participants (sprint (10) team sport (20), female (7) male (23), 21.4 ± 3.3 years, 185.8 ± 8.2 m, 85.2 ± 11.8 kg) volunteered and provided written informed consent. Participants were recruited if they (a) had experience with resistance and sprint training (minimum of 18 months), (b) were currently strength training, (c) were currently participating in competitive sprinting, or field based invasion team-sport and (d) were lower limb injury free (i.e. sprains and strains, joint dislocations, and fractures) for a minimum of 6 months. These criteria were chosen in order to reduce the chance of injury and to prevent delayed onset muscle soreness which might be caused by the dynamic nature of the testing protocols, as well as to improve ecological validity. The study was approved by the Technological University of the Shannon Ethics Committee (approval code: 20200307), and all procedures were completed in accordance with the declaration of Helsinki.

6.2.2 Experimental Approach to the Problem

This study analysed the change in kinematics (relative to unloaded sprinting) during RSS at various loads and strength, jump and SP measures of Irish sprint and field-based invasion team-sport athletes. Athletes completed 3 testing days, including a familiarisation day and two experimental days, each separated by a minimum of 48 hours (Figure 19). During the first session athletes were familiarised to the different resisted sprint loads while on the second testing day participants completed 40 m sprints on an indoor running track at each loading condition (unloaded, 10, 20 and 30%Vdec). Although fatigue is a factor to consider, three trials for each loading condition were conducted in a randomised order. Conducting multiple trials enhances the reliability and precision of collected data. A single trial can be susceptible to various factors such as random fluctuations, external distraction and measurement error or athlete variability. By averaging the outcomes from multiple trials, the influence of these variables is minimised [440]. During the third testing session athletes performed 1RMs (hip thrust and back squat) and vertical jumps (DJ and CMJ).

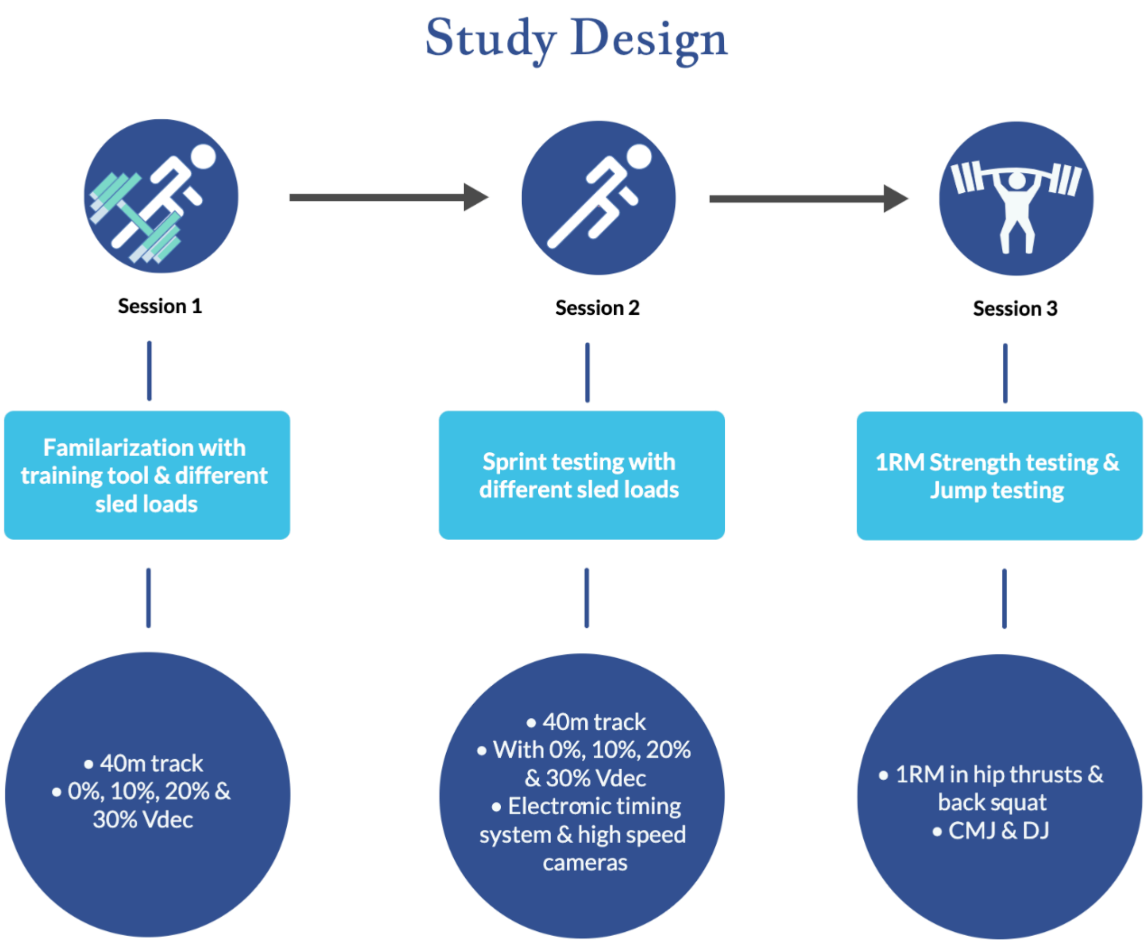

Figure 19 Experimental testing days.

6.2.3 Procedures

The set-up used for both the familiarisation and experimental sprint trials involved placing timing gates (Brower Timing Systems, 2016, Draper, UT USA) at 5 m intervals over a 40 m distance on an indoor running track (Mondo, Sportflex Super X 720 K39, Italy). This can be seen in Figure 21. The Brower Timing System was selected for testing, as it has previously demonstrated to have good reliability and validity [385]. For resisted sprints, a weighted sled was attached to each participant using a 3.6 m cord and waist harness to ensure minimal lateral displacements during sprinting[64]. Before each trial, participants completed a standardised 15-minute warm-up using the RAMP protocol, followed by sprints that gradually increased in intensity [388]. Participants were then given an additional 5 minutes to complete their own choice of warm-up exercises.

The 1RMs were performed with a competition standard Olympic style bar and weights (T-100G; Eleiko, Halmstad, Sweden), while the jumps were performed on force plates (Pasco, Roseville, California, USA; Model number: 2141).

Familiarisation: Participants performed two 40 m sprints at each loading condition (unloaded, 10, 20 and 30%Vdec) in a randomised order. A minimum 5-minute rest period was provided in between each sprint [389]. The method for calculating the load-velocity relationship established by Lockie, Murphy and Spinks [149] was utilised to estimate loading during familiarisation trials. Subsequently, the data generated from these trials was used to modify loadings by creating an individual linear regression equation for each participant, indicating the necessary load to achieve the planned Vdec (10, 20, and 30%Vdec) [329].

Experimental Sprint Trials: The participants were requested to complete a total of 12 sprints, wherein they had to perform three 40 m sprints under each loading condition (unloaded, 10, 20, and 30Vdec), in a randomised sequence. To ensure their well-being, a minimum rest period of 5 minutes was provided between each sprint [389]. Sprints during experimental trials were recorded for examination on two different cameras (Sony RX10 III, IPhone 7). The cameras were placed nine metres from the middle of the athlete's lane and the optical axis of the camera was perpendicular to the direction of running. The HSC and the IPhone 7 camera were mounted on a rigid tripod. The frame rate was set at 250Hz for both cameras [1,416]. The sprint trial setup was the same as in [439]. One camera captured from 0 to 5 m, which was considered as the early acceleration phase and the other camera captured between 25-30 m, which was considered as the maximum velocity phase [289,295]. For video analysis, markers (zinc oxide tape) were placed on the right-hand side of the participants' body. Landmarks were established through palpation [281]. A metre stick was placed in the field of view of each camera, for scaling purposes [417]. Marker placement and landmark description can be seen below in Figure 20 and Table 31.

Table 31 Marker placement landmark description.

Landmark	Description
Shoulder	Acromion process
Hip	Greater trochanter, located at the proximal, lateral part of the shaft of the femur
Knee	Lateral condyle, at the superior end of the tibia
Ankle	Lateral malleolus, at the low end of the fibula
Toe	Fifth metatarsal bone / transmetatarsal joint at the distal outer edges of the foot (on the shoe)

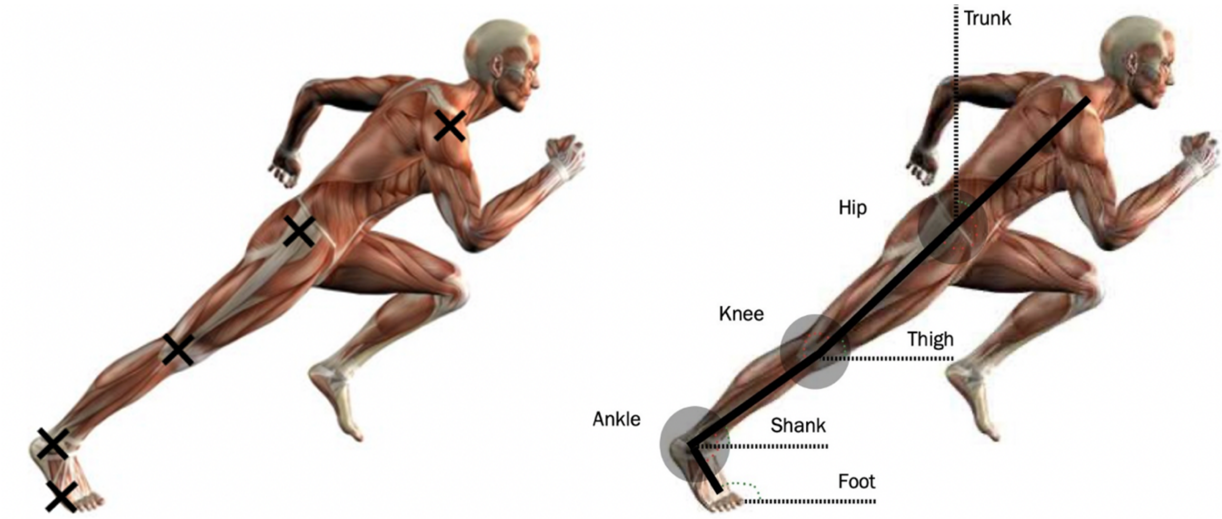

Figure 20 Marker placement.

Used to define segments and simplify Dartfish analysis and joint angle definition in the sagittal plane (Partly amended from FisioSport Pavona [418].

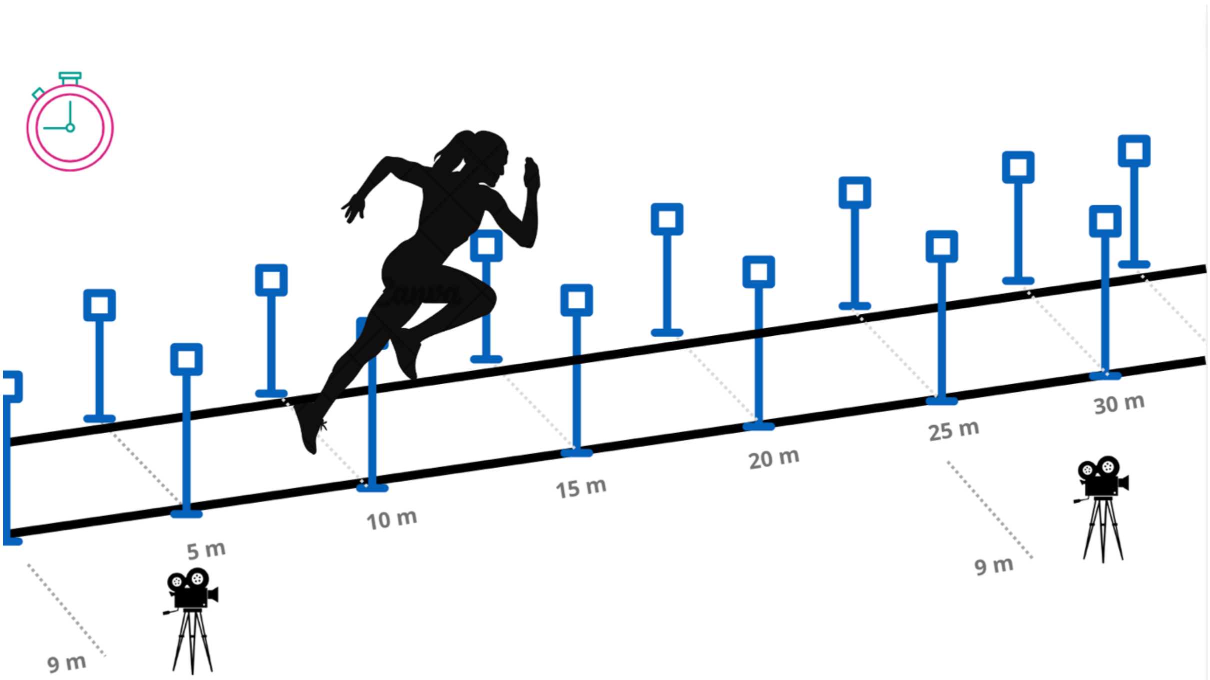

Figure 21 Experimental Set-up.

One Repetition Maximum: One RM was defined as the greatest amount of load a subject can raise through full range of motion once with a standard lifting technique. One RMs for back squat and hip thrust were performed with a competition standard

Olympic style bar and weights. Testing was completed in line with guidelines established by the National Strength and Conditioning Association [441]. Each participant performed 10 repetitions as warm-up sets. Progressively, weight was added until the 1 RM was determined. A lift was successful when the exercise was performed with proper technique, as indicated by the National Strength and Conditioning Association [441]. The back squat and the hip thrust were chosen because they demonstrated to be effective tools, in different ways, for enhancing sprint performance by increasing strength and power [257] and they demonstrate different force vectors.

Jump Tests: Subjects performed two vertical jump tests (CMJ and DJ). All jumps were completed on two synchronised single axis force platforms (Pasco, Roseville, California, USA; Model number: 2141) that measure vertical ground reaction force (1000 Hz) and subsequent analysis was completed with NMP Forcedeck software (ForceDecks Ltd., UK v1.2.6109). The variables obtained during these tests were as follows: maximum jump height (JH), peak power relative to BM (PPrel) and reactive strength index (RSI). For the CMJ, subjects were instructed to step onto dual force platforms, placing 1 foot on each, and remain motionless for a minimum of two seconds to normalise body weight and baseline force and then completed the jump when instructed with the verbal cue 'Jump'. Participants were told to quickly descend to a self- selected height and then rapidly accelerate and jump maximally. Hands were placed on hips to limit involvement of the upper body [442,443]. The DJ was carried out using a 30 cm high box [442]. Participants were asked to step forward from the box and upon hitting the force plate, to jump as high as possible while spending as little time as possible on the ground [442]. For both jumps three valid test trial attempts were recorded, with the mean of three trials used for analysis (mean was used as the distribution of the data values was symmetrical and there were no clear outliers) [442]. Participants were given a 30-second recovery between trials [444]. Jump inclusion criteria were, arms must remain on waist, feet must be centred while completely on the platform, leg must not tuck upward during flight and that subjects must land fully on the platforms. Participants must stick and hold the landing and not drift sideways or forward [442]. Any jumps that did not satisfy the criteria were excluded and trials were repeated.

High-Speed-Video Analysis: A kinematic analysis of the video footage was undertaken with Dartfish Software (Fribourg, Switzerland). Joint (trunk, hip, knee and ankle angles) variables were calculated for the two first contacts of the right foot during the acceleration and one within maximum velocity phases of each sprint trial [94,95]. All angles were measured at toe-off and touch down. TO was defined as the first frame in the video where the foot had left the ground and TD the first frame where the foot had contact with the ground [149]. These two discrete points were selected as a reflection of what is happening during the force producing component of each stride. One step for the maximum velocity phase was deemed sufficient, as kinematics are more consistent due to the athlete sprinting at a relatively constant velocity [124].

Percentage change was used as a way to express a change in kinematic variables (joint angles). It represents the relative change between the old value and the new one. This difference is calculated as V2 minus V1, indicating the magnitude of the joint angle change. To ensure meaningful comparison across various loading conditions, normalization occurs by dividing this change by V1. This step scales the change relative to the initial value, ultimately expressing it as a percentage. The final multiplication by 100% is a crucial conversion that turns the fractional change into a percentage change. This transformation simplifies the interpretation and comparison of joint angle variations under different loading conditions. The percentage change was calculated by the following formula:

Equ. 1:

$$\text{Angle Percentage Change Between Loads} = \frac{(V2 - V1)}{V1} \times 100\%.$$

Equation 1: Equation displaying the percentage change of kinematic variables between the different loading conditions.

Force Plate Analysis: The start of the jump was defined as the start of downward negative velocity. Eccentric phase was defined as the maximum negative velocity to zero velocity and concentric phase from zero velocity to the instant of take-off [445]. Jump height (JH) was determined through the impulse-momentum method. This involved the integration of the vertical ground reaction force-time curve to derive impulse. Impulse was then used to calculate the change in velcoityfrom which JH was subsequently calculated.

Equ. 2:

$$JH = [{}^{1}/_{2}\,(\frac{TO\ velocity^{2}}{9.81})]\ [446].$$

Equation 2: The jump height calculation using the impulse-momentum method.

Power was calculated as the product of force and velocity. In the case of a CMJ, the peak vertical force (ground reaction force) at take-off was multiplied by the vertical velocity of the COM. Mathematically, it can be expressed as:

Equ. 3:

Power (Watts) = Force (N) x Velocity (m/s).

The RSI was taken as the maximal height the athlete reached during the DJ divided by the ground contact time [447].

6.2.4 **Statistical Analysis**

All data is displayed as mean values with standard deviation. Normality of data was determined using Shapiro-Wilk test.

Multiple regression modelling was used to analyse the relationship between a dependent variable (change in kinematics observed for joint and segment angles at TD and TO) and multiple independent variables (DJRSI, CMJJH, Back squat, Hip thrust and sprint time). It aimed to determine the best combination of independent variables that could predict or explain the variation in the dependent variable. Forward selection was used, as it is a common method used in multiple regression modelling to select the most relevant independent variables for inclusion in the model [448]. It starts with an empty model and iteratively adds variables one by one, based on their significance and contribution to the model's predictive power. A collinearity diagnosis (variance inflation factor (VIF) < 10 and tolerance > 0.2) was performed to guarantee that variables were suitable for inclusion in the multiple regression model. Additionally, correlations between jump, strength, and sprint performance variables were determined by Pearson correlation. The r values were interpreted as trivial <0.1, small 0.1–0.29, moderate 0.3–0.49, large 0.5–0.69, very large 0.7–0.89, and nearly perfect >0.9 [449]. Significance level was set at $P < 0.05$. Apriori power calculations performed using G*Power (3.1; University of Düsseldorf, Düsseldorf, Germany) determined that a minimum of 17 subjects were required for a statistical power ≥ 0.90, for an α level of $p \leq 0.05$, with effect sizes of approximately 0.5. Statistical calculations were performed using IBM SPSS 20.0 (Chicago, IL, USA). Intratester and inter-trial (between sprints) reliability for joint angles was assessed by intraclass correlation coefficient (ICC), coefficient of variation (CV%), typical error (TE) with 95% confidence intervals, using Hopkins' spreadsheet [450].

6.3 RESULTS

6.3.1 Reliability

For within session (between sprints), ICC with 95% confidence intervals and CV% showed excellent reliability for all kinematic variables (0.96–1.00, CV%: 1.78–3.39). Intra-tester reliability also displayed excellent reliability for all variables (0.96–1.00, CV%: 0.63–2.99).

6.3.2 Hip and ankle kinematics

The assumptions can be found in the appendix on page 335. Multiple regression analysis was used to determine if DJRSI, CMJJH, Back squat, Hip thrust, unloaded average 5m and 10 m split time can predict the change in hip and ankle kinematics (TO and TD) observed between unloaded, 10%Vdec, 20%Vdec and 30%Vdec. These variables did not significantly predict change in hip or ankle kinematics.

6.3.3 Knee kinematics

Multiple regression analysis was used to determine if DJRSI, CMJJH, Back squat, Hip thrust, unloaded average 5 m and 10 m split time can predict the change in knee kinematics (TD) observed between unloaded, 10, 20 and 30%Vdec.

These variables did not significantly predict a change in knee kinematics for the first and second step of the sprint, except the model between unloaded and 30%Vdec at the second step. Variables significantly predicted change in knee kinematics, $F(13, 3) = 36.0$, $p < .007$, adjusted $R^2 = .96$. Five variables added statistically significantly to the prediction, $p < .05$ (Table 32).

6.3.4 Trunk kinematics

Multiple regression analysis was used to determine if DJRSI, CMJJH, Back squat, Hip thrust, unloaded average 5 m and 10 m split time can predict the change in trunk kinematics (TD and TO) observed between 0, 10, 20 and 30%Vdec for the acceleration phase. These variables did not significantly predicted change in trunk kinematics.

Multiple regression analysis was used to determine if DJRSI, CMJJH, Back squat, Hip thrust, unloaded average 5 m and 10 m split time can predict the change in trunk kinematics at TD & TO observed between 0, 10, 20 and 30%Vdec.

