BACKWARD RUNNING TRAINING: APPLICATIONS FOR IMPROVING ATHLETICISM IN MALE HIGH-SCHOOL ATHLETES

Aaron Matthew Uthoff
MSc (Dist)

A thesis submitted to
Auckland University of Technology
in fulfilment of the degree of
Doctor of Philosophy (PhD)

2019

School of Sport and Recreation

Supervisors:
Professor John Cronin
Dr. Jon Oliver
Dr. Paul Winwood
Dr. Craig Harrison

TABLE OF CONTENTS

ABSTRACT

Novel training methods such as backward running (BR) may promote unique adaptations to athletic performance compared to more traditional training methods, like forward running (FR). While advocates have recommended BR for athletes over 18 years of age, no empirical information existed as to the utility of unresisted or resisted BR in athletes around their adolescent growth spurt. This thesis sought to understand whether BR training modalities promote positive adaptations in athletic performance among male youth athletes. An introduction and review provided an overview of BR and the natural development and trainability of speed in males around the time of adolescence, establishing the thesis framework and need for further investigation into the use of BR modalities.

To understand how unresisted and resisted BR could be progressed in training, two repeated cross-sectional studies investigated the reliability of unresisted and resisted BR. In Chapter 3, it was found that after two habituation sessions, 34 high-school male athletes demonstrated good coefficient of variation for BR and FR (CV = 0.99% to 4.2%) and good to excellent intraclass correlational coefficients for BR and FR (ICC = 0.89 to 0.99). In Chapter 4, the load-velocity relationships of 21 high-school male athletes demonstrated that increases of ~13% ($r^2 = 0.99$) and ∼15% ($r^2 = 1.00$) body mass respectively, resulted in ∼10% decreases in running velocity during resisted BR and FR compared to unresisted maximal effort velocities in the respective running direction (CV ≤ 7.2%; ICC ≥ 0.83 – 0.91).

Chapters 5 and 6 used matched-paired randomised control designs to determine the effectiveness of unresisted and resisted BR training on sprinting, jumping, and leg compliance measures in high-school male athletes. Chapter 5 compared the effects of eight weeks of progressively overloaded BR training (BRT) versus volume matched FR training (FRT) in 67 boys. The main findings were that a) all measures improved in both training groups ($p \leq 0.01$; effect size [ES] = 0.25 to 1.56), b) compared to the control group (CON), BRT improved all performance tests ($p \leq 0.001$; ES = 0.63 to 1.59) and FRT enhanced sprinting and stiffness performance ($p \leq 0.01$; ES = 0.45 to 1.29), and c) BRT demonstrated greater training effects for sprint and countermovement jump performance ($p \leq 0.05$; ES = 0.54 to 0.76) compared with FRT. Chapter 6 compared the effects of eight weeks of progressively overloaded backward resisted sprint (BRS) training versus forward resisted sprint (FRS) training using equal loading strategies from 20% to 55% body mass in 115 boys. The main findings were that a) all performance metrics improved following BRS ($p \leq 0.01$; ES = 0.22 to 0.79), b) all except 10 m performance enhanced following FRS ($p \leq 0.05$; ES = 0.16 to 0.90), c) compared to the control group (CON), BRS resulted in improved performances for all tests except 10 m sprint time ($p \leq 0.05$; ES = 0.15 to 0.94) and FRS improved 10-20 m sprint times, jump height, and stiffness ($p \leq 0.05$; ES = 0.11 to 0.69), and e) no differences ($p \leq 0.05$) were found between training groups.

The culmination of the experimental studies is provided in Chapter 7 as a practitioner-orientated guide for why strength and conditioning coaches may wish to implement BR into their athletes' training and how to integrate BR into their overall strength and conditioning programme. Chapter eight is a summary of the findings, their applications, and future research directions in BR as a tool to develop athleticism.