Variables that significantly predicted change in trunk kinematics at TD between unloaded and 20%Vdec, $F(7, 8) = 5.26$, $p < .016$, adjusted $R^2 = .66$ and between unloaded and 30%Vdec, $F(7, 8) = 5.75$, $p < .012$, adjusted $R^2 = .68$. They also predicted change in trunk kinematics at TO between unloaded and 20%Vdec, $F(7, 8) = 7.11$, $p < .006$, adjusted $R^2 = .74$ and between unloaded and 30%Vdec, $F(7, 8) = 7.31$, $p < .006$, adjusted $R^2 = .74$. Results are presented in Table 33.

Table 32 Linear regression between knee kinematics and jump, strength and sprint variables.

Knee TD 0%Vdec – 30%Vdec									
	R	R2	Adjusted R2	F	df1	df2	p		
	0.997	0.994	0.966	36	13	3	0.007		
			95% Confidence Interval					95% Confidence Interval	
Predictor	Estimate	SE	Lower	Upper	t	p	Stand. Estimate	Lower	Upper
Intercept	-0.477	0.053	-0.646	-0.308	-8.996	0.003*			
DJRSI	0.041	0.005	0.024	0.058	7.726	0.005*	0.538	0.316	0.759
CMJJH	0.002	0.001	0.000	0.004	3.755	0.033*	0.429	0.065	0.792
Hip thrust	-0.000	0.000	-0.001	-0.000	-5.828	0.01*	-0.597	-0.923	-0.271
Unloaded 10m	0.048	0.012	0.010	0.087	3.985	0.028*	0.322	0.065	0.58
* p<0.05 significant correlation									

Table 33 Linear regression between trunk kinematics and jump, strength and sprint variables.

Trunk TD 0%Vdec – 20%Vdec									
	R	R2	Adjusted R2	F	df1	df2	p		
	0.906	0.821	0.665	5.26	7	8	0.016		
			95% Confidence Interval					95% Confidence Interval	
Predictor	Estimate	SE	Lower	Upper	t	p	Stand. Estimate	Lower	Upper
Intercept	13.038	9.529	-8.935	35.011	1.368	0.208			
CMJJH	0.299	0.118	0.026	0.572	2.527	0.035	0.586	0.051	1.121
Trunk TD 0%Vdec – 30%Vdec									
	R	R2	Adjusted R2	F	df1	df2	p		
	0.913	0.834	0.689	5.75	7	8	0.012		
			95% Confidence Interval					95% Confidence Interval	
Predictor	Estimate	SE	Lower	Upper	t	p	Stand. Estimate	Lower	Upper
Intercept	9.786	9.372	-11.826	31.396	1.044	0.327			
CMJJH	0.337	0.115	0.071	0.603	2.919	0.019	0.597	0.125	1.069

Trunk TO 0%Vdec – 20%Vdec									
	R	R2	Adjusted R2	F	df1	df2	p		
	0.928	0.862	0.74	7.11	7	8	0.006		
			95% Confidence Interval					95% Confidence Interval	
Predictor	Estimate	SE	Lower	Upper	t	p	Stand. Estimate	Lower	Upper
Intercept	1.308	3.924	-7.740	10.356	0.333	0.747			
CMJJH	0.155	0.049	0.042	0.267	3.171	0.013	0.648	0.177	1.119
Back squat	0.024	0.007	0.008	0.040	3.395	0.009	0.694	0.223	1.165
Trunk TO 0%Vdec – 30%Vdec									
	R	R2	Adjusted R2	F	df1	df2	p		
	0.930	0.865	0.747	7.310	7	8	0.006		
			95% Confidence Interval					95% Confidence Interval	
Predictor	Estimate	SE	Lower	Upper	t	p	Stand. Estimate	Lower	Upper
Intercept	-0.092	5.749	-13.348	13.165	-0.016	0.988			
CMJJH	0.264	0.071	0.101	0.428	3.734	0.006	0.689	0.264	1.115
Back squat	0.038	0.012	0.010	0.066	3.116	0.014	0.690	0.179	1.201
Hip thrust	-0.047	0.019	-0.091	-0.003	-2.469	0.039	-0.624	-1.206	-0.041
* p<0.05 significant correlation									

6.3.5 Strength, jump performance and change in kinematics

Correlations between back squat, hip thrust, DJRSI and CMJJH and change in kinematics for the acceleration and maximum velocity phase are presented in Table 34, Table 35, Table 36, Table 37, Table 38, Table 39, Table 40 and Table 41.

Significant correlations were observed between back squat and knee angle percentage change at TD (change from 0%-30% r = -.42, p = .03) (Table 34). Furthermore, significant correlations were observed between hip thrust and ankle angle percentage change at TO (first step) (Change from 0%- 20% r = .38, p = .05; Change from 0%-30% r = .50, p = .01), (second step) (Change from 0%-30% r = .57, p = .00), trunk angle percentage change at TD (first step) (Change from 0%-10% r = .40, p = .040), and at TO (second step) (Change from 0%-10% r = -.54, p = .004) (Table 36). For the maximum velocity phase significant correlations were observed between back squat and hip angle percentage change at TD (from 0%-30% r = -.44, p = .04), trunk angle percentage change at TO (from 0%- 20% r = .51, p = .02) and (from 0%-30% r = .50, p = .02). For the hip thrust there was a significant correlation with knee angle percentage change at TD (Change from 0%-20% r = -.56, p = .01).

Significant correlations were observed between DJRSI and hip angle percentage change at TD (first step) (Change from 0%-30% r = .51, p = .02); (second step) (Change from 0%-10% r = .51, p = .03; 0%-30% r = .50, p = .03), knee angle percentage change at TD (first step) (Change from 0%-10% r = .55, p = .01) and trunk angle percentage change at TD (first step) (Change from 0%-30% r = -.49, p = .03). Moreover, significant correlations were observed between

CMJH and hip angle percentage change at TD (second step) (Change from 0%-30% r = .47, p = .01) and at TO (first step) (Change from 0%-10% r = -.46, p = .01). For the maximum velocity phase significant correlations were observed between CMJJH and knee angle percentage change at TD (Change from 0%-20% r = -.44, p = .01).

Table 34 Correlation between maximum strength back squat 1RM and percentage change in acceleration sprint mechanics.

Back Squat			Touch Down			Toe Off		
			0%-10%	**0%-20%**	**0%-30%**	**0%-10%**	**0%-20%**	**0%-30%**
Hip Angle	**1**	**R value**	-0.06	-0.06	0.05	-0.06	-0.04	0.04
		P value	0.77	0.77	0.82	0.77	0.86	0.86
	2	**R value**	-0.01	-0.04	-0.11	0.28	0.16	0.01
		P value	0.97	0.86	0.57	0.16	0.41	0.95
Knee Angle	**1**	**R value**	-0.31	-0.21	-0.31	-0.12	-0.19	-0.13
		P value	0.12	0.29	0.12	0.54	0.35	0.53
	2	**R value**	-0.03	-0.3	-0.42*	-0.06	-0.15	-0.1
		P value	0.88	0.13	0.03	0.78	0.45	0.63
Ankle Angle	**1**	**R value**	-0.16	-0.11	0	-0.27	-0.19	0.26
		P value	0.44	0.57	0.99	0.18	0.35	0.18
	2	**R value**	0.14	-0.03	0.3	-0.02	0.08	-0.16
		P value	0.48	0.89	0.13	0.93	0.7	0.42
Trunk Angle	**1**	**R value**	-0.05	0.1	0.08	-0.05	-0.08	-0.04
		P value	0.82	0.61	0.69	0.8	0.7	0.84
	2	**R value**	-0.07	-0.08	0	-0.25	-0.27	-0.12
		P value	0.73	0.7	0.99	0.21	0.18	0.55
* p<0.05 significant correlation								

Note that: Change in kinematics from 0%-10% are the changes observed when 10%Vdec is compared to 0%Vdec.

Table 35 Correlation between back squat maximum strength 1RM and percentage change in maxV sprint mechanics.

Back Squat		Touch Down			Toe Off		
		0%-10%	**0%-20%**	**0%-30%**	**0%-10%**	**0%-20%**	**0%-30%**
Hip Angle	**R value**	0.00	-0.42	-0.44*	-0.14	-0.07	0.04
	P value	1.00	0.05	0.04	0.54	0.75	0.86
Knee Angle	**R value**	0.03	-0.28	-0.26	0.01	0.26	0.20
	P value	0.91	0.20	0.25	0.98	0.24	0.39
Ankle Angle	**R value**	0.30	0.26	0.29	0.02	0.08	-0.04
	P value	0.19	0.25	0.20	0.93	0.73	0.85
Trunk Angle	**R value**	0.36	0.36	0.38	0.37	0.51*	0.50*
	P value	0.11	0.11	0.09	0.10	0.02	0.02
* $p<0.05$ significant correlation							

Table 36 Correlation between hip thrust maximum strength 1RM and percentage change in acceleration sprint mechanics.

Hip Thrust			Touch Down			Toe Off		
			0%-10%	**0%-20%**	**0%-30%**	**0%-10%**	**0%-20%**	**0%-30%**
Hip Angle	**1**	**R value**	-0.39	0.07	0.02	-0.29	0.04	-0.10
		P value	0.05	0.73	0.92	0.15	0.84	0.63
	2	**R value**	0.14	-0.18	-0.06	0.37	0.14	0.02
		P value	0.5	0.38	0.77	0.06	0.50	0.92
Knee Angle	**1**	**R value**	0.11	-0.21	-0.13	-0.04	0.02	0.08
		P value	0.57	0.3	0.53	0.83	0.93	0.70
	2	**R value**	-0.01	-0.28	-0.26	-0.11	-0.28	0.23
		P value	0.97	0.16	0.18	0.57	0.15	0.25
Ankle Angle	**1**	**R value**	0.01	-0.03	0.13	0.19	0.38*	0.50*
		P value	0.97	0.90	0.51	0.35	0.05	0.01
	2	**R value**	0.23	0.31	0.29	0.16	0.35	0.57*
		P value	0.25	0.12	0.14	0.42	0.07	0.00
Trunk Angle	**1**	**R value**	0.40*	0.09	0.16	0.06	-0.06	0.10
		P value	0.04	0.64	0.42	0.77	0.77	0.60
	2	**R value**	-0.05	0.05	0.17	-0.54*	-0.3	-0.06
		P value	0.81	0.79	0.41	0.00	0.12	0.77

* $p<0.05$ significant correlation

Table 37 Correlation between hip thrust maximum strength 1RM and percentage change in maxV sprint mechanics.

Hip Thrust		Touch Down			Toe Off		
		0%-10%	**0%-20%**	**0%-30%**	**0%-10%**	**0%-20%**	**0%-30%**
Hip Angle	**R value**	0.05	-0.20	-0.39	0.04	0.09	0.28
	P value	0.84	0.37	0.08	0.85	0.69	0.22
Knee Angle	**R value**	-0.31	-0.56*	-0.25	0.04	0.25	0.23
	P value	0.18	0.01	0.27	0.86	0.25	0.32
Ankle Angle	**R value**	-0.10	-0.23	-0.02	0.31	0.19	0.11
	P value	0.67	0.30	0.92	0.17	0.39	0.64
Trunk Angle	**R value**	0.11	0.14	0.32	0.18	0.15	0.14
	P value	0.63	0.56	0.16	0.42	0.51	0.55

* p<0.05 significant correlation

Table 38 Correlation between DJRSI and percentage change in acceleration sprint mechanics.

DJ			Touch Down			Toe Off		
			0%-10%	0%-20%	0%-30%	0%-10%	0%-20%	0%-30%
Hip Angle	**1**	**R value**	0.39	0.37	0.51*	0.05	0.09	0.12
		P value	0.10	0.12	0.02	0.84	0.71	0.63
	2	**R value**	0.51*	0.35	0.50*	0.26	0.39	0.25
		P value	0.03	0.14	0.03	0.29	0.10	0.30
Knee Angle	**1**	**R value**	0.55*	0.38	0.44	-0.12	0.05	-0.03
		P value	0.01	0.11	0.06	0.61	0.84	0.89
	2	**R value**	0.29	0.28	0.29	-0.06	0.28	-0.05
		P value	0.22	0.25	0.23	0.81	0.25	0.83
Ankle Angle	**1**	**R value**	-0.20	0.00	0.28	-0.11	-0.17	-0.06
		P value	0.41	0.99	0.24	0.64	0.48	0.82
	2	**R value**	-0.14	-0.15	0.06	0.42	-0.11	0.23
		P value	0.56	0.54	0.82	0.07	0.64	0.34
Trunk Angle	**1**	**R value**	-0.22	-0.38	-0.49*	-0.31	-0.10	-0.34
		P value	0.36	0.11	0.03	0.20	0.67	0.15
	2	**R value**	-0.26	-0.21	-0.18	-0.32	-0.43	-0.43
		P value	0.29	0.39	0.47	0.18	0.06	0.07
* p<0.05 significant correlation								

Table 39 Correlation between DJRSI and percentage change in maximum velocity sprint mechanics.

DJ		Touch Down			Toe Off		
		0%-10%	0%-20%	0%-30%	0%-10%	0%-20%	0%-30%
Hip Angle	**R value**	0.18	0.19	-0.10	0.01	-0.09	-0.26
	P value	0.50	0.44	0.71	0.97	0.71	0.32
Knee Angle	**R value**	-0.17	-0.42	-0.34	0.08	-0.30	-0.04
	P value	0.51	0.08	0.18	0.77	0.22	0.88
Ankle Angle	**R value**	-0.32	-0.15	-0.25	0.15	-0.01	0.04
	P value	0.21	0.56	0.34	0.57	0.96	0.88
Trunk Angle	**R value**	0.04	0.07	0.10	-0.03	0.24	0.25
	P value	0.88	0.79	0.69	0.92	0.33	0.34

* p<0.05 significant correlation

Table 40 Correlation between CMJJH and percentage change in acceleration sprint mechanics.

CMJ			Touch Down			Toe Off		
			0%-10%	0%-20%	0%-30%	0%-10%	0%-20%	0%-30%
Hip Angle	**1**	**R value**	0.09	0.2	0.37	-0.46*	-0.33	-0.17
		P value	0.66	0.3	0.05	0.01	0.09	0.38
	2	**R value**	0.32	0.23	0.47*	0.08	0.12	-0.06
		P value	0.1	0.24	0.01	0.68	0.56	0.75
Knee Angle	**1**	**R value**	0.31	0.21	0.25	-0.08	0.37	0.37
		P value	0.11	0.28	0.2	0.69	0.05	0.05
	2	**R value**	0.12	0.1	0.24	-0.03	0.08	-0.09
		P value	0.55	0.62	0.22	0.89	0.69	0.66
Ankle Angle	**1**	**R value**	0.1	0.21	0.15	-0.07	0.14	0.14
		P value	0.61	0.27	0.46	0.72	0.48	0.49
	2	**R value**	0.13	0.08	0.36	0.1	-0.29	0.14
		P value	0.52	0.67	0.06	0.63	0.14	0.49
Trunk Angle	**1**	**R value**	0.13	0.08	0.02	0.16	0.31	0.14
		P value	0.5	0.68	0.92	0.42	0.11	0.47
	2	**R value**	-0.19	-0.25	-0.19	-0.12	-0.14	-0.06
		P value	0.32	0.2	0.33	0.54	0.49	0.76
* $p<0.05$ significant correlation								

Table 41 Correlation between CMJJH and percentage change in maximum velocity sprint mechanics.

CMJ		Touch Down			Toe Off		
		0%-10%	0%-20%	0%-30%	0%-10%	0%-20%	0%-30%
Hip Angle	**R value**	-0.40	-0.30	0.00	-0.20	0.00	-0.20
	P value	0.10	0.20	0.90	0.40	0.80	0.50
Knee Angle	**R value**	-0.30	-0.44*	-0.10	0.00	0.20	-0.20
	P value	0.10	0.010	0.60	0.90	0.30	0.30
Ankle Angle	**R value**	-0.20	-0.10	0.20	0.10	0.10	-0.20
	P value	0.50	0.70	0.5	0.80	0.60	0.40
Trunk Angle	**R value**	0.20	0.20	0.10	0.20	0.20	0.20
	P value	0.40	0.50	0.50	0.40	0.50	0.50
* $p<0.05$ significant correlation							

6.4 DISCUSSION

In an effort to improve sprinting performance, RST is frequently prescribed for field-based invasion team-sport athletes and sprinters [4,34,51,280,285,294]. It is thought that these improvements through an increase in lower-limb power and strength are possibly achieved in a more specific manner than standard resistance training [4,34,282,352]. Despite this, some concerns with regard to the transfer of RST to sprinting performance have been highlighted [280,302,349], due to how RST may alter kinematics during acceleration and maximum velocity sprinting. However, to date there remains a lack of clarity around what way loading influences kinematics during RST and how an athlete's strength characteristics play a role in this.

The aim of this study was to gain an understanding of the factors that influence changes in kinematics during RSS in sprint and field-based invasion team-sport athletes. Multiple regression analysis was utilised to examine regression models that considered variations in split times, maximum strength, and jump performance as predictors for the observed kinematic changes induced by the resistance applied during sprinting.

The results of the study demonstrated several important findings. Firstly, maximum strength, jump and sprint performance measures were found to partially explain the kinematic changes observed during RSS. This means that certain variables, such as DJRSI, CMJJH, hip thrust, back squat and unloaded 10 m split time, were found to be significant predictors of changes in knee and trunk kinematics during RSS. More specifically, the results of the multiple regression analysis examining the change in knee kinematics during resisted sprinting indicate that the predictor variables (DJRSI, CMJJH, back squat, hip thrust, unloaded 5 m and 10 m split time) did not significantly predict changes in knee kinematics during early acceleration for 10%Vdec or 20%Vdec, however were able to explain 96% of the kinematic changes during acceleration for the 30%Vdec.

When looking closer at the estimates in this regression model we can see that a one-unit change in RSI is associated with a 0.041% increase in the angle change at the knee at 30%Vdec. In this case, this means that as RSI increases the knee becomes more extended at TD. A similar pattern is observed for CMJ, where a one cm increase in jump height is associated with a 0.002% increase in knee angle change, which again is indicative of a more extended knee position at TD. Although these variables present significant contributions to the regression model, the ecological importance of these findings may be limited. A one-unit increase in RSI, is an extremely large increase in an athlete's reactive strength, with interventions that target improved RSI demonstrating increases ranging from 0.91 to 1.05 and 1.19 to 1.39 [451,452]. Changes of this magnitude in RSI would be associated with knee angle % changes of 0.037 to 0.043% and 0.048 to 0.057%. Similarly, reported increases in CMJ from specific interventions range from 42.2 to 44.3 cm or 40 to 41 cm [453,454], and in this first case such a change would only explain a 0.084 to 0.089% in knee angle change under loading conditions. Thus, given the relationship between these unit changes it is unlikely that improving such characteristics would result in significant changes to an athlete's knee angle when running under load, however, may offer some insight into differences observed between different athletes. For example, sprinters present CMJH and RSI values ranging from 36 cm to 45 cm and 0.54 to 2.06 [455-458], with team sport athletes presenting values of 30 cm to 40 cm and 0.36 to 0.90 [459,460].

The results of the multiple regression analysis on the change in trunk kinematics during the acceleration phase suggest that the predictor variables (DJRSI, CMJJH, back squat, hip thrust, unloaded 5 m, and 10 m split time) did not significantly predict changes in trunk kinematics (TD and TO) observed between different loading conditions (unloaded, 10%Vdec, 20%Vdec, and 30%Vdec). However, the subsequent multiple regression analysis on the change in trunk kinematics at TD and TO during maxV phase showed more interesting findings. The predictor variables significantly predicted changes in trunk kinematics (TD and TO) at specific loading conditions. For the TD phase of the sprint, the predictor variables were able to significantly predict changes in trunk kinematics between unloaded and 20%Vdec, as well as between unloaded and 30%Vdec. Similarly, for the TO phase of the sprint, the predictor variables significantly predicted changes in trunk kinematics between unloaded and 20%Vdec, as well as between unloaded and 30%Vdec.

The results of the previous study (chapter 5) indicate that loading led to an increase in trunk lean during TD and TO of the maximum velocity phase. When looking closer at the estimates in this regression model we can see that a one-unit change in hip thrust strength (1 kg) was associated with a -0.047 change in trunk lean at

30%Vdec. In this case, this means that as hip thrust strength increases it was less of an increase seen in the trunk lean at TO, which is closer to what we want to see in an unloaded context. One plausible interpretation of these observations is that athletes with superior hip thrust strength exhibit an enhanced capability to maintain trunk posture, particularly during the maximum velocity phase of resisted sprinting. This variable presents a significant contribution to the regression model, which is larger than the RSI or CMJ previously discussed, indicating a higher ecological importance of this finding. Reported increases in hip thrust strength from specific interventions range from 116 to 165 kg [231], and in this case such a change would explain a trunk angle change under loading conditions of 2.3%. Thus, given the relationship between these unit changes it is likely that improving such characteristics would result in significant changes to an athlete's trunk angle when running under load, and may offer some more insight into differences observed between different athletes. For example, college sprinters present hip thrust values ranging from 161 to 205 kg and team sport athletes present values of 116 to 165 kg [231,461].

These results indicate that certain predictor variables can be useful in predicting changes in trunk kinematics during resisted sprinting. However, the predictive ability seems to vary depending on the specific loading conditions and the phase of the sprint (TD or TO).

Secondly, the relationship between back squat, hip thrust, DJRSI, CMJJH, and the changes in kinematics during the acceleration and maximum velocity phases demonstrated significant correlations between some of these variables and changes in hip, knee, and trunk angles during different phases of sprinting. In the acceleration phase, significant negative correlations were observed between back squat and changes in knee angle at TD (second step: 0%-30%Vdec, r = -.42). Results indicated that with increased sled loading knee flexion increased. This may suggest that athletes with higher back squat strength possibly experience less change (flexion) in knee angle when subjected to loading, specifically during the TD phase of the second step. There are several possible explanations for this observed correlation. Stronger athletes do not need to put themselves in a more flexed position to overcome the load because their power enables them to resist force better. Athletes probably flex more to increase their ROM, helping them overcome the load by creating more impulse and momentum. So, a person with greater strength can likely maintain similar (unloaded) positions under heavy loads. Meaning, a higher level of strength may have acted as a protective factor against changes in kinematics. It is possible that greater strength allowed these athletes to generate force more effectively through the knee joints, leading to more efficient movement patterns. Alternatively, the correlation might be indicative of how strength levels can influence movement strategies when subjected to load. Athletes with higher back squat strength could be using their strength advantage to overcome the added resistance and mimic movements seen in unresisted sprinting. On the other side, weaker athletes might struggle to maintain similar knee kinematics once the load is applied during the acceleration phase. There could be two main reasons for this. First, weaker athletes might adopt different movement strategies to deal with the added resistance. They might deliberately increase knee ROM (results from previous chapter) and time over which force is applied during the TD phase to generate greater impulse and momentum. This could be a compensatory mechanism to overcome the limitations in their strength levels. However, such adaptations in movement patterns may not always be ideal, and it may lead to less efficient sprinting mechanics and possibly increase the risk of injury. Second, weaker athletes might lack the strength required to maintain stable positions under the resistance, leading to greater changes in knee flexion. They may not have the necessary strength to counteract the forces imposed by the loading, preventing them from adopting unloaded positions, resulting in more pronounced changes in knee kinematics.

For hip thrust, significant correlations were found with changes in ankle angle at TO during both the first (0%- 20%Vdec, $r = .38$; 0%-30%Vdec, $r = .50$) and second step (0%-30%Vdec, $r = .57$). These correlations were positive, indicating that as hip thrust strength increased, there was an increased change in ankle angle at TO. Even though ankle angle did not increase significantly during TO, a slight increase in dorsiflexion was reported. This may suggest that athletes with higher hip thrust strength possibly experience more change (dorsiflexion) in ankle angle when subjected to loading. This result may not be expected, as it appears to contradict conventional logic, where higher hip thrust strength could imply an increased potential for hip extension and consequently triple extension, which should correspond to plantarflexion.

Hip thrust also showed significant correlations with changes in trunk angle at TD (acceleration phase, first step: 0%-10%Vdec, r = .40) and at TO (second step: 0%-10%Vdec, r = -.54). Results indicated that loading increased trunk lean during TD and TO during the second step of the sprint. The positive correlation between hip thrust strength and changes in trunk angle at TD during the first step indicates that athletes with stronger hip extensors tend to exhibit a more forward-leaning trunk position when their foot makes initial contact with the ground. This increased trunk lean during TD could be beneficial for stronger athletes as it allows them to position themselves in a way that optimises their ability to generate horizontal force through contact with the ground. Since resisted sprinting applies a load that acts horizontally backward, it makes sense that stronger hip extensors could enable athletes to achieve a more forward trunk lean when the resistance is applied. This position may facilitate more efficient force generation and better acceleration during the initial phase of the sprint. The reasons for the shift from a positive correlation between TD and TO in trunk angle to a negative correlation between hip thrust strength and these trunk angles are not entirely clear from the information provided. However, one possible explanation is that stronger athletes strategically alter their kinematics at TD to position themselves for optimal force development and then return to a position more similar to unloaded sprinting at TO. This transition from more trunk lean at TD to a more upright position at TO may facilitate optimal force application and minimise energy wastage during the sprint.

Moving to the maximum velocity phase, significant positive correlations were found between back squat strength and changes in trunk angle at TO (0%- 20%Vdec, r = .51; 0%-30%Vdec, r = .50). Results indicated that loading increased trunk lean during TD and TO. One possible explanation for these findings is that stronger athletes are better able to maintain a more forward trunk lean during the maximum velocity phase of resisted sprinting. In order to continue moving forward and generate horizontal force effectively, it appears that athletes with higher back squat strength can sustain a more forward-leaning trunk angle. This forward trunk position allows them to overcome the resistive load and apply force in a more horizontally directed manner, which may contribute to better acceleration and sprinting performance. In unloaded running, maintaining a constant forward trunk lean over longer distances is not feasible due to fatigue and the need to conserve energy. As runners' transition to the maximum velocity phase in unresisted conditions, they typically adopt a more upright running position to optimise their sprinting mechanics and conserve energy. However, during resisted sprinting the additional load acts as a counterweight, providing a unique training environment that allows athletes to maintain the forward trunk lean over longer distances that would not be possible in unresisted conditions. The findings from this study suggest that athletes who are stronger in the hip thrust at TO can sustain this forward trunk lean for a longer duration during the maximum velocity phase of resisted sprinting. This indicates that strength levels, play a crucial role in influencing trunk positioning and movement patterns during sprinting under resisted conditions. The use of heavier loads in resisted sprinting is a common practice to stimulate force production and power development, particularly targeting the critical initial acceleration phase where horizontal force generation is of utmost importance. However, it is essential to recognise that the increase in trunk angle associated with heavier loads during resisted sprinting may have implications for maximum velocity sprinting performance. During the maximum velocity phase, the body should be relatively upright [338], with vertical forces playing a more significant role in maintaining maximum velocity [124,129,338,439]. Previously it has been recommended that lighter loads (>12.5%BM) be used to train maximum velocity mechanics while maintaining force production capacity [4,34]. This allows athletes to maintain mechanics similar to unresisted running.

Additionally, at the maxV phase significant negative correlations were observed between back squat and changes in hip angle at TD (0%-30%Vdec, $r = -.44$). Results from the previous study, while not significant, indicated that loading increased hip flexion. This suggests that as the resistive load increases, there may be a tendency for athletes to exhibit more hip flexion during resisted sprinting. This increased hip flexion means athletes are more folded at the hip joint, which is not ideal for optimal sprinting mechanics. When considering the negative correlation between back squat strength and changes in hip angle at TD, we can interpret it as follows: Athletes who are stronger in the back squat can better maintain a more extended position through the hip joint during the maxV phase of resisted sprinting. In other words, their hips are less folded, and they exhibit less hip flexion compared to athletes with lower back squat strength. This finding aligns with the assumption that as athletes become stronger in the back squat, they are better able to resist the forces imposed by the resistive load and maintain more optimal hip positioning during the sprint. As a result, the changes in hip angle relative to unloaded sprinting, as indicated by the negative correlation, are minimised in stronger athletes. Maintaining a more extended hip position during the maxV phase of resisted sprinting is advantageous for several reasons. First, it allows athletes to generate more force through the hip joint, which is crucial for powerful hip extension and forward propulsion during maximum velocity sprinting [424-426]. Second, a more extended hip position contributes to better alignment and transfer of force through the kinetic chain, optimising overall sprinting mechanics. Bezodis, *et al.* [462] reported that highest horizontal power during ground contact was produced by a sprinter, who exhibited the greatest total stance leg joint extension. Thus, a large extension of the leg joints appears to benefit performance.

Finally, the significant correlations between DJRSI and CMJJH and changes in joint angles during both the acceleration and maximum velocity phases provide valuable insights into how jump performance and reactive strength influences sprinting mechanics under resisted conditions. The correlations between DJRSI and hip (first step: 0%-30%Vdec, $r = .51$); (second step: 0%-10%Vdec $r = .51$; 0%-30%Vdec, $r = .50$, p), knee (first step: 0%-10%Vdec, $r = .55$) and trunk (0%-30%Vdec, $r = -.49$) angle change at TD during the acceleration phase, as well as the significant correlation between CMJJH and knee angle change at TD (0%-20%Vdec, r = -.44) during the maximum velocity phase, suggest that these reactive strength measures are associated with changes in joint angles, respectively. As previously mentioned, results (previous study) indicated that increasing load resulted in a significant increase in trunk lean, hip flexion and knee flexion.

Regarding the positive correlations between DJRSI and hip angle at TD during the acceleration phase, it indicates that athletes with better reactive strength tend to demonstrate an increase in hip flexion angles when their foot makes contact with the ground under resisted conditions. There are two possible explanations for the observed hip flexion at TD under loaded conditions. Firstly, athletes might not be powerful enough to overcome the load, resulting in a change in their running style to compensate for the added resistance. This change in technique may involve adopting a more flexed hip position to cope with the increased load. However, over time and with appropriate training, athletes may adapt to the additional load, developing stronger and more powerful hip extensors, and subsequently facilitating hip extension more similar to that observed in unloaded sprinting. This adaptation could lead to a more efficient hip extension during the acceleration phase, potentially enhancing horizontal power production during the first stance of the sprint, as suggested by previous research [153,156].

The negative correlation between CMJJH and knee angle at TD during the maximum velocity phase implies that athletes with better CMJ performance tend to have reduced knee extension angles when their foot makes contact with the ground during sprinting. This suggests that more powerful athletes, as reflected by better CMJJH scores, are able to maintain a sprinting technique more similar to unloaded running even under resisted conditions. This is in accordance with results from the previous chapter, where no differences in knee angles were identified. Therefore athletes do not need to significantly alter their running style to overcome the added load, indicating a more efficient and direct leg extension during the early phase of the sprint. This ability to maintain a technique similar to unloaded running even during resisted sprinting may contribute to better overall sprinting performance [462].

However, it's important to note that while these significant correlations suggest a relationship between strength/power and changes in joint angles during the acceleration and maximum velocity phase, correlation does not necessarily imply causation, and further research is needed to establish the causal mechanisms behind these observed associations.

Maximum strength accounts for a lot of changes in movement at very heavy loads. Future studies should look more into these heavy loads. This is important because most research on RST often uses loads greater than 50%Vdec, sometimes even up to 80% or more. Based on, strength likely has an even bigger impact on how movements change at these heavier weights. So, when planning and prescribing RST programs, this should be considered.

Limitations

Several study limitations should be considered when interpreting the results. First, it should be emphasised that the majority of participants were recreational athletes with only a small number of elite athletes (five Irish national sprinters). Hence, these results may not be applicable to a highly trained population. Secondly, the study had a small to moderate sample size, therefore the findings may not be fully reflective of the population the sample was taken from. Thirdly, most studies including ours look at single time points (TD; TO), however, discrete point analysis may result in loss of extremely important information during other parts of the movement [427-430]. The very initial touchdown phase, although conventionally perceived as a non-loading phase, was important in the analysis. Despite the absence of external loading in its initial part, this phase constitutes a critical component of the overall loading sequence. Our primary objective was to investigate changes in body positioning throughout this phase. It is important to note that our estimation may not precisely pinpoint the moment of transition. Nonetheless, this approximation offers valuable insights into the pre- and post-transition states of the body during this phase. A more ideal approach is likely the analysis of waveforms, such as the statistical parametric mapping method [430] but was beyond the scope of this project.

Participants were asked to refrain from training before the testing (48h), however this could not be controlled, and this could potentially have affected our findings. Despite our best attempts at reducing fatigue via appropriate rest periods, it is possible that this still played a role [294]. Sled loads however, were performed in randomised order; therefore, all conditions have been similarly affected by this fact. Finally, the study design employed in this research, necessitates a thoughtful consideration of the possibility of Type 1 and Type 2 errors in result interpretation [463]. The use of multiple regression modelling, along with the selection of independent variables through forward selection, enhances the robustness of the statistical analysis by identifying the most relevant variables contributing to the predictive power of the model. However, it is essential to acknowledge that this process carries a potential risk of Type 1 errors, wherein variables might be included in the model that appear statistically significant but do not have a genuine impact on the dependent variable. Conversely, Type 2 errors are a concern, as variables that could genuinely influence the dependent variable might be omitted due to statistical insignificance. To mitigate these errors, stringent criteria, such as a significance level set at $P < 0.05$ and collinearity checks, were implemented [464]. Additionally, the power analysis ensured an adequate sample size for a robust statistical outcome. Despite these measures, researchers should remain vigilant in the interpretation of results and consider the broader context of their findings, keeping in mind the possibility of both Type 1 and Type 2 errors inherent in the study design.

Lastly, while the assumption of normality was met based on the Q-Q plots (Appendix F, page: 335), the presence of heteroscedasticity in the residual plots for the trunk implies that the variance of the errors is not uniform across the range of the independent variable. This should be taken into consideration when interpreting the results of the linear regression analysis. It suggests that adjustments or transformations to the trunk data may be necessary to account for the heteroscedasticity effect, which has not been done in this research. Despite these limitations this study is novel and has added to the existing body of knowledge, advancing research on resisted sprints and has important practical implications to be considered.

6.5 CONCLUSION

The findings of this study illuminate the intricate interplay between reactive strength measures, strength levels, and loading conditions in shaping sprinting mechanics during resisted conditions. A nuanced analysis of the results underscores the significance of considering both the direction and consistency of the findings, which do not all point into the same direction, in relation to the overarching conclusion. While the initial multiple regression analysis did not reveal significant predictions during the acceleration phase, subsequent investigations unveiled substantial correlations between back squat, hip thrust, DJRSI, CMJJH, and alterations in hip, knee, and trunk angles throughout both the acceleration and maximum velocity phases.

The observed correlations between back squat strength and knee angle at TD during the acceleration phase imply that athletes with greater strength tend to maintain more consistent knee positions under resistive loads. This phenomenon likely stems from their heightened capacity to generate force efficiently through the knee joints, promoting stable knee kinematics. Conversely, weaker athletes may adapt their movement strategies in response to resistance, resulting in less efficient sprinting mechanics characterized by fluctuating knee angles.

Furthermore, the study highlights the importance of trunk lean, especially during the acceleration phase. Stronger athletes exhibited more consistent trunk lean, sustaining a forward-oriented posture during the maximum velocity phase. This ability allowed them to effectively overcome the resistive load and apply force in a predominantly horizontal direction, potentially extending their capacity for acceleration over more extended distances. However, it is crucial to exercise caution when translating these findings into practical training recommendations. To optimise sprinting mechanics for maximum velocity, a nuanced approach involving the use of lighter loads is recommended to avoid excessive trunk lean and hip flexion, which may adversely affect vertical force application.

In addition to these observations, the correlations between DJRSI and CMJJH and changes in joint angles across both acceleration and maximum velocity phases further underscore the impact of jump performance and reactive strength on sprinting mechanics during resisted conditions. Coaches can leverage these insights to design effective training programs focusing on reactive strength training exercises like plyometrics, aiming to enhance athletes' capacity to generate rapid force and maintain proper sprinting mechanics under resistive conditions.

Moreover, athletes themselves can benefit from this research by prioritising strength exercises in their training routines. These exercises not only enhance overall strength but also have the potential to optimise knee, hip, and trunk positioning during both acceleration and maximum velocity phases of resisted sprinting. Consequently, improved force application and power generation can lead to enhanced sprinting performance.

While these findings contribute substantially to our comprehension of the intricate relationship between loading, strength, and kinematics during resisted sprint training, it is essential to acknowledge the need for further investigation. Future research endeavours should explore the long-term effects of various loading conditions following resisted sprint training, examining the transferability of kinematic changes to unloaded sprinting. Additionally, the inquiry should extend to evaluate whether athletes exhibiting fewer kinematic alterations derive more significant benefits from heavier loading conditions. Comprehensive studies incorporating multiple joint and segment angles, along with diverse loading conditions, can provide a more holistic understanding of the intricate interplay between loading and kinematics during resisted sprinting.

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CHAPTER 7

7 SUMMARY, FUTURE RESEARCH AND CONCLUSION

7.1 SUMMARY

Kinematics are the cornerstone of understanding the intricate mechanics of sprinting. Kinematics, encapsulating the study of dynamic body movements and positional dynamics during locomotion, affords comprehensive insights into the nuanced alterations of biomechanical patterns experienced by athletes during RST. Precise quantification of parameters such as body angles and spatio-temporal variables provide researchers and coaches with the ability to identify kinematic changes [465] resulting from diverse resistance modalities and different loads. This information is vital for understanding how athletes' movement patterns are affected during or after RST. Assessing kinematic data enables the evaluation of whether certain resistance conditions lead to more or less 'efficient' sprinting mechanics, thereby informing coaches on the most 'effective' training strategies [190]. Ultimately, the goal of RST is to enhance sprinting performance. Kinematic measurements can provide valuable feedback on whether resisted training is translating into improved sprinting mechanics. Athletes and coaches can use these data to track progress, refine training protocols, and optimise performance gains. This research embarks on a comprehensive exploration of the intricate domain of resisted sprint training, with the primary objective of elucidating its multifarious impacts on kinematic parameters. By exploring this intricate relationship, we not only cater to athletes' immediate requirements but also establish the groundwork for a deeper understanding of this training approach.

The first study revealed a multifaceted landscape within RST, elucidating key insights into coaches' perceptions, practices and knowledge of RST. Coaches both through empirical wisdom and scientific validation, strongly endorse RST as a pivotal tool to enhance sprint performance. Within this work the majority of coaches may not be fully cognisant of the potential benefits of incorporating heavier loads, which can provide a unique training stimulus, fostering greater force production and power development, key attributes for enhanced sprinting performance [331,380,466]. Furthermore, previous literature accentuates the changing dynamics of sprinting mechanics under load. While some alterations can be viewed as positive, such as trunk lean and its influence on horizontal force production [331]. Athletes may adapt to RST over time, potentially restoring their kinematics closer to unloaded sprinting. However, future research needs to explore this.

Despite the literature recommending the use of %Vdec, practitioners in this current research seem to use %BM because of its practicality. This research reported that, in practice, coaches pragmatically navigate RST method selection based on considerations such as availability, accessibility, and logistical feasibility, rather than exclusively adhering to science.

Moreover, the reliability of RST method for load selection is of paramount importance, as inconsistencies in resistance may compromise coaches' confidence in load application, athletes' exertion levels, and the overall training workload. This, in turn, can potentially impact training programming and periodisation. While selected resistance levels (2, 5, and 8 oz) generally proved suitable and reliable in this current research, issues of reliability did surface, particularly in specific load-distance combinations. This underscores the need for coaches and practitioners to carefully consider equipment reliability when designing training programs and prescribing resistance loads to optimise athletes' training outcomes.

In the context of kinematic changes, this research identified that the magnitude of kinematic changes increases with increased load. Importantly, most of these changes manifest similarly across team sport athletes and sprinters, although noteworthy differences are apparent with regard to range of motion of the knee, which exhibits a more substantial increase in sprint athletes with increasing load. This may suggest an avenue for optimising propulsive forces, likely attributed to higher hip extensor strength.

Delineating the role of strength and power in modulating sprint technique during RST, this research identifies that stronger and more powerful athletes tend to maintain sprint mechanics more similar to unloaded sprinting. In contrast, weaker athletes may adapt movement strategies to cope with added resistance, potentially leading to less efficient mechanics. Lastly, the research unveils nuanced approaches within RST, revealing how stronger athletes, by maintaining more trunk lean during maximum velocity training, may hone acceleration over longer distances, thereby as shown by previous literature [331], enhancing horizontal power production and acceleration mechanics. Conversely, coaches and athletes targeting maximum velocity mechanics may benefit from lighter loads, facilitating more upright trunk positions.

Despite the insights gained through the studies, it is essential to acknowledge certain limitations inherent in each. For instance, the studies sample sizes were moderate, and therefore the findings may not be fully reflective of the entire population. The majority of studies, including the studies of this thesis, predominantly focus on single time points during the movement. This approach may result in a loss of important information during other phases of the sprinting motion. A more ideal approach would involve the analysis of waveforms, such as the statistical parametric mapping method. Unfortunately, this method was beyond the scope of this project. Additionally, it is essential to note that this research only investigated the acute changes in kinematics resulting from resisted sprint training. Therefore, it is challenging to extrapolate this information into a longitudinal context regarding the change and development of kinematics and enhancement of sports-specific performance. Lastly, despite efforts to standardise participant conditions by asking them to refrain from training before testing, it was challenging to control this factor completely. Individual variations in participants' compliance with this requirement may have influenced the findings. Furthermore, although an athletes fatigue was minimised through appropriate rest periods, it is possible that it still played a role in some aspects of the study.

Despite these limitations, this research provides valuable insights into the intricate relationship between load and sprinting kinematics. It emphasises the essential role of coaches in making informed decisions that bridge scientific principles and practical feasibility. Additionally, it highlights the potential advantages of higher loads when using RST and underscores the significance of reliable equipment for precise load measurement. This comprehensive knowledge may equip coaches and practitioners with the tools needed to create more efficient, customised training regimens, to enhance sprinting performance.

7.2 SUGGESTIONS FOR FUTURE RESEARCH

The thesis has opened doors to several intriguing avenues for future research within the realm of resisted sprint training. These potential research directions promise to deepen our understanding of the complex interplay between resistance, sprinting mechanics, and athletic performance.