LIST OF FIGURES

LIST OF TABLES

LIST OF COMMON ABBREVIATIONS

%: Percentage

%BM: Percentage of body mass

$\%V_{dec}$: Percentage of velocity decrease

BM: Body mass

BR: Backward running

BRS: Backward resisted sprinting

BRT: Backward running training

CI: Confidence interval

cm: Centimetres

CMJ: Countermovement jump

CON: Control

CV: Coefficient of variation

$d \cdot wk^{-1}$: Days per week

e.g.: Example

ES: Effect size

FR: Forward running

FRS: Forward resisted sprinting

FRT: Forward running training

GRF: Ground reaction force

Hz: Hertz

ICC: Intraclass correlation coefficient

i.e.: That is

kg: Kilogram

K_N: Vertical leg stiffness

L_V: Load-velocity

LWC: Largest worthwhile change

m: Metre

MWC: Moderate worthwhile change

$m \cdot s^{-1}$: Metre per second

N.B.: Nota bene, “note well”

PE: Physical education

PHV: Peak height velocity

r^2: Coefficient of determination

ROM: Range of motion

RS: Resisted sprinting

s: Seconds

SD: Standard deviation

SE: Standard error

SWC: Smallest worthwhile change

V_{dec}: Velocity decrease

y: Years of age

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly noted in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Chapters 2 to 7 of this thesis represent separate papers that have either been published or have been submitted to peer-reviewed journals for consideration for publication. The contributions of myself and the various co-authors of these papers are outlined at the beginning of each chapter. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Aaron Matthew Uthoff

PUBLICATIONS AND PRESENTATIONS

The publications listed below are a result of the research conducted in fulfilment of the degree of Doctor of Philosophy.

Articles In-Press or Under Review

Uthoff, A., Oliver, J., Cronin, J., Harrison, C., Winwood, P. (2018). A new direction to athletic performance: understanding the acute and longitudinal responses to backward running. *Sports Medicine, 48*(5), 1083-1096. doi: 10.1007/s40279-018-0877-5.

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Craig Harrison, Paul Winwood, 10%)

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C. (2018). Prescribing target running intensities for high-school athletes: can forward and backward running performance be autoregulated? *Sports, 6*(3), E77. doi: 10.3390/sports6030077.

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Craig Harrison, Paul Winwood, 10%)

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C. (under review). Load-velocity relationships during resisted forward and backward running in high-school athletes. *Science and Sport.*

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Paul Winwood, Craig Harrison, 10%)

Uthoff, A., Oliver, J., Cronin, J., Harrison, C., Winwood, P. (2018). Sprint-specific training in youth: backward running vs. forward running training on speed and power measures in adolescent male athletes. *Journal of Strength and Conditioning Research,* Published Ahead of Print. doi: 10.1519/JSC.0000000000002914.

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Craig Harrison, Paul Winwood, 10%)

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C., Lee, J. (2019). Resisted sprint training in youth: the effectiveness of backward vs. forward sled towing on speed, jumping, and leg compliance measures in high-school athletes. *Journal of Strength and Conditioning Research.* Published Ahead of Print. doi:10.1519/JSC.0000000000003093

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Paul Winwood, Craig Harrison, Jeong Eun Lee, 10%)

Uthoff, A., Oliver., J., Cronin, J., Winwood, P., Harrison, C. (2019). Backward running; the why and how to program for better athleticism. *Strength and Conditioning Journal.* Published Ahead of Print. doi:10.1519/SSC.0000000000000459

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Paul Winwood, Craig Harrison, 10%)

<u>Conference Proceedings</u>

Uthoff, A., Oliver., J., Cronin, J., Winwood, P., Harrison, C. (2018). Resisted sprint training in adolescence: the effectiveness of backward versus sled towing on speed, power, and stretch-shorten cycle measures in youth athletes. Podium presentation at the 2018 International Conference of Strength Training, Perth.

(Aaron Uthoff 90%, Jon Oliver, John Cronin, Paul Winwood, Craig Harrison, 10%)

Uthoff, A. (2018). Moving performance forward by running backward…update. Podium presentation at the 2018 Sport Performance Research Institute New Zealand Strength and Conditioning Conference, Auckland.