Firstly, there's a pressing need to explore the role of maximal strength in the context of RST, particularly when heavy loads are involved. Contemporary RST studies often employ loads that exceed 50% of an athlete's maximal velocity. Some even go as high as 80% or more. Our research suggests that an athlete's maximal strength levels play a significant role in influencing movement changes, especially under these higher-intensity conditions. This finding underscores the importance of considering an athlete's strength when designing RST programs, especially when heavier loads are used. Understanding the relationship between strength, movement alterations, and overall performance is paramount for coaches and practitioners.

Another vital area of investigation is the long-term adaptations in joint and segment angles under various load conditions during RST. This research aims to shed light on how athletes adapt to the resistance over time. It's crucial to understand whether these adaptations eventually lead athletes to positions and mechanics more closely resembling those in unloaded sprinting. This insight can illuminate the durability of technique changes induced by RST and their applicability to regular sprinting.

The link between kinematic changes resulting from RST and their impact on sprinting performance forms another intriguing research direction. Does the altered sprinting technique translate into tangible improvements in an athlete's sprinting ability? Moreover, is there a difference in performance gains between stronger athletes, who may experience fewer kinematic disruptions, and weaker athletes, who might undergo more substantial changes in their mechanics?

Moving into the realm of biomechanics, future research can delve deeper into the underlying physiological and biomechanical mechanisms responsible for the observed technique changes during RST. This could involve detailed analyses of muscle activation patterns, joint kinetics, and muscle-tendon behavior. Such investigations would provide valuable insights into the precise mechanisms through which RST influences sprinting mechanics.

Lastly, there's a need to explore the effects of different resistance types used in RST. This could encompass a comparison of various resistance configurations, including mechanical resistance devices, harnesses, and parachutes. Researchers can assess how each method influences joint angles and sprint performance. This understanding can assist coaches in selecting the most effective and practical tools for incorporating RST into training programs.

These avenues for future research promise to enhance our comprehension of the intricate relationship between resistance, sprinting mechanics, and athletic performance. By pursuing these research directions, scholars and practitioners can contribute valuable insights that optimise training strategies and elevate the performance of sprint athletes and team-sport participants alike.

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8 APPENDICES

Appendix A

8.1 Publications

Osterwald, K. M., Kelly, D., Braga Rodrigues, T., & Ó Cathain, C. (2020). Kinematic Characteristics Of Resisted Sled Sprints Under Different Loading Conditions. ISBS Proceedings Archive, 38(1), 844.

Available at: https://commons.nmu.edu/isbs/vol38/iss1/213

38th International Society of Biomechanics in Sport Conference, Physical conference cancelled, Online Activities: July 20-24, 2020

KINEMATIC CHARACTERISTICS OF RESISTED SLED SPRINTS UNDER DIFFERENT LOADING CONDITIONS

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The purpose of this study was to identify the kinematic characteristics of resisted sled sprinting under different loading conditions (0%, 10%, 20% and 30% velocity decrement (Vdec)) and in different sporting populations. Thirty-three healthy athletes (Sprinters n=10; Invasion team sport athletes n=23) were recruited and completed 3 days of testing. Kinematics were captured with high-speed cameras and processed using Dartfish Software. Loads of 20% and 30% Vdec resulted in a significant increase in trunk lean relative to unloaded sprinting, during both acceleration and maximum velocity phases, with no difference between groups (sprint & team sport athletes). This increase in trunk lean with load (20% and 30% Vdec) appeared to prevent athletes transitioning into upright maximum velocity mechanics, and therefore extended the distance of the acceleration phase. The trunk lean increase was related to the heavy loads and athletes were not able to reach mechanics that were truly reflective of maximum velocity (maxV) sprinting. However, heavy loading extended the distance over which it is possible to train acceleration.

KEYWORDS: resisted sprinting, kinematics, training specificity.

INTRODUCTION: The ability to improve sprint performance is a central training goal in numerous sports. With this in mind, coaches target increased force characteristics, and/or improved technical execution (Petrakos et al., 2016). Resistance training exercises such as squats are regularly employed to target improved force characteristics (Suchomel et al., 2018). However, the extent to which an increase in performance of these movements transfers to improved sprint performance may be limited (de Villarreal et al., 2013). The principle of specificity dictates that training should correspond to the functioning of the neuromuscular system in the specific event an athlete is training for and may explain the limited transfer from traditional resistance training to improved sprint performance (Haff et al., 2012). Considering this, the addition of an external load to the action of sprinting (using a weighted sled) may offer a more specific form of resistance training for athletes. However, the kinematic characteristics, and therefore specificity, of resisted sled sprinting is currently unclear. To elucidate this, the purpose of this study was to identify the kinematic characteristics (trunk lean) of resisted sled sprinting (RSS) under different loading conditions and in different sporting populations.

METHODS: Thirty-three athletes were recruited (Sprinters n=10; Invasion team sport athletes n=23; age (yrs)=21.4±3.3; height (cm)=185± 8.2; mass (kg)=80.2±11.8). Participants were recruited if they (a) had experience with resistance and sprint training (minimum of 18 months), (b) were currently strength training and had history of strength training for a minimum of two years, (c) were currently participating in sprinting, Rugby or Gaelic football and (d) were injury free (for at least 6 months). Participants were required to complete 3 testing days. Day 1 was a familiarization session. On day 2 participants completed 12 40 m sprints at different loads (unloaded and 10%, 20%, 30% velocity decrement, three sprints with each load), and on day 3 a battery of strength and power tests were completed. A first estimation for the loads was calculated with the equation from Lockie et al (2003).

After all familiarization trials were finished an individual load–velocity relationship was established for each participant and checked for linearity. The linear regression of the load–

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Publication:

Osterwald, K. M., Kelly, D. T., Comyns, T. M., & Catháin, C. Ó. (2021). Resisted Sled Sprint Kinematics: The Acute Effect Of Load And Sporting Population. Sports, 9(10), 137.

Available at: https://doi.org/10.3390/sports9100137

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Resisted Sled Sprint Kinematics: The Acute Effect of Load and Sporting Population

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Sports **2021**, *9*(10), 137; https://doi.org/10.3390/sports9100137

Received: 12 June 2021 / Revised: 6 August 2021 / Accepted: 27 September 2021 / Published: 30 September 2021

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Abstract

In this study, we assessed the acute kinematic effects of different sled load conditions (unloaded and at 10%, 20%, 30% decrement from maximum velocity (Vdec)) in different sporting populations. It is well-known that an athlete's kinematics change with increasing sled load. However, to our knowledge, the relationship between the different loads in resisted sled sprinting (RSS) and kinematic characteristics is unknown. Thirty-three athletes (sprinters n = 10; team sport athletes n = 23) performed a familiarization session (day 1), and 12 sprints at different loads (day 2) over a distance of 40 m. Sprint time and average velocity were measured. Sagittal-plane high-speed video data was recorded for early acceleration and maximum velocity phase and joint angles computed. Loading introduced significant changes to hip, knee, ankle, and trunk angle for touch-down and toe-off for the acceleration and maximum velocity phase ($p < 0.05$). Knee, hip, and ankle angles became more flexed with increasing load for all groups and trunk lean increased linearly with increasing loading conditions. The results of this study provide coaches with important information that may influence how RSS is employed as a training tool to improve sprint performance for acceleration and maximal velocity running and that prescription may not change based on sporting population, as there were only minimal differences observed between groups. The trunk lean increase was related to the heavy loads and appeared to prevent athletes to reach mechanics that were truly reflective of maximum velocity sprinting. Lighter loads seem to be more adequate to not provoke changes in maxV kinematics. However, heavy loading extended the distance over which it is possible to train acceleration.

Keywords: resisted sprints; sled sprint; kinematics; gait; team sport; sprint athlete

1. Introduction

Sprinting is a powerful action where the muscles of the lower limbs produce high amounts of vertical and horizontal net force with each step [1]. Research indicates that the body is oriented with a large degree of forward lean during the acceleration phase but becomes more upright as velocity increases and as athletes progress through a sprint [2,3]. Sprint performance (SP) is a result of both the absolute physical capability of the body, and technical ability to apply this raw capacity in an effective manner [4,5]. Recent literature has established that acceleration and maximal velocity SP are related to the technical ability to apply resultant ground reaction forces in a more horizontal

Appendix B

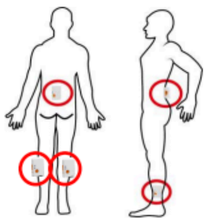
8.2 Information and Consent

SPRINT AIT SPRINT STUDY

The test seeks to collect data of sprint characteristics of **resisted sled sprints** with a sled and additional weights on it. Also, **1 repetition maximum in squat and hip thruster** (*these are two resistance exercises to measure your maximum strength*) will be collected alongside **counter movement jumps** (*this is a vertical jump*). For the testing you will need to sign a consent form *(consenting to assessment, data collection and records to be used for research purposes)*. Participation in the research study will involve attending AIT Sports arena **or** Morton Stadium (Santry) for two appointments which will last approximately 1.5 hours and one appointment in your club gym, lasting about 45 minutes. It is important to come **10 minutes** before your appointment time because we want to assure a smooth testing procedure with little delay as possible.

TO BRING WITH YOU:

- **Shorts**
- **Ankle socks**
- **Runners (shoes you would use to play sports)**
- **Towel**
- **Drinks**
- **A sports bra (female)**

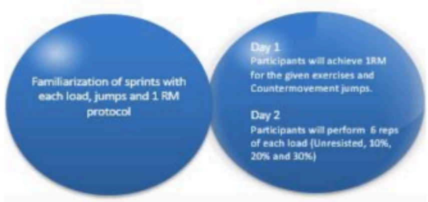


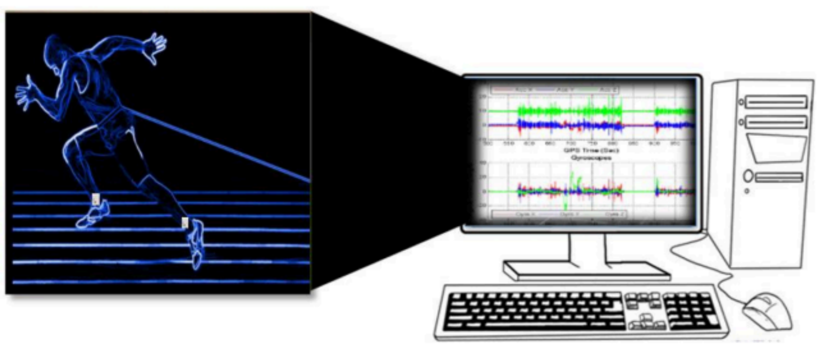
Preparation:

- A set of sensors will be placed over various landmarks on your body to capture the biomechanical data during the Resisted sled sprints. See figure above.
- **Do not apply any moisturiser/oils to the skin** because they interfere with attachment of sensors.

Testing:

- You will be taken through a standardized warm up with additional time for your own warm up.
- Counter movement jumps will be captured on a force platform.
- Maximum strength testing will happen in the same session (squat + hip thruster).
- Sprints will be conducted with the following conditions: Unresisted, 10, 20, 30% of velocity decrement on a separate day.
- Sled weight will be calculated during the familiarization session.





CONSENT FORM

The participants must complete this form themselves

Title of Project: Biomechanical assessment of kinetic and kinematic characteristics of resisted sled sprints (RSS) under different loading conditions using inertial sensors.

Participant ID Number: ____________________

PLEASE TICK YOUR RESPONSE IN THE APPROPRIATE BOX

I have read and understood the attached participant information leaflet	Yes ☐	No ☐
I have had the opportunity to ask questions and discuss the study	Yes ☐	No ☐
I have received satisfactory answers to all my questions	Yes ☐	No ☐
I understand that I am free to withdraw from the study at any time without giving a reason and without this affecting my future medical care	Yes ☐	No ☐
I agree to take part in this study without prejudice to my legal or ethical rights	Yes ☐	No ☐

Participant's Signature: Date:

Participant's Name in Print:

Investigator's Signature: Date:

Investigator's Name in Print:

Appendix C

8.3 One repetition maximum testing

(1) The athlete will be instructed to warm up with a light resistance that easily

allowed to complete 5 to 10 repetitions.

(2) A 1-minute rest period will be provided.

(3) A warm-up load will be estimated that would allow the athlete to complete three to five repetitions by adding 14-18 kg or 10% to 20% for lower body exercise.

(4) A 2-minute rest period will be provided.

(5) A near-maximal load will be estimated that would allow the athlete to complete

two or three repetitions by adding 14-18 kg or 10% to 20% for lower body exercise.

(6) A 2 - 4-minute rest period will be provided.

(7) The load will be increased with 14-18 kg or 10% to 20% for lower body exercise.

(8) The athlete will be instructed to attempt a 1RM.

(9) If the athlete was successful,

a. A 2- to 4-minute rest period will be provided and step 7 was repeated.

b. If the athlete failed, a 2- to 4-minute rest period will be provided; and the load decreased by subtracting 7-9kg or 5% to 10% for lower body exercise AND then step 8 repeated. Adequate rest periods will be given between reps and sets to ensure participants are able to perform optimally without the risk of fatigue. For a valid hip thrust the participant must begin with the bar placed across the hips and with their buttocks in contact with the ground and end with the bar on their hips with their back parallel with the ground by extending through the hip.

Appendix D

8.4 Survey

Background Information

1. What is your age? (tick one answer)

☐ 18-24

☐ 25-34

☐ 35-44

☐ 45-54

☐ 55-65

☐ 65+

2. A) Which of the below best describes your current job/coaching title? (tick all that apply)

☐ Strength & Conditioning Coach / Athletic Performance Coach

☐ Sprint Coach / Track and field Coach

☐ Sports Coach

☐ Sports Scientist

☐ Other (please specify)

2. B) What is your current occupational status? (tick one answer)

☐ Full-time paid work (30+ hours per week)

☐ Part-time paid work (8-29 hours per week)

☐ Part-time paid work (under 8hours per week)

☐ Part-time unpaid work / intern

☐ Consultant

☐ Volunteer

☐ Retired

☐ Other (please specify)

3. Number of years' experience coaching speed and sprint development? (tick one answer)

☐ < 1

☐ 1-5

☐ 6-10

☐ 11-15

☐ 16-20

☐ 20+

4. Where are you currently coaching (country)? (tick one answer)

☐ Ireland

☐ UK

☐ USA

☐ Germany

☐ Other (please specify)

5. What sport/sports are you currently working in? (at least 1 hour per week) (list below)

6. What gender of athlete are you currently working with? (tick one answer)

☐ Male

☐ Female

☐ Both

☐ Prefer not to answer

7. What other sports have you previously coached? (at least 1 hour per week) (if you have worked in more than 3 sports please list your 3 most recent)

8. A) Please state the age-group (e.g., adult, youth, under 18s, etc.) you are currently coaching?

8. B) Please state the competition level of athletes you are currently coaching? (select all relevant)

 Professional

 Amateur

 International

 National

 Intercounty

 Club

 Academy

 Collegiate

 Other (please specify)

9. What was the highest competition level of athletes you have coached in your career?

 Professional

 Amateur

 International

 National

 Intercounty

 Club

 Academy

 Collegiate

 Other (please specify)

Education & Qualifications

10. A) What is the highest level of education you have completed? (tick one answer)

 None

 Primary School (Grudschule)

☐ Secondary School to age 15/16 (Junior Certificate, GCSE, O Levels, Haupt-und Realschulabschluss)

☐ Secondary School to age 17/18 (Leaving Certificate, A Levels, HNC, Abitur)

☐ University Undergraduate Degree, BSc

☐ University Postgraduate Degree, MSc (taught)

☐ Magister/ Diplom (Staatsexamen)

☐ University Postgraduate Degree, PhD / Dr.

☐ Non-degree courses

☐ Other (please specify)

10. B) What is the related field/area of your education? (tick all that apply)

☐ Coaching

☐ Sports Science

☐ Strength & Conditioning

☐ Biomechanics

☐ Exercise Physiology

☐ Other (please specify)

11. Do you have any coaching qualifications/accreditations? If so, please list below (e.g. sports coaching qualifications, Strength & Conditioning accreditations etc.)

(Please list a maximum of 3 in the boxes provided below)

Resisted sprinting: A method which applies an external resistance/load to the sprinting movement e.g. weighted sleds, vests, uphill sprinting, etc.

Perception

12. Where do you source your information on how to utilize resisted sprint training as a training method? (tick all that apply)

□ Scientific Journals

□ Coaching Journals

□ Social Media

□ Workshops

□ Other coaches

□ Other (please specify)

13. Using the options listed below please indicate if you agree or disagree with the following statements:

A) Resisted sprint training is a useful training tool for improving unresisted sprint performance. (from your experience)

Strongly disagree
Disagree
Neutral
Agree
Strongly agree

Only answer if you have read scientific literature, if not please select N/A:

B) Resisted sprint training is a useful training tool for improving unresisted sprint performance. (from scientific literature)

Strongly disagree
Disagree
Neutral
Agree
Strongly agree
NA

C) Resisted sprint training compared to other methods is as good a training tool for improving unresisted sprint performance. (from your experience)

Strongly disagree
Disagree
Neutral
Agree
Strongly agree

Only answer if you have read scientific literature, if not please select N/A:

D) Resisted sprint training compared to other methods is as good a training tool for improving unresisted sprint performance. (from scientific literature)

Strongly disagree
Disagree
Neutral
Agree

Strongly agree
NA

14. Have you used resisted sprint training with your athletes in the past 24 months?

☐ Yes

☐ No

If you answered Yes:

☐ During single training sessions

☐ In a planned programme with defined goals

If you answered Q14 with No, please complete Q 15.

If you answered Q14 with Yes, please skip to Q 16.

15. What is your reason for not using resisted sprint training? (tick all that apply)

☐ I believe it is not effective for improving speed or acceleration

☐ I don't know enough about it

☐ There is not enough time during training

☐ I believe there are better/more efficient ways to improve sprinting performance

☐ I believe it changes sprinting technique

☐ Fear of injury

☐ I don't have access to the necessary equipment

☐ It is too time consuming to manage

☐ Other (please specify)

Please expand on your reason/s for not using resisted sprint training below.

If you answered Yes to Q 14 please complete the following.

16. Using the options listed below please indicate how confident you are with:

A) Your theoretical knowledge of resisted sprint training?

no confidence
slight confidence
moderate confidence
high confidence

B) Coaching resisted sprint training during training sessions?

no confidence
slight confidence
moderate confidence
high confidence

C) Prescribing and coaching resisted sprint training in training programmes?

no confidence
slight confidence
moderate confidence
high confidence

17 A) Give up to 3 main aims/goals for prescribing resisted sprint training? (e.g., increase strength specific to sprinting, Improving sprint acceleration/maxV) (list below)

17. B) What qualities of speed do you prescribe resisted sprint training for? (tick all that apply)

☐ Initial acceleration

☐ Late acceleration

☐ Transition

☐ Max Velocity

☐ All

Acceleration is defined as distances ranging from 0-25 m

Initial acceleration is defined as distances ranging from 0-

Transition is defined as

Maximum velocity is defined as distances ranging from 25 and 70 m

17. C) Is your aim/goal and training content (resistance, repetitions and sets, distances, total volume), when prescribing resisted sprint training, the same for acceleration and maximum velocity?

☐ Yes
☐ No

Please explain below:

Methodology

18. A) What resisted sprinting modalities do you use? (tick all that apply)

☐ Aerodynamic (e.g., parachutes)

□ Motorized/robotic (e.g., 1080 Sprint, Dynaspeed MuscleLab)

□ Pulley (e.g., Exer-Genie)

□ Sliding (e.g., sled, tire pulls)

□ Other (please specify)

If you selected multiple modalities, please elaborate on your reasoning for choosing multiple modalities. (e.g. based on availability of equipment, easy access, easy transport, based on sprint phase, etc.)

18. B) Which aspect would you consider being most important for your choice (what modalities to use)? (e.g. aim/goal of session, effect on technique)

Can you elaborate on this?

19. A) Do you implement resistance as a technical and/or physical stimulus?

□ Technical

□ Physical

□ Both

□ I have not considered this before

19. B) What strategy do you use to prescribe resisted sprinting load? (tick all that apply)

□ Percentage of body-mass

□ Percentage velocity decrement

□ Percentage of maximum resisted sled load (Can be used with other measurable resisted sprint methods e.g. Run Rocket or Exer-Genie)

□ Absolute load

□ Degree of hill incline

□ No strategy

□ Other (please specify)

19. C) What are your reasons for selecting this method of load/resistance prescription. (list no more than 3)

19. D) Do you prescribe resistance for a group of athletes (e.g., X %BM/%Vdec for whole group) or individualized (e.g., X %BM/%Vdec for each individual, based on training targets for athlete)?

20. Listed below are factors you may consider before selecting a resisted sprinting load/resistance. Please read the list of factors and then rate their importance using the scale provided.

(This scale will be in the form of a likert scale e.g., extremely important, very important, moderately important, slightly important, not important, I have not considered this factor before)

□ Sprint phase identified for improvement e.g. acceleration or maximum velocity

□ Different positional sprint demands (Team sports)

□ Athlete's force-velocity characteristics

□ Athlete's training age

□ Athlete's speed capabilities

□ Athlete's level of experience with resisted sprints

□ Athlete's strength capabilities

□ Surface being trained on

□ Number of days pre/post competition

□ Resisted sprinting modality

□ Acute change in technique (changes that occur during the sprint)

□ Long-term change in technique

□ Other (please specify)

21. A) For unresisted sprinting, what technique characteristics do you associate with good technique? (e.g. posture, mechanics, etc.)