(Aaron Uthoff 100%)

Uthoff, A. (2017). Moving performance forward by running backward. Podium presentation at the 2017 Sport Performance Research Institute New Zealand Strength and Conditioning Conference, Auckland.
(Aaron Uthoff 100%)

The student was the main contributor (90%) of the research and subsequent analysis and interpretation of the research results in this thesis. Additionally, the student was the primary contributor (90%) to the writing of research ethics applications, progress reports and papers, as well as being the main presenter at conferences.

We, the undersigned, hereby agree to the percentages of participation to the chapters identified above:

Supervisors

Dr. Craig Harrison, Primary

Dr. Jon Oliver, Secondary

Dr. Paul Winwood, Tertiary

Prof. John Cronin, Mentor

Collaborators

Dr. Jeong Eun Lee

ACKNOWLEDGEMENTS

This is for all the people in my life who have provided me academic, physical, and emotional support. Thanks to my family, friends, and supervisors for always having my back and helping guide me on this adventure.

Mom and Dad: You know better than anyone that this has been a long and winding journey. You have always been supportive of my outlandish ideas and encouraged my exploration. Thank you for showing me that compassion, hard work, and scruplous values are required to achieve goals and make life-long relationships.

To my colleagues at Tauranga Boys’ College: Firstly, thank you Darrell for providing me the opportunity to coach, giving me the freedom to mould the athlete development programme, and supporting me with more resources than I could have ever imagined. To the lads in the PE department, you brought me in and treated me like family from day one. Thank you for giving up your time, knowledge, and space to help me out and make me feel like I belonged. Flemmo, I couldn’t have asked for a better coach to work alongside. It has been an absolute honour mate, and I am proud to call you my friend.

To the crew at SPRINZ and AUT Millenium: You are an amazing group of human beings. From the monthly strength and conditioning catch ups to sport, there was always some sort of antics going on. Frank, Enora, and Eric, thanks for giving me a sofa to crash on. It was always home away from home. Thanks to the post graduate staff for all your help keeping me on track and answering my questions.

To my friends: Thank you for the encouraging chats and helping shape the direction of this thesis. Being able to bounce ideas off you generated ideas which I would have never developed on my own. It’s great to be surrounded by people who are smarter than me.

Special thanks to the athletes. Without you, this would not exist.

To my supervisors: You all have made a profound postive impact on me as an academic, strength coach, and person. JC, who would have thought that a bit of manual labour would be the catalyst for a PhD? In addition to a leading sports scientist, your approach to life and willingness to help people make you an all around great human. JLO, thank you for keeping me on track and making sure my ‘T’s were crossed and ‘I’s dotted. You’re a magician, your ability to turn around large documents and provide detailed feedback in short periods of time is astounding. Paul, thank you for guiding me with stats and giving me the true ‘Kiwi Experience’, ensuring I got enough fishing in. I always look forward to geeking out with you about some new piece of technology, statistical approach, or training method. Elvy, thank you for filing down the corners on this square and helping adujust my thinking to tell this research story. Your way of approaching challenges has opened my eyes to see there are many roads leading to Rome.

This would be incomplete without mentioning those closest to me. To my feline friends, Mu and Leo, you are the best study buddies and lap warmers this proud fur-daddy could wish for. Thanks most of all to my partner, Dacey, for allowing me to drag you around the world to pursue my dream. Your adventurous spirit and “go get ‘em” attitude pushes me to strive for the best. Without you, none of this would have been possible. I promise to one day find a hobby that is not ‘sport related’.

CHAPTER 1. PREFACE

1.1 Background

The desire to enhance athleticism has long been the goal of sports scientists and coaches. Athleticism can be considered the physical qualities necessary to execute movements during sports competition. Sprinting ability is one such characteristic which is a validated measurement of athleticism frequently used to assess performance (144), identify talented athletes (189, 199) and predict future athletic success (11, 70, 90, 143). Overground athletes, whether they are on a court, track, or field, need to be fast and harness explosive characteristics to gain the competitive edge over their opponents. Recently, special attention has been given to the natural development and trainability of sprinting speed in youth athletes (152, 154-156, 168, 209) given its ability to discriminate between the most skilled young athletes and those of the next highest level (76, 80, 84).