During acceleration:

During maximum velocity:

21 B) For resisted sprinting, do you consider the same technique characteristics important?

During acceleration:

□ No

□ Yes

If no, please explain. What you do associate with good sprinting technique during resisted sprinting and why you have different considerations concerning unresisted sprinting.

During maximum velocity:

□ No

□ Yes

If no, please explain. What you do associate with good sprinting technique during resisted sprinting and why you have different considerations concerning unresisted sprinting.

In the following part questions will be asked first, concerning acute resisted sprint effects followed by long-term effect questions.

Acute changes:

22. A) In your experience does resisted sprint training change ACUTE sprinting technique during the acceleration phase compared to unresisted sprinting?

□ No

□ Yes

□ I have not considered this before

If yes, please expand:

22. B) In your experience does resisted sprint training change ACUTE sprinting technique during the maximum velocity phase compared to unresisted sprinting?

□ No

□ Yes

□ I have not considered this before

If yes, please expand:

22. C) Listed below are variables that may be impacted by resisted sprinting. Which in your experience will be ACUTELY affected by resisted sprint training?

Please read the list and then tick the box and rate their importance using the scale provided. (This scale will be in the form of a likert scale e.g., majorly affected, minorly affected, affected, not affected)

For acceleration phase:

- Contact time
- Flight time
- Step length
- Step frequency

- Joint angles

□ Other (please specify)

□ None of the above

For maximum velocity phase:

- Contact time
- Flight time
- Step length
- Step frequency
- Joint angles

□ Other (please specify)

□ None of the above

22. D) From your experience, in what way do different resistances impact sprinting technique ACUTE, overall and for different sprint phases?

22. E) Do you think the different modalities impact ACUTE sprinting technique in different ways? (e.g., Sled, 1080 Sprint, Parachute, Weighted vest, Exer-Genie)

□ No

□ Yes

□ I have not considered this before

If yes, please explain:

Long-term changes:

22. F) In your experience does resisted sprint training change sprinting technique LOMG-TERM in the acceleration phase?

□ No

□ Yes

□ I have not considered this before

If yes, please expand:

22. G) In your experience does resisted sprint training change sprinting technique LOMG-TERM in the maximum velocity phase?

□ No

□ Yes

□ I have not considered this before

If yes, please expand:

22. H) Listed below are variables that may be impacted by resisted sprinting. Which in your experience will be affected by resisted sprint training LOMG-TERM?

Please read the list and then tick the box and rate their importance using the scale provided. (This scale will be in the form of a likert scale e.g., majorly affected, minorly affected, affected, not affected)

For acceleration phase:

- Contact time
- Flight time
- Step length
- Step frequency
- Joint angles

□ Other (please specify)

□ None of the above

For maximum velocity phase:

- Contact time
- Flight time
- Step length
- Step frequency
- Joint angles

□ Other (please specify)

□ None of the above

22. I) From your experience, in what way do different resistances impact sprinting technique LOMG-TERM, overall and for different sprint phases?

22. J) Do you think the different modalities impact sprinting technique in different ways? (e.g., Sled, Tire Pulls, 1080 Sprint, Parachute, Weighted vest, Exer-Genie)

□ No

□ Yes

□ I have not considered this before

If yes, please explain:

22. K) Changes in technique during resisted sprint training negatively impact unresisted sprint performance.

Strongly disagree
Disagree
Neutral
Agree
Strongly agree
I have not considered this before

This part of the survey is not about long-term effects anymore

23. Are you concerned about technique alteration for load prescription?

□ Yes

□ No

□ I have not considered this before

Please explain:

24. A) If your training modality requires a harness attachment, do you think the attachment point (shoulder, hip) impacts sprinting technique?

□ Yes

□ No

□ I have not considered this before

If so, please explain:

24. B) Where do you prefer to attach the harness on the athlete?

□ Shoulder

□ Hip

25. A) Do you monitor changes in technique during <u>unresisted</u> sprinting?

☐ No

☐ Yes

If Q 25 A yes:
If Q 25 A no, continue with Q26:

25. B) How do you monitor changes in technique during <u>unresisted</u> sprinting? (e.g., High Speed Camera, Camera, Optojump etc.)

25. C) What variables related to technique do you monitor during <u>unresisted</u> sprinting?

☐ Sprint time

☐ Contact time

☐ Flight time

☐ Step frequency

☐ Joint angles

☐ Segment angles

☐ Other (please specify)

☐ I have not considered this before

25. D) Do you measure changes in technique during <u>resisted</u> sprint training?

☐ No

☐ Yes

If Q 25 D, yes:

If Q 25 D no, please still fill out the below (what would you do, how would you do it, etc.):

25. D) What variables related to technique do you monitor during <u>resisted</u> sprint training?

☐ Sprint time

☐ Contact time

☐ Flight time

☐ Step frequency

□ Joint angles

□ Segment angles

□ Other (please specify)

25. E) How do you monitor changes in technique during <u>resisted</u> sprinting? (e.g., High Speed Camera, Camera, Optojump etc.)

26. Does alteration in sprinting technique influence how you prescribe load?

Acute:

□ No

□ Yes

□ NA

If yes, how:

Long-term:

□ No

□ Yes

□ NA

If yes, how:

27. A) You are training an athlete and you believe their technique has changed during acceleration while using resisted sprinting, do you: (tick all that apply)

Acute:

□ Stop using it

□ Adjust the resistance

□ Make load heavier

□ Make load lighter

☐ Resistance easier

☐ Resistance harder

☐ Give them time to adjust to the training modality

☐ Allow time to adjust to resistance

☐ Change modality

☐ Change attachment point

☐ Provide verbal feedback on technique

☐ Other (please specify)

Elaborate to explain your answer:

27. B) You are training an athlete and you believe their technique has changed ACUTELY <u>during maximum velocity</u> while using resisted sprinting, do you: (tick all that apply)

<u>Acute:</u>

☐ Stop using it

☐ Adjust the resistance

☐ Make load heavier

☐ Make load lighter

☐ Resistance easier

☐ Resistance harder

☐ Give them time to adjust to the training modality

☐ Allow time to adjust to resistance

☐ Change modality

☐ Change attachment point

☐ Provide verbal feedback on technique

☐ Other (please specify)

Elaborate:

27. C) You are training an athlete and you believe their technique has changed <u>during acceleration</u> while using resisted sprinting, do you: (tick all that apply)

Long-term:

 Stop using it

 Adjust the resistance

 Make load heavier

 Make load lighter

 Resistance easier

 Resistance harder

 Give them time to adjust to the training modality

 Allow time to adjust to resistance

 Change modality

 Change attachment point

 Provide verbal feedback on technique

 Other (please specify)

Elaborate:

27. D) You are training an athlete and you believe their technique has changed during maximum velocity while using resisted sprinting, do you:

Long-term:

 Stop using it

 Adjust the resistance

 Make load heavier

 Make load lighter

 Resistance easier

 Resistance harder

 Give them time to adjust to the training modality

 Allow time to adjust to resistance

 Change modality

 Change attachment point

□ Provide verbal feedback on technique

□ Other (please specify)

Elaborate:

Appendix E

8.5 Validating a questionnaire in the area of RST using the e-Delphi method

The survey in this thesis utilized the e-Delphi methodology to acquire feedback and attain agreement on the specific research topic, which entailed the advancement and authentication of a questionnaire. The Delphi technique, which was initially created by the Rand Corporation during the early 1950s to determine military priorities, serves as the foundation for this approach. The Delphi technique strives to establish accord among a group of specialists on a specific topic by conducting several rounds of anonymous expert opinion gathering through questionnaires.

The e-Delphi methodology, which constitutes a digital adaptation of the Delphi technique, involves the use of electronic and internet-based questionnaires to accumulate expert opinions. This approach presents several benefits, including diminished resource costs, reduced response times, and heightened anonymity for participants.

The e-Delphi methodology's process is as follows:

Questionnaire Development: The study commences with the creation of a preliminary questionnaire that comprises pertinent closed and open-ended inquiries. The initial questionnaire forms the basis for collecting expert opinions.

Selection of Experts: A panel of carefully selected experts, possessing knowledge and experience relevant to the research topic, is identified. These experts are considered valuable contributors whose opinions are respected by their peers.

Round 1 - Identifying Issues: The experts receive the initial survey via email. In Round 1, the experts are solicited to provide feedback on the questionnaire, identify any challenges in its creation, and recommend its structure and content. The feedback is collected using a Likert scale to assess agreement levels and a section for alternative suggestions or comments.

Round 2 - Consensus on Draft Questionnaire: After Round 1, supervisor meetings are held to comprehensively scrutinize the feedback received. The questionnaire is subsequently revised based on the consensus reached in these meetings. The updated draft questionnaire is dispatched to the experts via email for further evaluation, following a similar procedure as in Round 1. The experts once again use the Likert scale and provide remarks on the revised version.

Round 3 - Final Feedback and Consensus: The questionnaire undergoes one more revision based on the feedback and consensus attained in Round 2. The final version of the questionnaire is sent to all experts for individual assessment. Round 3 facilitates an autonomous evaluation of the final questionnaire document and any additional remarks.

The process continues until a satisfactory level of agreement is reached among the expert panel concerning the content and format of the questionnaire. If a satisfactory level of consensus is achieved in Round 3, additional rounds may be unnecessary.

Consensus is determined through the use of the Likert scale in which experts rate their level of agreement with the questions in the survey. The opinions and comments provided by the experts are meticulously examined and graded. The iterative process of questionnaire revision and feedback gathering helps to bridge the gap between scientific findings and coaching practice, ensuring that the questionnaire becomes more applicable and tailored to the particular needs of coaches and athletes.

The e-Delphi methodology, in general, is an invaluable instrument for acquiring the insights of experts, establishing agreement, and enhancing the relevance of research discoveries in practical coaching. It offers researchers a better comprehension of the decision-making processes of coaches, the determinants of their perspectives, and the optimal methods for integrating scientific knowledge into training regimens.

First contact email:

Hi XXX,

My name is Katja Osterwald and I am a PhD candidate at Athlone Institute of Technology, Ireland. I am supported by my supervisory team of Dr. David Kelly and Dr. Ciarán O'Catháin. The title of my research is 'An Investigation into Specificity of Resisted Sprints'. My current research study is a proposed online, self-completed survey, designed specifically to investigate the current resisted sprint training practices of team sport coaches/ speed coaches/ sprint coaches and their perception of how it may alter technique. The main aims of this survey are to:

- survey information regarding resisted sprint training implementation and understanding of kinematics of coaches
- investigate the factors which influence coaches decisions to use resisted sprints as a training method

As a Sport Scientist (prevention and rehab coach) who has previously worked in the field of biomechanics at the Sports Surgery Clinic in Dublin, I believe this information will be highly valuable to coaches/players in their quest for optimizing training and performance. This study presents a unique opportunity for coaches to gain insights into the current practices and perception of kinematics of fellow practitioners in the area of resisted sprinting. Additionally, the information gathered will highlight any gaps which may exist between research-based knowledge and what coaches are implementing in practice.

To ensure the survey is an accurate resource and capable of fulfilling the aims of our brief, we have decided to undertake a validation process via the modified Delphi technique. This process requires a panel of experts to volunteer to review and rate each question using likert scales (will be provided on an excel file by the principal investigator). The experts will also be asked to add any further recommendations/changes to the questions, their wording or the order of questions. This will be a **three round** review process with a **one-week period** allocated for each review round. Within this window, once the expert has returned the excel file, I will make changes to the survey based on this feedback and return the updated version for the next review.

The process is planned to commence at the end of this month, when the initial draft survey will be emailed to the panel of experts.

We believe that your extensive knowledge and experience in this area will help ensure that our survey is appropriately designed to gather valid and reliable information. Therefore, we ask if you would kindly consider participating in this process and offer your expert evaluation of our survey? Your participation would be greatly appreciated Matt, by myself and my supervisory team. Please get in contact with us if you have any further questions on the validation process before committing to take part.
Thank you for your time and consideration.

Yours Sincerely
Katja
Hi XXX,

Hope you are keeping safe and well.
Firstly, I want to thank you again for taking part in this review process. Your input into a project like this is invaluable and both myself and my supervisors are really appreciative of your time and expertise.

To begin with, I have laid out the schedule for the 3 round review process which begins today.

Review Round	Start Date	Submission Date
1	15th July	24th July
2	1st August	10th August
3	15th August	28th August

As you will see, you have a 10-day window in which to complete review rounds 1 and 2, and a 14 day window to complete round 3.

Attached below are 2 files, the **Excel Review file 1** and the **Research Questionnaire Draft 1**.

As explained previously, this process requires you to review and rate each question using the Likert scales provided on the Excel Review file. You may also add any further recommendations/changes to the questions, their wording, or the order of questions. Each step of the process is outlined at the top of the Excel Review file.

Once you have completed the review, you can return your Excel review file (attached below) to me via email and I will make the necessary changes based on the collective feedback from all expert coaches. I will then return the updated Questionnaire and a new Excel review file to you on the following Monday morning.

If you have any further questions on the review process, please do not hesitate to contact me.
Finally, thank you once more for your time and expertise.

Kind Regards,
Katja

Excel Review File – Initial Survey

Section 1 - Background and Instructions
1. This is round 1 of the Delphi process.
2. Please read the questionnaire which has been sent to you through email and rate each question on the below Likert scales in **SECTION 2**
e.g. if you fully agree that question 1 of the questionnaire should be included, place a tick in column 10 for Q1 etc.
3. The second box in **SECTION 2** refers to the degree with which you agree/disagree with the formulation of the question. Please rate each question.
4. Should you disagree with the formaulation of a question or have any comments or suggestions, please provide details beside the relevant question number in **SECTION 3** below.

Section 2 – Level of Agreement

To what degree do you agree/disagree with the formulation of the question?												
		0 = Disagree										10 = Agree
Section		0	1	2	3	4	5	6	7	8	9	10
Background Information	Q1											
	Q2											
	Q3											
	Q3 A											
	Q3 B											
	Q4											
	Q5											
	Q6											
	Q7											
	Q8											
	Q9											
	Q10											
Education & Qualifications	Q11 A											
	Q11 B											
	Q12											
Perception	Q13											
	Q14											
	Q15											
	Q16											
	Q17 A											
	Q17 B											
	Q17 C											
	Q17 D											
Methodology	Q18 A											
	Q18 B											
	Q18 C											
	Q19 A											
	Q19 B											
	Q20											
	Q21 A											
	Q21 B											
	Q22 A											
	Q22 B											
	Q22 C											
	Q22 D											
	Q22 E											
	Q23 A											
	Q23 B											
	Q24 A											
	Q24 B											
	Q24 C											
	Q24 D											
	Q24 E											
	Q25											
	Q26 A											
	Q26 B											
	Q27 A											
	Q27 B											
	Q28											
	Q29											

Section 3 - Alternative Suggestions / Comments

Background Information	**Q1**	
	Q2	
	Q3	
	Q3 A	
	Q3 B	
	Q4	
	Q5	
	Q6	
	Q7	
	Q8	
	Q9	
	Q10	
Education & Qualifications	**Q11 A**	
	Q11 B	
	Q12	
Perception	**Q13**	
	Q14	
	Q15	
	Q16	
	Q17 A	
	Q17 B	
	Q17 C	
	Q17 D	
Methodology	**Q18 A**	
	Q18 B	
	Q18 C	
	Q19 A	
	Q19 B	
	Q20	
	Q21 A	
	Q21 B	
	Q22 A	
	Q22 B	
	Q22 C	
	Q22 D	
	Q22 E	
	Q23 A	
	Q23 B	
	Q24 A	
	Q24 B	
	Q24 C	
	Q24 D	
	Q24 E	
	Q25	
	Q26 A	
	Q26 B	
	Q27 A	
	Q27 B	
	Q28	
	Q29	

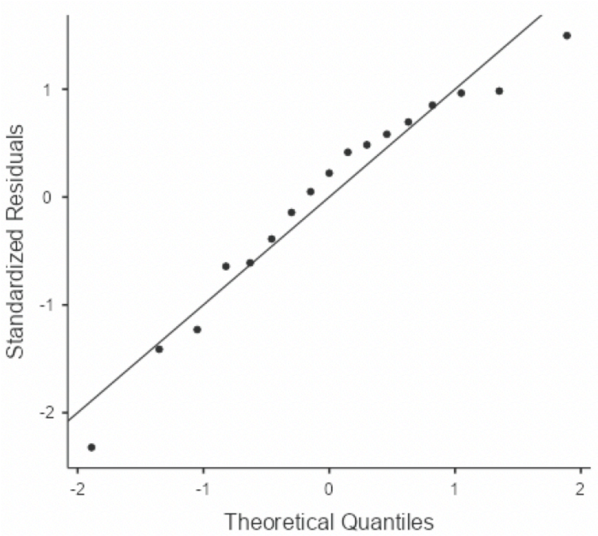
Appendix F

8.6 Assumptions of multiple regression analysis

We carefully assessed the assumptions in our linear regression model to ensure the validity of the findings. Two essential diagnostic tools, the Quantile-Quantile (Q-Q) plot and the residual plot, were employed for this purpose [467].

The Q-Q plots, a graphical representation of the distribution of the standardised residuals against the expected values under the assumption of normality, provided an encouraging result. In these plots, the observed data points closely align with the diagonal line, indicating that the assumption of normality for the residuals of the knee and trunk was met. This suggests that the residuals, when standardised, exhibited a nearly normal distribution. However, when examining the residual plots, a different picture emerged for the trunk. The residual plot, which portrays the residuals against the fitted values, revealed a distinct pattern. This phenomenon is indicative of heteroscedasticity, suggesting that the variance of the residuals is not constant across all levels of the independent variable.

Table 42 Q-Q Plot and Residual Plot of Knee TD2 0%Vdec – 30%Vdec



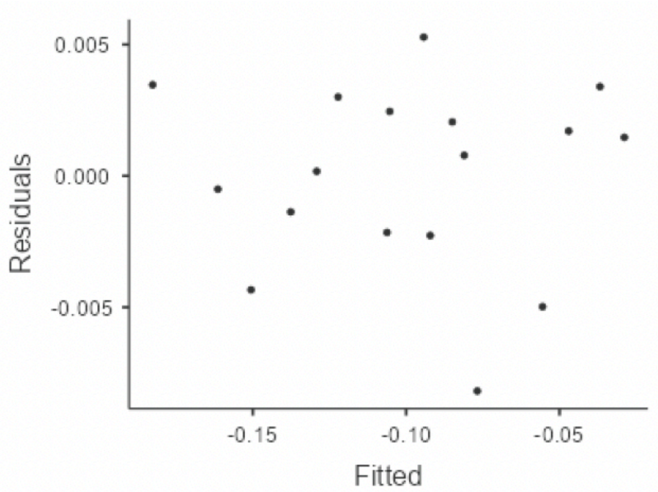
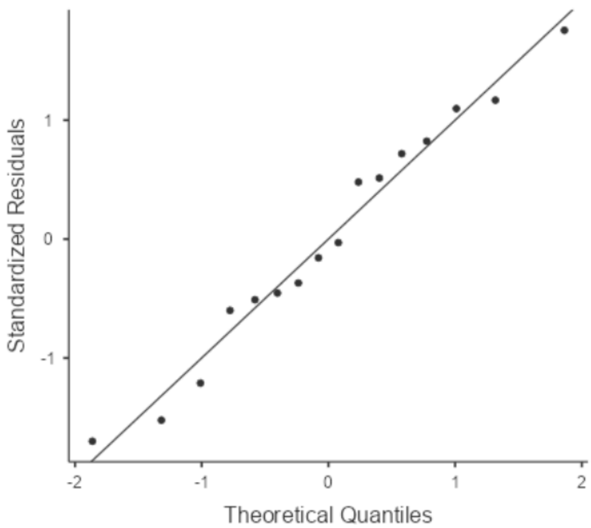


Table 43 Q-Q Plot and Residual Plot of Trunk TO 0%Vdec – 20%Vdec



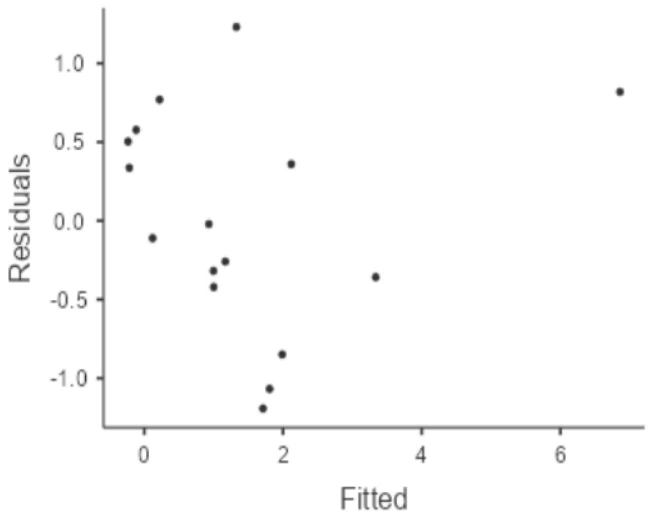
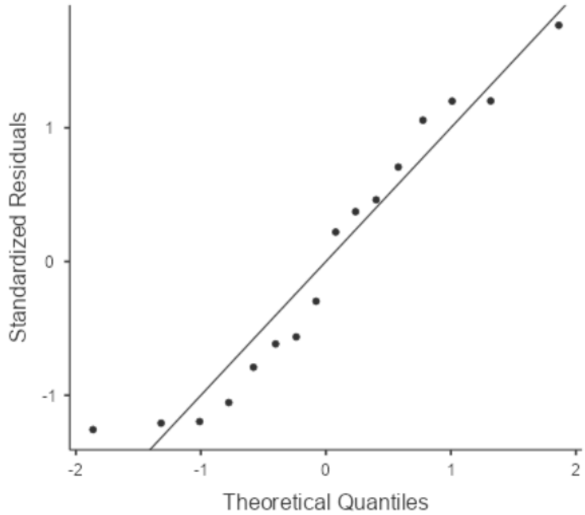