1.1.2 Natural Development of Speed in Boys

Sprinting ability has been suggested to improve through childhood and adolescence, with periods of accelerated development occurring in preadolescence (5-9 years old) and adolescence (12-16 years old) in boys (67, 233, 241, 246). Sprint performance naturally increases by approximately 3% each year in boys between 11-16 years of age (246) with the largest gains in sprint speed reported to align with the adolescent growth spurt (176, 194). This indicates that maturation plays a role in the natural progress of sprint ability (154, 155). Neural development has been suggested as the primary mechanism for increased speed in less mature, preadolescent, boys (241), while continued myelination of the central nervous system, increases in androgenic hormones, greater muscle cross-sectional area, and architectural alterations to musculotendinous structures help explain performance increases in more mature adolescent boys (175, 187). While it seems relatively straight forward that speed increases with maturation, the interaction of so many variables make it difficult to decipher the primary mechanism contributing to improvements in speed during adolescence.

In its simplest form, speed is the function of stride length and stride frequency (98). As boys age, they become taller, their limbs become longer, and their body mass increases (137). With increased age and maturation, speed is facilitated by increased stride length which makes up for decreases in stride frequency and longer contact times (156, 176). Accompanying increases in adolescent stride length and running speed is the development of greater relative horizontal propulsive forces (176) and increased lower limb stiffness (153, 208). Superior acceleration ability appears to be related to the ability to "push more" (i.e. generate greater horizontal propulsive forces) (172) whereas maximal velocity sprinting is reliant on the lower limbs' ability to withstand vertical forces and utilise the stretch-shorten cycle (i.e. greater lower limb stiffness) (23, 208).

Collectively, cross-sectional and longitudinal research suggests that maturing athletes are capable of overcoming decreased step frequencies and longer ground contact times due to growth related adaptations. These adaptations facilitate increased lower limb stiffness and horizontal propulsive force, enabling them to propel themselves further during each step. Since the natural development of running speed is known to increase in boys (152, 188) due to maturation factors associated with growth and neuromusculotendinous functioning (150, 157, 197), understanding optimal training strategies becomes essential for boys around the time of their adolescent growth spurt. Furthermore, it is important to understand whether training can promote gains in speed over and above natural development.

1.1.3 Trainability of Speed in Boys

Given the role of sprint ability for competition and recruitment, it’s no surprise that strength and conditioning coaches have devised a number of nonspecific and specific training methods to improve this characteristic of athleticism in young athletes (15, 168, 209). Nonspecific training commonly refers to forms of resistance, plyometric, or combined training methods which do not include sprinting (209). Specific sprint training typically involves either free, or unresisted, sprinting, resisted sprinting (e.g. sled towing or uphill running), or assisted sprinting (e.g. towed or downhill running) with periods of passive recovery (209). Nonspecific training is prevalent in literature with multiple reviews determining that it is an effective method for improving sprint performance in youth males (15, 121). However, comparatively less research is available on the training effects of specific sprint training methods in boys.

Adhering to the principle of specificity, specific-sprint training is intended to promote neuromuscular and musculotendinous adaptations which directly transfer to the velocity and direction specific task of sprinting (43). Two reviews examining the effectiveness of specific sprint training methods have determined that specific sprint training promotes moderate to large beneficial effects on sprinting performance in youth athletes (168, 209). However, it should be pointed out that the review by Rumpf et al. (209) only included two specific sprint training studies, both in pre-adolescent boys. Further, the 14 studies included in the review by Moran et al. (168) also included sport training (37), sprint games (193) sprint intervals (26, 147, 216, 232), change of direction sprinting (26, 34, 82, 140), and combined training (136, 211) methods. Therefore, using the definition of sprint-training as identified by Rumpf et al. (209), the true number of reviewed research available is limited to two unresisted sprint studies in pre-adolescent boys.