Table 44 Q-Q Plot and Residual Plot of Trunk TO 0%Vdec – 30%Vdec



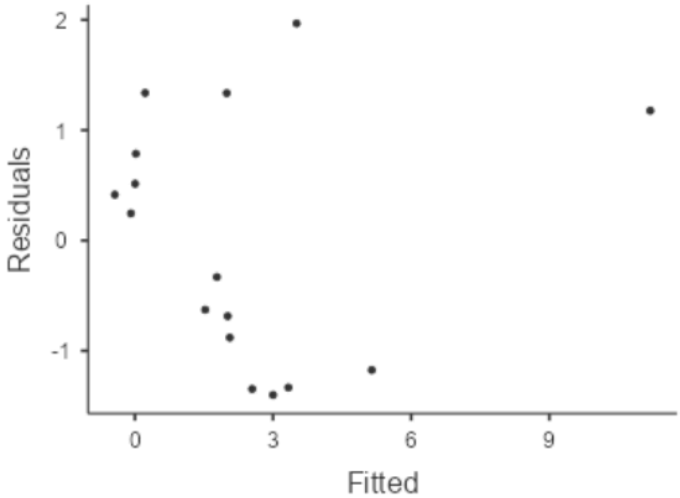
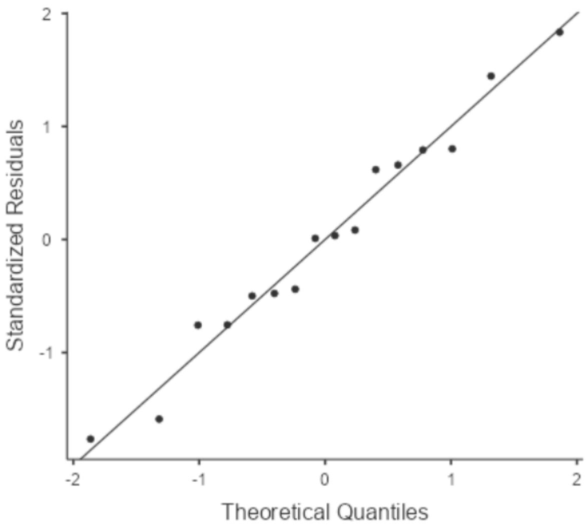


Table 45 Q-Q Plot and Residual Plot of Trunk TD 0%Vdec – 20%Vdec



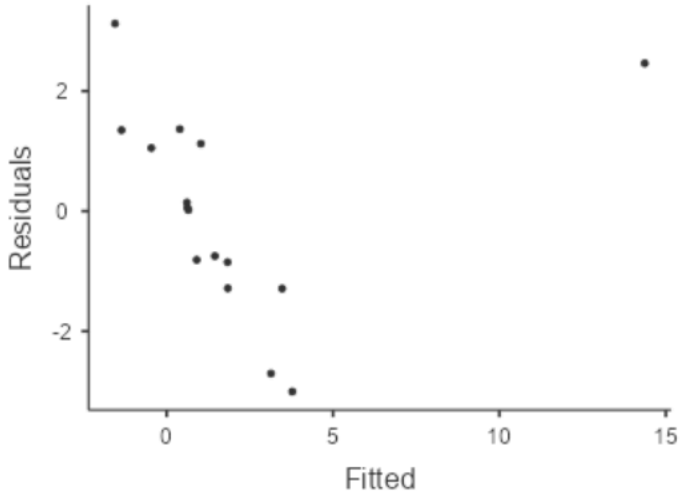
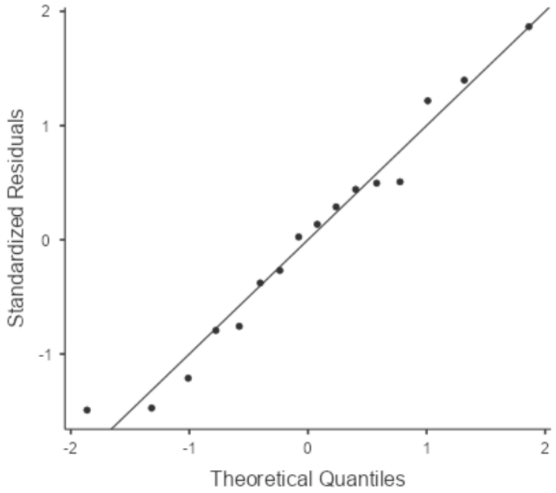
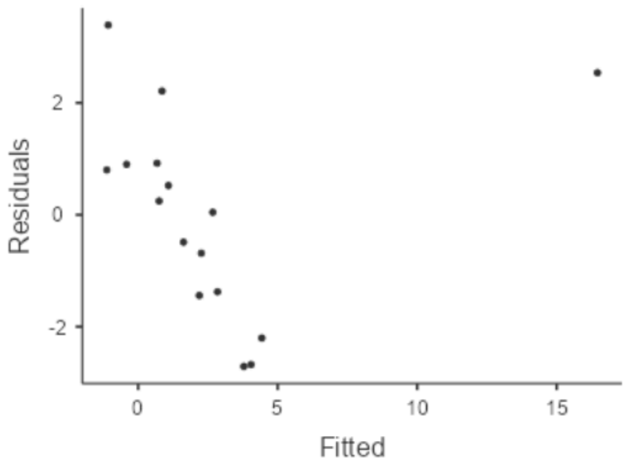


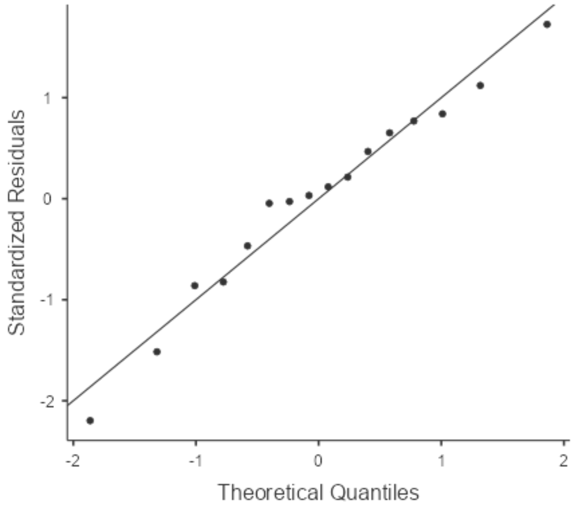
Table 46 Q-Q Plot and Residual Plot of Trunk TD 0%Vdec – 30%Vdec

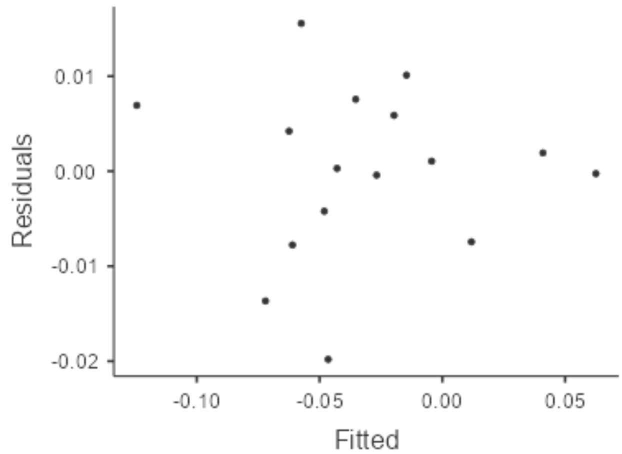




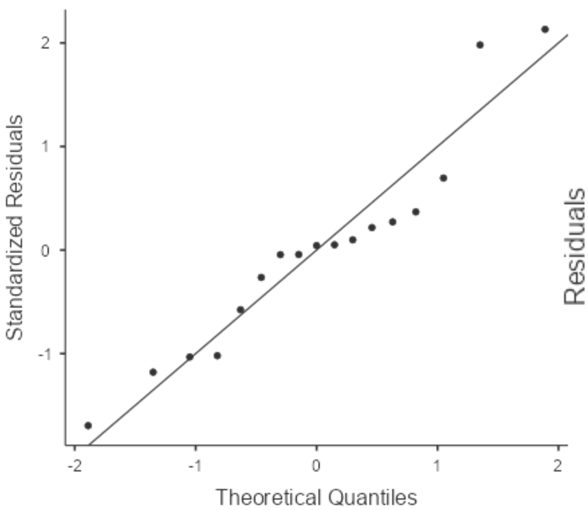
Additional Q-Q and Residual Plots of non-significant linear regressions:
Acceleration phase:

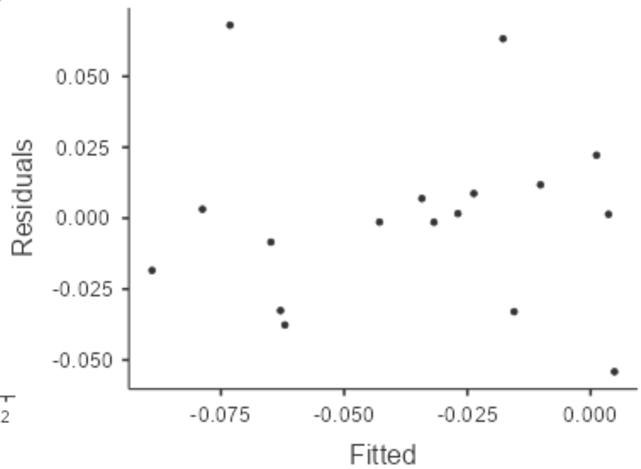
Knee TD 0%Vdec – 10%Vdec



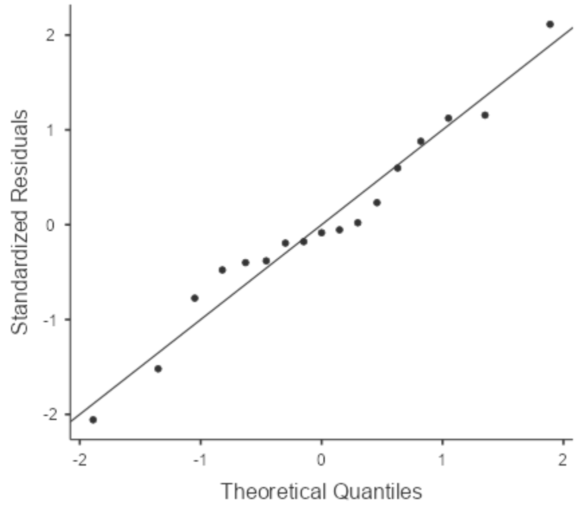


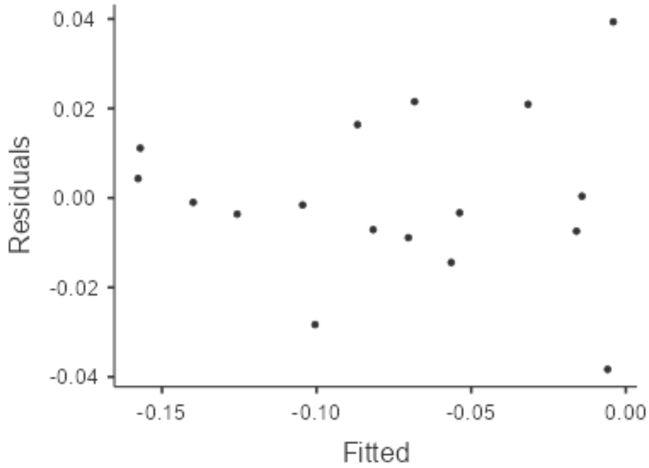
Knee TD2 0%Vdec – 10%Vdec



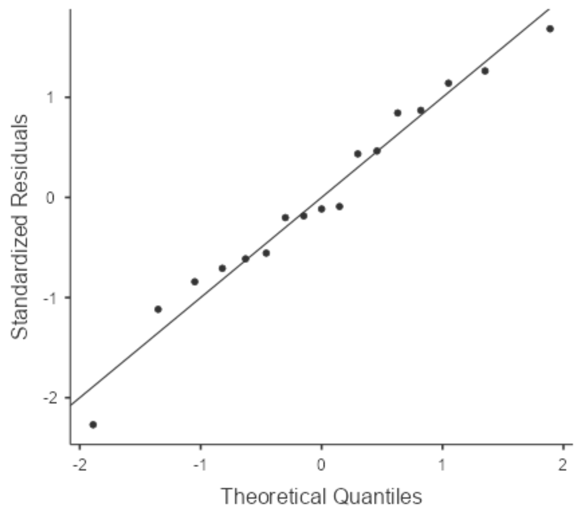


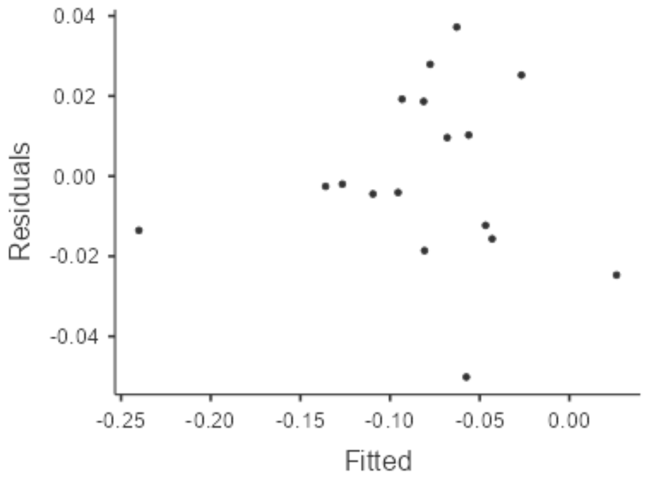
Knee TD 0%Vdec – 20%Vdec



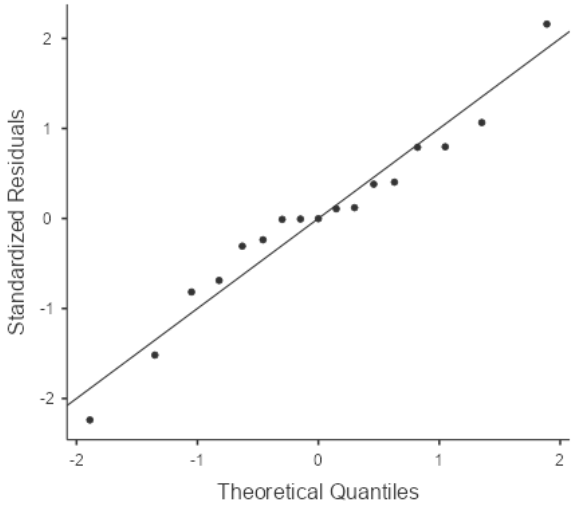


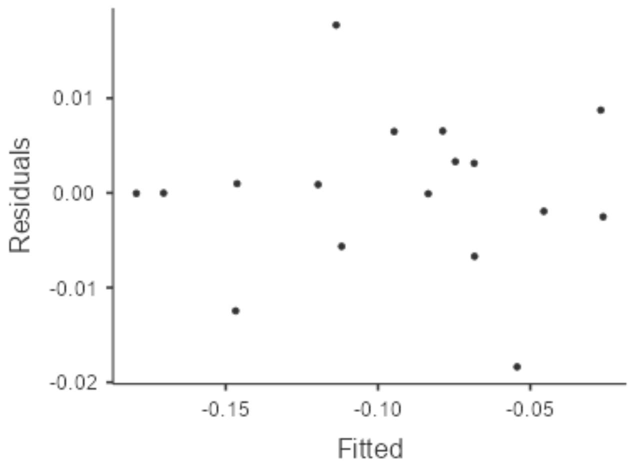
Knee TD2 0%Vdec – 20%Vdec



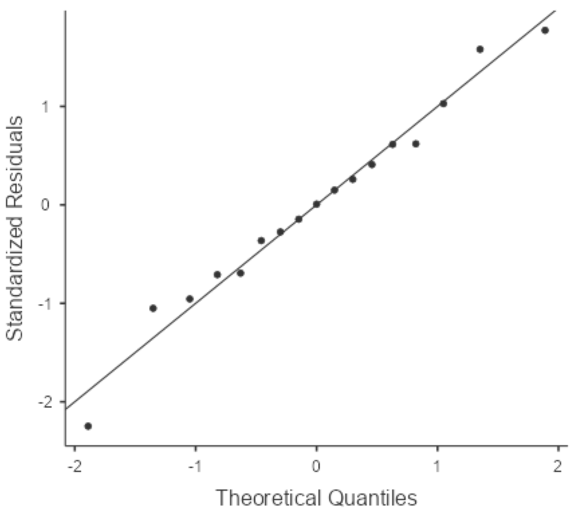


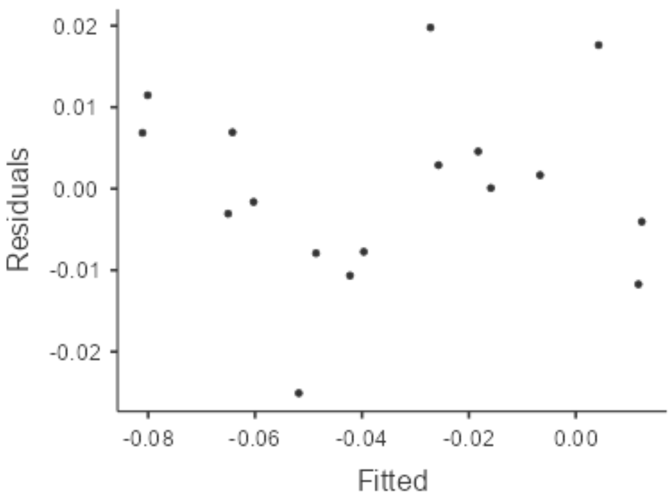
Knee TD 0%Vdec – 30%Vdec



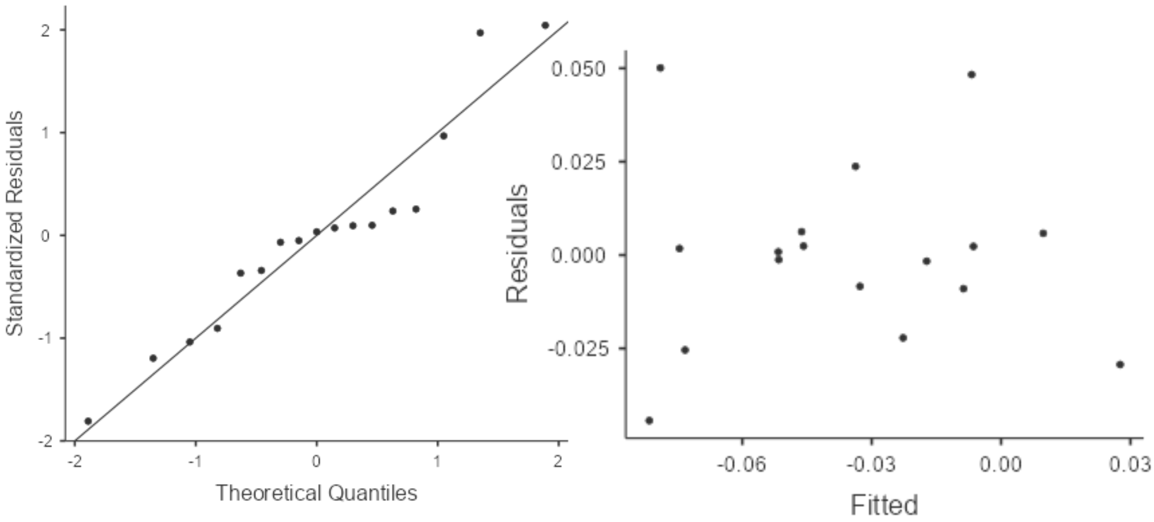


Hip TO2 0%Vdec – 20%Vdec

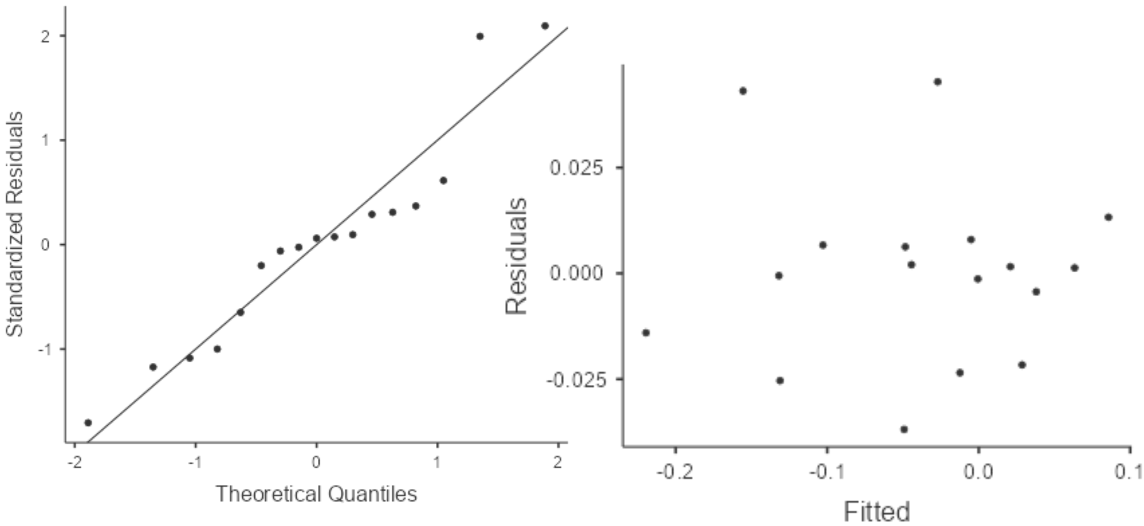




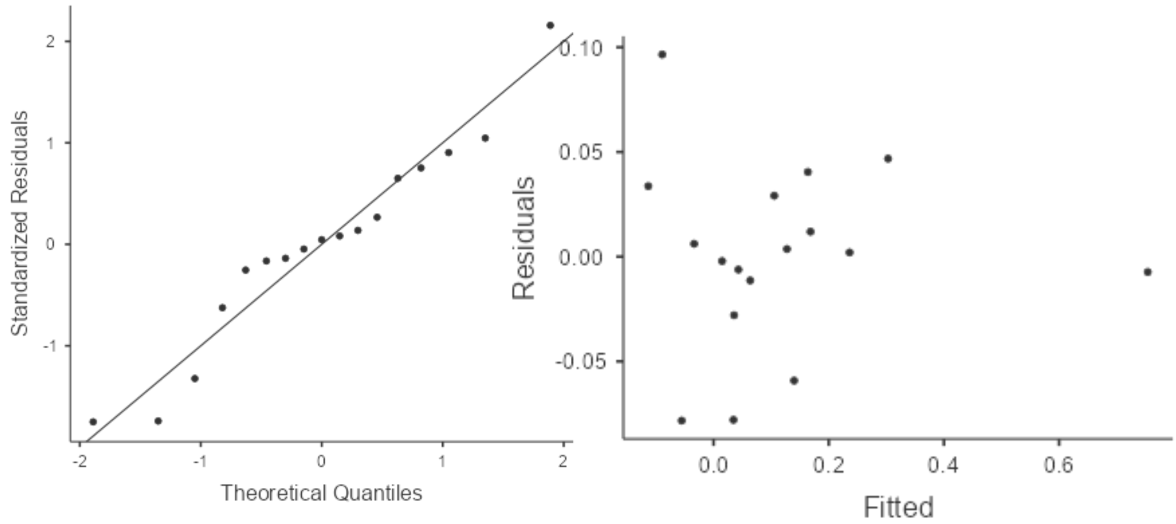
Hip TO2 0%Vdec – 30%Vdec



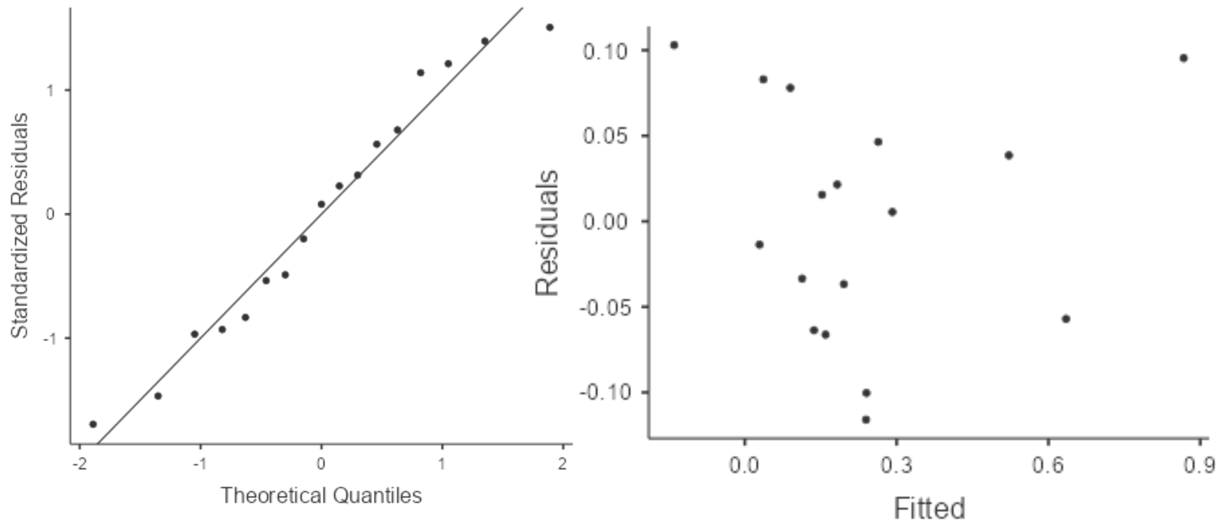
Ankle TD2 0%Vdec – 10%Vdec



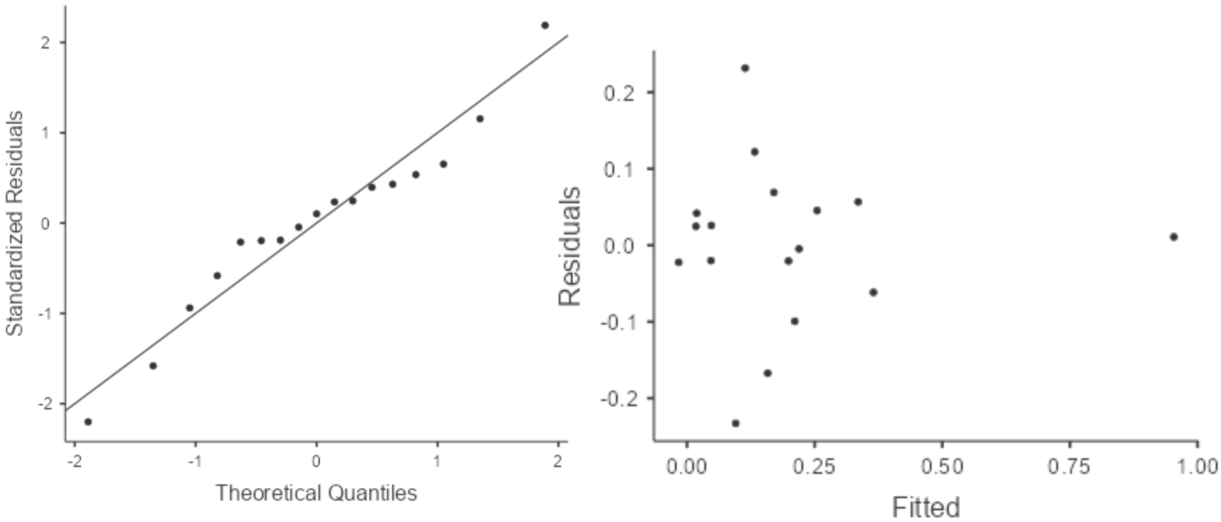
Trunk TD2 0%Vdec – 10%Vdec



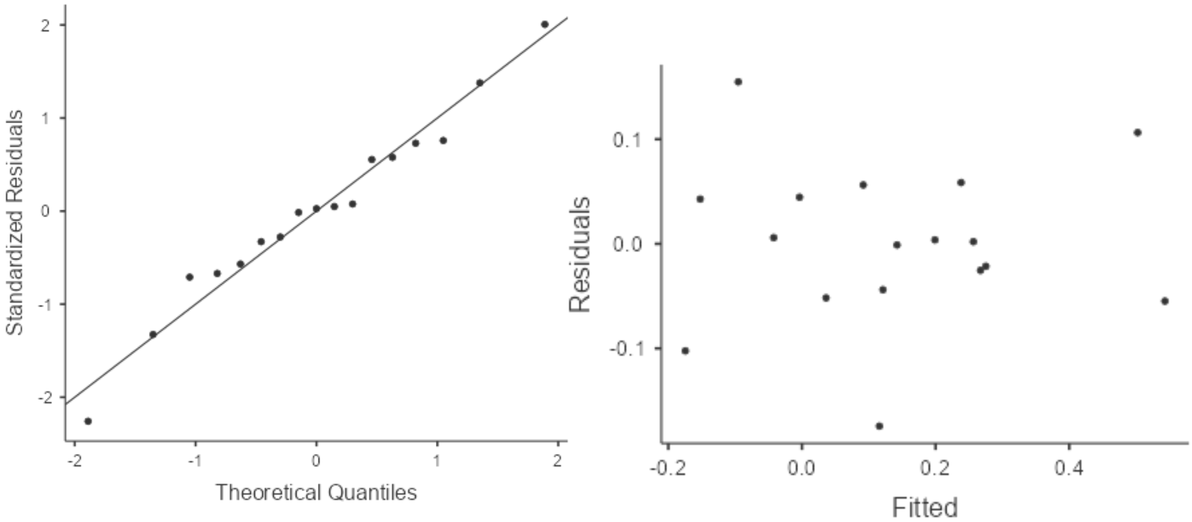
Trunk TD2 0%Vdec – 20%Vdec



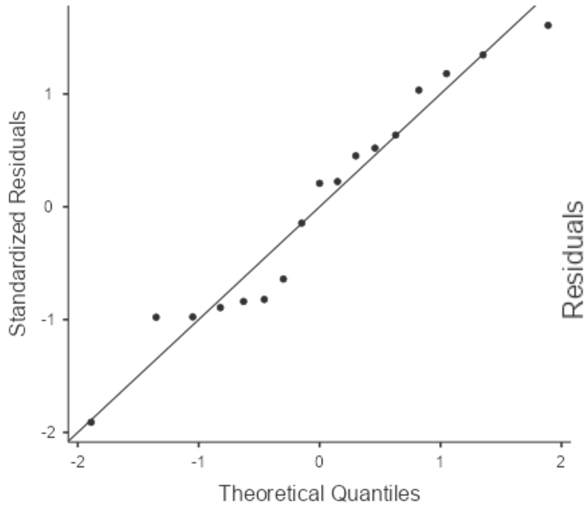
Trunk TD2 0%Vdec – 30%Vdec

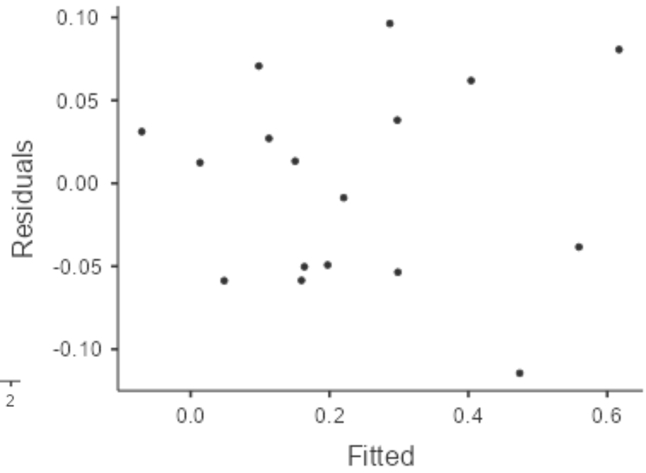


Trunk TO2 0%Vdec – 10%Vdec

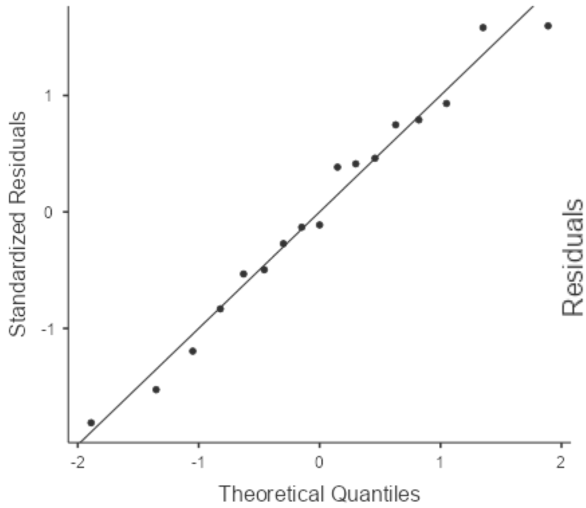


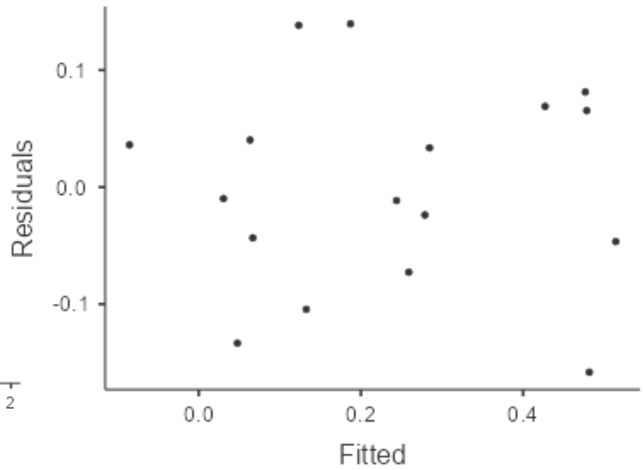
Trunk TO2 0%Vdec – 20%Vdec





Trunk TO2 0%Vdec – 30%Vdec





8.8 Correlations between CMJH, peak power during the CMJ, DJRSI and sprint time

Significant correlations were observed between CMJH and sprint time for all distances and all loads. In contrast, no significant correlations were found between peak power and sprint time. Similarly, no significant correlations were observed between DJRSI and sprint time.

Table 47 Correlation between CMJ measures and sprint performance.

CMJ Height								
	0%Vdec		10%Vdec		20%Vdec		30%Vdec	
	R Value	P Value	R Value	P Value	R Value	P Value	R Value	P Value
10m	-0.32	0.08	-0.58	0.001	-0.42	0.04	-0.34	0.001
15m	-0.46	0.01	-0.64	0.001	-0.50	0.01	-0.39	0.001
20m	-0.55	0.001	-0.65	0.001	-0.54	0.01	-0.43	0.001
25m	-0.61	0.001	-0.67	0.001	-0.58	0.001	-0.44	0.001
30m	-0.65	0.001	-0.71	0.001	-0.60	0.001	-0.45	0.001
40m	-0.70	0.001	-0.73	0.001	-0.63	0.001	-0.47	0.001
	CMJ Peak Power							
10m	-0.40	0.25	-0.48	0.49	-0.39	0.81	-0.57	0.19
15m	-0.49	0.15	-0.51	0.41	-0.42	0.76	-0.61	0.13
20m	-0.50	0.12	-0.51	0.39	-0.42	0.67	-0.60	0.1
25m	-0.53	0.10	-0.51	0.35	-0.43	0.55	-0.57	0.1
30m	-0.54	0.08	-0.52	0.29	-0.44	0.49	-0.57	0.09
40m	-0.53	0.07	-0.50	0.27	-0.45	0.43	-0.56	0.1
All variables (jump height) were p<0.05 significant correlations.								

Table 48 Correlation between DJ RSI and sprint performance.

DJ RSI (Flight Time/Contact Time)								
	0%Vdec		10%Vdec		20%Vdec		30%Vdec	
	R Value	**P Value**	**R value**	**P Value**	**R Value**	**P Value**	**R Value**	**P Value**
10m	-0.09	0.73	0.04	0.86	0.13	0.61	0.07	0.78
15m	-0.07	0.79	0.08	0.77	0.14	0.58	0.05	0.85
20m	-0.06	0.83	0.04	0.87	0.13	0.63	0.00	0.98
25m	-0.05	0.84	-0.01	0.96	0.08	0.77	-0.02	0.94
30m	-0.05	0.85	-0.04	0.88	0.07	0.79	-0.01	0.98
40m	-0.09	0.74	-0.06	0.82	0.05	0.84	-0.02	0.95
* p<0.05 significant correlation.								

Correlations between 1RM and URSP.

Significant correlations were observed between 1RM and unresisted sprint times (r= 0.44-0.47 for BS; r= 0.71-0.72 for HT). One RMs and 40m sprint time demonstrated significant correlations for each loading condition (r= 0.47-0.72).

Table 49 Correlation between 1RM and unresisted sprint performance.

1 RM				
	Back squat		Hip thrust	
	R Value	**P Value**	**R Value**	**P Value**
10m	-0.44*	0.05	-0.71*	0.001
15m	-0.46*	0.04	-0.71*	0.001
20m	-0.45*	0.05	-0.7*	0.001
25m	-0.48*	0.03	-0.71*	0.001
30m	-0.48*	0.03	-0.71*	0.001
40m	-0.47*	0.04	-0.72*	0.001
* p<0.05 significant correlation				

Table 50 Correlation between 1RM and resisted 40m sprint performance.

1 RM				
	Back squat		**Hip thrust**	
	R Value	**P Value**	**R Value**	**P Value**
0%Vdec	-0.47*	0.04	-0.72*	0.00038
10%Vdec	-0.54*	0.01	-0.70*	0.0006
20%Vdec	-0.53*	0.02	-0.70*	0.0005
30%Vdec	-0.61*	0.004	-0.67*	0.0012
* p<0.05 significant correlation				

Significant correlations between URSP and RSP were demonstrated for all loads (r=0.43 to 0.63).

Table 51 Correlation between URSP and RSP.

			5m		10m		40m	
10%Vdec	5m	**R value**	0.676	***	0.499	**	0.477	**
		P value	< .001		0.004		0.006	
	30m	**R value**	0.579	***	0.605	***	0.634	***
		P value	< .001		< .001		< .001	
	40m	**R value**	0.566	***	0.589	***	0.631	***
		P value	< .001		< .001		< .001	
20%Vdec	5m	**R value**	0.648	***	0.476	**	0.427	*
		P value	< .001		0.006		0.015	
	30m	**R value**	0.606	***	0.611	***	0.622	***
		P value	< .001		< .001		< .001	
	40m	**R value**	0.553	**	0.612	***	0.639	***
		P value	0.001		< .001		< .001	
30%Vdec	5m	**R value**	0.67	***	0.498	**	0.468	**
		P value	< .001		0.004		0.007	
	30m	**R value**	0.612	***	0.588	***	0.599	***
		P value	< .001		< .001		< .001	
	40m	**R value**	0.619	***	0.576	***	0.593	***
		P value	< .001		< .001		< .001	

* p < .05, ** p < .01, *** p < .001

Acceleration kinematics at the hip (10%Vdec) demonstrated a significant correlation with RSP at 10m (r=-0.37). Also, knee kinematics (10%Vdec) demonstrated a significant correlation with RSP at 5, 10m (r=-0.55, r=-0.62) and for 20%Vdec with RSP at 10m (r=-0.33) and at the ankle with 5m (r=-0.42). Maximum velocity kinematics (0%Vdec) at trunk demonstrated a significant correlation with SP at 40m (r=0.462). Kinematics at the hip (20%Vdec) (r=-0.414) and at the ankle (-0.446) demonstrated a significant correlation with RSP at 40m.

Table 52 Correlation between URSP or RSP and kinematics during step 1 & 2 of the sprint.

		0%Vdec		10%Vdec		20%Vdec		30%Vdec	
		5m	**10m**	**5m**	**10m**	**5m**	**10m**	**5m**	**10m**
Hip TD Step 1	**R value**	-0.129	-0.148	-0.095	-0.072	-0.12	-0.126	-0.08	-0.103
	P value	0.496	0.436	0.619	0.704	0.526	0.506	0.676	0.587
Hip TD Step 2	**R value**	-0.173	-0.34	0.022	-0.016	-0.118	-0.127	0.037	-0.002
	P value	0.361	0.066	0.907	0.933	0.535	0.503	0.844	0.992
Hip TO Step 1	**R value**	-0.021	-0.149	-0.252	-0.379 *	-0.068	-0.196	-0.241	-0.323
	P value	0.911	0.431	0.18	0.039	0.72	0.299	0.199	0.081
Hip TO Step 2	**R value**	0.098	0.076	0.016	-0.013	-0.031	-0.129	-0.075	-0.129
	P value	0.607	0.69	0.933	0.946	0.869	0.498	0.695	0.498
Knee TD Step 1	**R value**	0.321	0.032	0.345	0.33	0.074	0.129	0.357	0.348
	P value	0.084	0.868	0.062	0.075	0.699	0.498	0.053	0.06
Knee TD Step 2	**R value**	0.16	-0.141	0.169	0.075	-0.192	-0.214	0.148	0.164
	P value	0.399	0.457	0.371	0.692	0.311	0.255	0.435	0.388
Knee TO Step 1	**R value**	0.097	-0.106	-0.558 **	-0.624 ***	-0.188	-0.336	-0.225	-0.304
	P value	0.608	0.578	0.001	< .001	0.319	0.07	0.233	0.102
Knee TO Step 2	**R value**	-0.005	-0.134	-0.054	-0.159	-0.277	-0.41 *	-0.175	-0.218
	P value	0.979	0.48	0.777	0.401	0.138	0.024	0.356	0.248
Ankle TD Step 1	**R value**	0.051	-0.233	0.22	0.352	-0.146	-0.056	-0.32	-0.257
	P value	0.789	0.215	0.242	0.056	0.441	0.769	0.085	0.17
Ankle TD Step 2	**R value**	0.016	-0.306	0.148	0.218	0.235	0.315	-0.112	-0.207
	P value	0.931	0.1	0.434	0.248	0.212	0.09	0.555	0.272
Ankle TO Step 1	**R value**	0.013	-0.258	-0.108	-0.115	-0.181	-0.224	-0.245	-0.245
	P value	0.945	0.168	0.568	0.546	0.338	0.234	0.192	0.191
Ankle TO Step 2	**R value**	0.034	-0.102	-0.212	-0.188	-0.419 *	-0.291	-0.111	-0.107
	P value	0.857	0.592	0.261	0.32	0.021	0.119	0.561	0.573
Trunk TD Step 1	**R value**	0.038	0.162	-0.152	-0.15	0.122	0.168	-0.035	0.01
	P value	0.841	0.393	0.424	0.43	0.522	0.375	0.854	0.957
Trunk TD Step 2	**R value**	-0.048	-0.02	-0.12	-0.072	0.295	0.26	-0.128	-0.1
	P value	0.801	0.917	0.528	0.707	0.113	0.165	0.501	0.599
Trunk TO Step 1	**R value**	0.028	0.175	-0.101	-0.017	0.088	0.06	-0.062	-0.031
	P value	0.884	0.356	0.597	0.928	0.645	0.755	0.744	0.87
	R value	-0.236	-0.176	-0.159	-0.214	0.016	0.019	-0.059	-0.042

Trunk TO Step 2	**P value**	0.209	0.353	0.402	0.256	0.934	0.921	0.758	0.825

* p < .05, ** p < .01, *** p < .001

Table 53 Correlation between URSP or RSP and kinematics during maxV phase of the sprint.