Outside of the aforementioned specific sprint training reviews, unresisted sprint training has been shown to improve 10 m and 20 m sprint performance in youth mid peak-height velocity (PHV; ES = 0.51 and 0.33, respectively) (167). Additionally, resisted sprinting has been shown to improve mid-PHV and post-PHV boys' sprint performance by 0.01% to 5.88% (ES = 0.19 to 1.18), respectively, and pre-PHV boy's sprint performance by 0.99% (ES = 0.1) (21, 204, 215). These recent investigations add to the current body of research available on the effectiveness of specific sprint training in youth, yet relying on a total of six studies to guide the practical application of youth sprint training leaves room for speculation.

Nonspecific training has resulted in small to moderate improvements in sprint performance (15, 121), while specific sprint training has been shown to result in moderate to large improvements in sprinting performance for boys mid-PHV and post-PHV (168, 209). This information suggests that specific sprint training may be a more effective method for inducing positive adaptations to sprint performance in youth, although this posit is limited by the dearth of specific sprint training research. While both specific and nonspecific sprint training methods have been shown to enhance sprint speed in youth, the current scientific literature available does not fully encompass the range of modalities utilised by speed and strength coaches, such as backward running (BR).

1.1.4 Backward Running for Performance

Backward running is used in practice by runners and team sport athletes, yet it has received relatively little scientific attention compared to forward running (FR). Like FR, BR is a locomotive strategy used by athletes during many overground sports (e.g. soccer, rugby union, rugby league, American football, and many racquet sports) (164). During competition, BR may serve as a means for athletes to reposition into a more advantageous playing position while maintaining vision of a ball or opposition player (9). Outside of competition, BR has been included as a warm-up strategy to reduce injuries and enhance performance (13, 178, 185, 220), a training method to improve components of athleticism (227, 230), and as a return to play protocol for athletes following injury (32). Beyond the fact that BR occurs during competition, coaches and clinicians advocate for the use of BR due to higher lower limb muscle activity (64, 222) and increased concentric musculotendinous utilisation (29, 30) accompanied by lower knee joint stress (65, 201) compared to FR.

Scientists posit that a common neural network exists to produce both FR and BR (100, 148), although the specific pathways responsible for each running direction are not fully understood (100). Shared common neural networks for FR and BR indicate that training one running direction may result in performance gains in the other. Training adaptations from BR may transfer to FR (100, 148), however, few studies have investigated the effectiveness of this proposed phenomenon (186, 230). Within this limited body of research, BR has been found to improve FR economy (186) and maintain FR sprinting performance (230) in adult athletes. Although the literature on BR suggests this may be a promising training method for adults, it is unknown how these types of training adaptations might transfer to younger athletes around the time of their adolescent growth spurt. Furthermore, there are currently no empirically recognised resources available that provide guidance on how to progressively overload BR modalities and prescribe BR training to improve components of athleticism, such as sprinting and jumping performance.

1.2 Thesis Rationale

Adolescence appears to be an important period to utilise training methods focused on developing force capabilities and sprinting performance in boys. It has been recommended by Behm et al. (15) that young athletes establish a base level of strength in order to express high force potential during sprinting. Given that BR is an effective method for increasing lower limb strength and power measures in adults (64, 231), this training method may be a means to promote positive adaptations in musculotendinous function, and thus, transfer gains to athletic tasks such as sprinting and jumping in maturing athletes. However, the use of BR to improve athletic tasks such as sprinting and jumping is not well-understood, and no research is available guiding strength and conditioning coaches on the integration of BR training into youth athlete development programmes. This thesis provides original scientific research into why BR may be useful for athletes and how to prescribe BR training modalities for athletes by providing a broad experimental application to this body of knowledge.

1.3 Purpose and Aims of the Research

This PhD was conducted with the purpose of answering the overarching question: “can BR training modalities promote positive adaptations in athletic performance among male youth athletes”? A review, four experimental studies, and a programming considerations chapter were constructed to understand and explain the training responses of unresisted and resisted BR in strength and conditioning practice for high-school athletes. The specific aims of these six chapters were to:

1. Review and understand the differences in acute and chronic performance, neuromuscular and metabolic responses to BR vs FR.