		0%Vdec	10%Vdec	20%Vdec	30%Vdec
		40m			
Hip TD	**R value**	-0.421	-0.429	-0.414 *	-0.218
	P value	0.051	0.046	0.05	0.318
Hip TO	**R value**	-0.387	-0.178	-0.197	0.104
	P value	0.075	0.427	0.369	0.638
Knee TD	**R value**	0.415	0.049	0.14	0.216
	P value	0.055	0.829	0.524	0.322
Knee TO	**R value**	-0.013	-0.143	0.051	-0.015
	P value	0.954	0.525	0.816	0.947
Ankle TD	**R value**	0.086	0.28	-0.073	-0.162
	P value	0.703	0.208	0.74	0.461
Ankle TO	**R value**	0.26	0.075	-0.446 *	-0.134
	P value	0.242	0.74	0.033	0.542
Trunk TD	**R value**	0.303	0.142	0.17	-0.023
	P value	0.17	0.53	0.438	0.916
Trunk TO	**R value**	0.462 *	0.051	0.349	-0.051
	P value	0.03	0.826	0.103	0.817

* p < .05, ** p < .01, *** p < .001

Correlations between 1RM and ROM.

One RM and ROM showed no significant correlations for the first step of the sprint (Table X). However, for the second step significant correlations were found for BS and hip ROM (r=0.41, p=0.36) and for HT and knee ROM (r=-0.39, p=0.048) during unloaded sprinting and (r=0.41, p=0.35) 10%Vdec. During maxV significant correlations were found for HT and hip ROM (r=0.56, p=0.009) during 30%Vdec and for knee ROM (r=-0.56, p=0.009) during unloaded sprinting.

Table 54 Correlation between 1RM and ROM for the acceleration phase step one, two and maxV phase..

			Step One		Step Two		MaxV	
			Back Squat	Hip Thrust	Back Squat	Hip Thrust	Back Squat	Hip Thrust
Hip	0%	R value	-0.268	-0.167	-0.413 *	-0.325	0.022	0.071
		P value	0.186	0.414	0.036	0.105	0.924	0.761
	10%	R value	-0.223	0.055	-0.024	0.008	-0.165	0.047
		P value	0.273	0.791	0.906	0.971	0.476	0.84
	20%	R value	-0.18	-0.089	-0.27	-0.079	0.13	0.145
		P value	0.38	0.667	0.182	0.7	0.563	0.519
	30%	R value	-0.262	-0.201	-0.203	-0.21	0.324	0.557 **
		P value	0.196	0.324	0.319	0.304	0.153	0.009
Knee	0%	R value	-0.18	-0.306	-0.141	-0.391 *	0.014	-0.557 **
		P value	0.38	0.128	0.491	0.048	0.952	0.009
	10%	R value	-0.197	-0.273	-0.133	-0.414 *	-0.137	-0.354
		P value	0.334	0.177	0.516	0.035	0.555	0.115
	20%	R value	-0.032	-0.062	0.05	-0.257	0.39	0.169
		P value	0.875	0.765	0.809	0.205	0.073	0.453
	30%	R value	0.009	-0.091	0.103	-0.008	0.191	-0.09
		P value	0.964	0.658	0.616	0.968	0.408	0.698
Ankle	0%	R value	-0.092	-0.041	0.261	-0.049	0.26	-0.188
		P value	0.653	0.842	0.197	0.812	0.255	0.414
	10%	R value	-0.168	-0.032	0.101	-0.189	-0.066	-0.082
		P value	0.413	0.877	0.624	0.356	0.775	0.725
	20%	R value	-0.092	0.231	0.318	-0.162	0.1	0.016
		P value	0.654	0.257	0.113	0.428	0.659	0.945
	30%	R value	0.046	0.053	-0.228	-0.019	-0.103	-0.014
		P value	0.823	0.799	0.263	0.926	0.656	0.953
Trunk	0%	R value	0.254	0.156	0.31	0.019	0.057	-0.077
		P value	0.21	0.445	0.123	0.926	0.806	0.741
	10%	R value	0.216	-0.229	0.068	-0.279	-0.062	0.051
		P value	0.289	0.261	0.743	0.167	0.788	0.827
	20%	R value	0.04	-0.035	0.041	-0.235	-0.081	-0.195
		P value	0.847	0.867	0.844	0.247	0.727	0.396
	30%	R value	0.129	0.081	0.205	-0.049	0.113	-0.347
		P value	0.529	0.693	0.315	0.814	0.626	0.124

* p < .05, ** p < .01, *** p < .001

Contact time during maximum velocity phase at 30%Vdec displayed significant correlations with 1RM (HT: r= -0.504, p=0.014).

Table 55 Correlation between 1RM and CT.

			Back Squat	Hip Thrust	
Step 1	10%Vdec	R value	0.205	0.149	
		P value	0.305	0.458	
	20%Vdec	R value	0.006	-0.07	
		P value	0.976	0.729	
	30%Vdec	R value	0.042	-0.308	
		P value	0.834	0.118	
Step 2	0%Vdec	R value	-0.174	0.043	
		P value	0.385	0.832	
	10%Vdec	R value	-0.108	-0.068	
		P value	0.593	0.737	
	20%Vdec	R value	-0.141	-0.091	
		P value	0.482	0.652	
	30%Vdec	R value	-0.175	-0.283	
		P value	0.382	0.152	
maxV	0%Vdec	R value	-0.038	-0.065	
		P value	0.863	0.768	
	10%Vdec	R value	-0.076	-0.167	
		P value	0.731	0.445	
	20%Vdec	R value	0.113	-0.131	
		P value	0.607	0.552	
	30%Vdec	R value	-0.299	-0.504	*
		P value	0.166	0.014	

* p < .05, ** p < .01, *** p < .001

Statistical analysis revealed significant correlations at step one between CMJ peak power and CT at 10%Vdec, CMJ JH and CT at 20%Vdec and for maxV between DJ RSI, CMJH and CT at 0%Vdec.

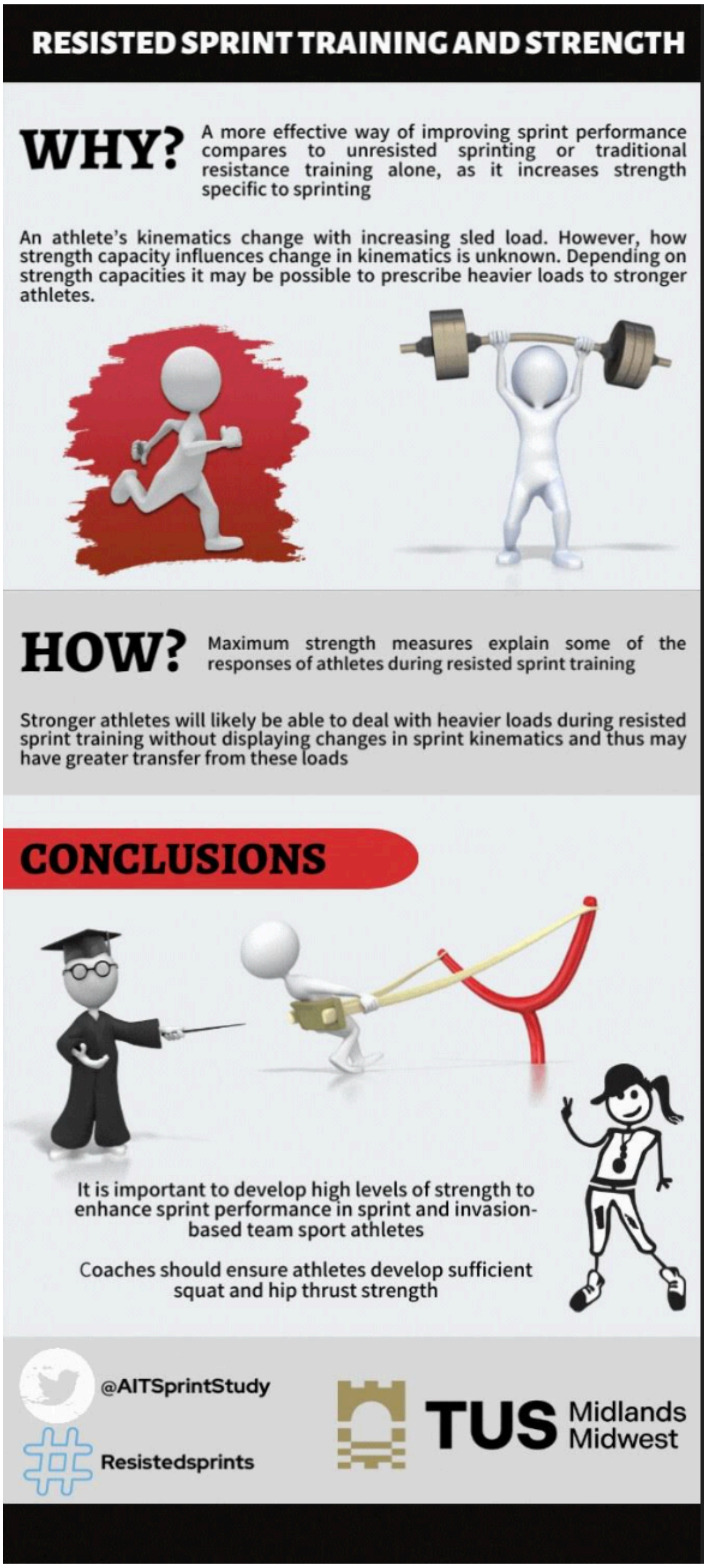
Table 56 Correlations between CT and jump measures (DJ RSI, CMJ jump height and peak power) for acceleration and maximum velocity phase.

Step one		**RSI (Flight Time/Contact Time)**	**CMJ Peak Power / BW**	**CMJH**
0%Vdec	**R value**	-0.067	-0.172	-0.034
	P value	0.799	0.457	0.865
10%Vdec	**R value**	-0.26	-0.508 *	-0.22
	P value	0.313	0.019	0.261
20%Vdec	**Rvalue**	-0.338	-0.417	-0.403 *
	P value	0.185	0.06	0.034
30%Vdec	**R value**	-0.407	-0.334	-0.309
	P value	0.105	0.138	0.11
Step two		**RSI (Flight Time/Contact Time)**	**CMJ Peak Power / BW**	**CMJH**
0%Vdec	**R value**	-0.391	-0.159	-0.138
	P value	0.121	0.49	0.485
10%Vdec	**R value**	-0.454	-0.135	-0.136
	P value	0.067	0.558	0.489
20%Vdec	**R value**	-0.481	-0.171	-0.105
	P value	0.051	0.46	0.594
30%Vdec	**R value**	-0.358	-0.307	-0.372
	P value	0.158	0.175	0.051
maxV		**RSI (Flight Time/Contact Time)**	**CMJ Peak Power / BW**	**CMJH**
0%Vdec	**R value**	-0.545 *	-0.389	-0.437 *
	P value	0.029	0.1	0.029
10%Vdec	**R value**	-0.409	-0.419	-0.383
	P value	0.115	0.074	0.059
20%Vdec	**R value**	-0.322	-0.253	-0.146
	P value	0.225	0.295	0.486
30%Vdec	**R value**	-0.305	-0.275	-0.217
	P value	0.25	0.254	0.298
* p < .05, ** p < .01, *** p < .001				

Appendix G

8.9 Infographic of study 2

Designed and created by Katja Magdalena Osterwald



Appendix H

8.10 Poster Presentations

Presented at ISB Conference 2021

Presented at the AIT research symposium 2021

THE TIMES THE SUNDAY TIMES GOOD UNIVERSITY GUIDE 2020 INSTITUTE OF TECHNOLOGY OF THE YEAR

AIT Research

Kinematic Characteristics of Resisted Sled Sprints Under Different Loading Conditions

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INTRODUCTION

- Resistance training exercises have been associated with improved sprint performance
- The principle of specificity states that training should be relevant and appropriate to the sport for which the athlete is training and may explain the limited transfer from traditional resistance training to improved sprint performance
- Considering the principle of specificity, the addition of an external load to the action of sprinting may offer a more specific form of resistance training for athletes
- AIM: To elucidate the specificity of resisted sled sprints (RSS) by examining the kinematic characteristics of RSS under different loading conditions and in different sporting populations

METHODS

Familiarization Session
- Sprinters n = 10
- Team Sport Athletes n = 23

Sprint Session
- 12 sprints at different loads (unloaded, 10, 20, 30% velocity decrement)
- Velocity measured with an electronic timing system (40m distance)
- Kinematics measured using High-Speed Cameras

Strength & Power Session
- One repetition maximum in hip thruster and back squat
- Countermovement and drop jumps

RESULTS

- Different loading conditions display different kinematics. Load significantly affected most kinematics within the two groups. There was no between group differences.
- Knee, hip, ankle, thigh, shank and foot angle reduced linearly with increasing loading conditions, trunk lean and contact times for field and sprint athletes increased linearly with increasing loading conditions (Figure 1).
- There was a significant change in ROM of the knee during ground contact. It seems possible that RSS may have increased the work contribution done at the knee joint.

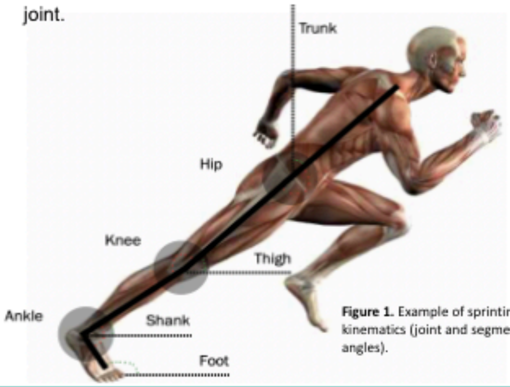

Figure 1. Example of sprinting kinematics (joint and segment angles).

CONCLUSION

- Not all loading conditions display similar kinematics and that different loads display different levels of specificity depending on the phase of sprinting assessed.
- Changes that were induced may have been positive changes such as increased trunk lean, enabling athletes to place themselves in an optimal position to maximize propulsive forces.
- Athletes were not getting into upright running. Thus, instead extending the distance over which it is possible to train acceleration.

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SPORT HEALTH EXERCISE

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@AITSprintStudy

Refenrences

Appendix I

8.11 Book of abstracts

ECSS 2022 Sevilla

Book of abstracts ECSS 2023 Paris

RELIABILITY OF AN ISOTONIC SPRINT DEVICE IN RECREATIONALLY TRAINED PARTICIPANTS

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INTRODUCTION: An increasing number of coaches have employed isotonic sprint devices to provide an external resistance while sprinting. The device has been demonstrated to help improve sprint performance [1], however from a scientific perspective it is currently unclear if such a device provides external load in a reliable manner. This is important as the magnitude of load dictates adaptation, therefore it is crucial to understand if this load prescription is reliable within and between sessions, in order to be used with confidence [2]. The main purpose of this study was to determine the reliability of an isotonic sprint device in recreationally trained individuals. More specifically, the question was: does it result in changes of split times at the same load over multiple runs, and between sessions?
METHODS: Thirteen recreationally active participants (age, 21 ± 1.61 years; height (cm), 180.08 ± 2.88cm; weight (kg), 84.27 ± 10.87 kg) were recruited and required to complete 2 testing days, 5-7 days apart. Three maximal 20m sprints, with an isotonic resistance device (Exer-Genie, Thousand Oaks, CA, USA), at three resistance levels (2oz, 5oz & 8oz) on a sprint track were undertaken, in a randomized order on two separate testing days (18 sprints in total). The device was attached to the participant by a waist harness which connected on to the rope (36m) via a safety clip. The device itself was attached to the railing of the sprint track via an anchor strap (91.44cm) and safety clip. Sprint time was assessed using photocells, which were set up at 5-meter intervals. Intrasession (comparison of the 3 sprints of the second session) and intersession (comparison of the average of the 3 sprints across days) reliability of sprint time for 5m, 10m, 15m & 20m at all resistance levels, were assessed by intrasession correlation coefficient (ICC) and coefficients of variation (%CV) and associated 90% confidence intervals (CI). The scale of magnitude for effect statistics used were rated as trivial (<0.1), small (0.1-0.29), moderate (0.3-0.49), large (0.5-0.69), very large (0.7-0.89) or nearly perfect (0.9-0.99) [3].
RESULTS: The device showed moderate intersession reliability for 2oz & 5oz and large reliability for 8oz across all distances (ICC 0.18 – 0.77), (%CV 5.6 – 12.9). Intrasession reliability was moderate to nearly perfect across the distances for the resistance level of 2oz (ICC 0.35 - 0.91), (%CV 3.1 - 14.6%). At 5oz reliability ranged from large to nearly perfect across the distances, (ICC 0.58 - 0.95), (%CV 2.9 - 10.7%). At 8oz reliability ranged from very large to nearly perfect across the distances, (ICC 0.80 - 0.97), (%CV 3.9 - 8.4%).
CONCLUSION: To conclude, isotonic resistance appears to be a reliable method to provide a desired training stimulus to athletes engaging in sprinting activities and therefore could be considered as part of a training programme for those wishing to enhance their performance.
1. Bremec (2018), 2. Koo et al. (2016), 3. Hopkins (2002)

HOW DOES MAXIMAL STRENGTH SPRINT AND JUMP PERFORMANCE EFFECT RESISTED SPRINT KINEMATIC VARIABLES?

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INTRODUCTION:
Sprint performance (SP) is an essential skill to target within many sports [1]. Resisted sprint training is believed to increase strength specific to sprinting [2]. It is well-known that an athlete's acute kinematics change with increasing resistance [3]. However, to our knowledge, there remains a lack of clarity on how maximal strength and jump performance influences resisted sprint (RS) kinematics. Therefore, this study aimed to examine the correlation between back squat (BS) and hip thrust (HT) maximum strength (1RM) and jump measures with SP and change in kinematics (Ch).
METHODS:
20 sprint and 23 team sport athletes were tested over three days. After one familiarization session 1RMs, vertical jumps (CMJ and DJ) and resisted sprints with a resistance of 0, 10, 20, 30%Vdec were conducted on day 2 and 3. Timing gates were set up at 5-meter intervals to measure sprint time over 40m and average velocity. Kinematics (knee, hip, trunk, ankle angle) were measured at touch-down and toe-off using high-speed cameras. Then the percentage change of the angles between loads was calculated. Jumps were completed on force platforms. Jump height (JH) was calculated using the impulse-momentum method and the RSI was taken as the maximal height the athlete reached during the DJ divided by the ground contact time [4]. Pearson's correlation coefficient (r) was used to investigate the relationship between levels of strength, jump, SP and kinematic variables at each resistance.
RESULTS:
Significant negative correlations were found between 1RMs and Ch (hip, knee and trunk angle) for the different loading conditions. Furthermore, correlations were displayed between acceleration SP and Ch (for trunk, knee, ankle angle) and between resisted (RSP) and unresisted SP (USP). Significant correlations were observed between 1RM and 40m RSP (BS: r= -0.47 to -0.61; HT: r= -0.67 to -0.72). Moreover, 1RM and USP presented significant correlations (BS: r= 0.44-0.47; HT: r= 0.71-0.72). Lastly, significant correlations were observed between CT at 30% Vdec and 1RM (HT) during maxV phase. (r= -0.504, p=0.014).
CONCLUSION:
Faster RS times were associated with Ch, indicating that faster athletes see less change at the knee under load. Stronger athletes displayed less change in knee and hip kinematics, more similar to URS kinematics. The higher HT strength seemed to allow to create force through hip and knee. Faster and stronger athletes were also faster under load. Maybe the knee and hip were driving velocity under loaded conditions. Moreover, the stronger athletes (HT) demonstrated shorter CTs under load during the maxV phase, suggesting that the hip may be a greater contributor to the force produced. It could be concluded that maximum strength and SP measures explain some of the responses of athletes during RS, suggesting that stronger and faster athletes might be able to handle a higher overload without displaying changes in kinematics.