2. Investigate youth athletes' ability to consistently achieve prescribed running intensities during overground unresisted BR and FR.
3. Explore the load-velocity relationships during resisted BR and FR and determine the consistency of running performance.
4. Investigate and compare the effects of unresisted BR and FR training programmes on speed, jumping, and stiffness performance in high-school athletes.
5. Examine and compare the training effects of resisted BR and FR programmes on speed, jumping, and stiffness performance in high-school athletes.
6. Provide programming considerations on why and how to integrate BR to improve athleticism.

1.4 Research Location

Athlete development programmes are becoming commonplace in sports academies and secondary schools. Each athlete development programme will be unique in its structure given the particular scheduling confines. It is generally assumed that participating in these types of programmes will increase athleticism. For example, Wrigley, Drust, Stratton, Atkinson and Gregson (252) found that 12-16 year old athletes enrolled in a soccer academy programme improved sprinting and jumping ability by a moderate to large effect size relative to athletes not enrolled in an athlete development programme. The particular athlete development programme within which the research studies comprising this thesis were embedded was part of a New Zealand high-school curriculum and thus, conducted during normal school hours.

Serving a dual role as a researcher and head strength and conditioning coach embedded in the school where the participants were recruited, my position was beneficial for overseeing the athlete development programme and ensuring sound research methodology was followed. The entirety of the strength and conditioning programming was developed by myself and therefore allowed careful manipulation of training load to ensure the research designs could be implemented. Particulars around the athlete development programme and athletes are as follows:

1. The weekly structure of the athlete development programme for year 9 (age 13-14 years), 10 (age 14-15 years), and 11 (age 15-16 years) athletes comprised of three 50 minute long sessions consisting of two class periods designated to organised training with the head strength and conditioning coach and one class period that was led by a physical education (PE) teacher to develop tactical game skills.
2. Year 9 students were enrolled in the athlete development programme for one school term, lasting approximately 10 weeks where they were exposed to introductory resistance training, taught fundamental weightlifting techniques, and learned foundational medicine ball exercises.
3. Year 10 students were enrolled in the athlete development programme for two approximately 10 week, school terms where they were introduced to a structured resistance training programme advancing upon the movements learned in year 9.
4. Year 11 students were enrolled in the athlete development programme for the entirety of the school year (i.e. four terms) and participated in organised resistance training using similar exercises to those learned in year 9 and 10, but now using linear block progression to overload the movements.
5. The training studies in this thesis were ran by the head strength and conditioning coach in place of the traditional resistance training curriculum for all year groups.

1.5 Research Design

A review, four experimental studies, and a programming considerations chapter were used to achieve the aims of the thesis:

1. A narrative review using a systematic approach was undertaken to examine and compare the acute and longitudinal implications of using BR for athletic populations.
2. A repeated measures design was used to quantify the consistency of youth athletes to achieve targeted speeds using an autoregulation strategy.
3. A repeated measures design was used to establish the load-velocity relationships during resisted BR and resisted FR. Additionally, the slope and velocity data was compared over multiple testing session to establish the consistency of these movements in adolescent male athletes.
4. A match-paired randomised comparative trial was used to determine the chronic effects of unresisted backward running training versus unresisted forward running training on aspects of sprinting, jumping, and stiffness measures in adolescent male athletes.
5. A match-paired randomised comparative trial was used to examine the chronic effects of resisted BR training versus resisted FR training on sprinting, jumping, and stiffness measures in adolescent male athletes.
6. To provide practitioners with why and how to include BR into a training programme, an empirically supported programming considerations chapter was written.

1.6 Originality of the Thesis

Currently, very little evidence in the scientific literature exists on specific sprint training in youth, and no research is available on BR in youth athletes:

1. No reviews on the acute or trained responses to BR exist in the literature in any population.
2. No study has determined the consistency of self-selecting running speed during BR and FR using autoregulation.

3. No study has established the load-velocity relationship during resisted BR and no study has determined the reliability of the load-velocity relationship during resisted BR or resisted FR in adolescent athletes.
4. No study has investigated the training effects of unresisted nor resisted BR on FR speed, jumping ability, or stiffness performance in adolescent athletes
5. No programming considerations have been proposed for integrating BR into athletic training programmes.

1.7 Structure of the Thesis

All chapters except the first and last were written in the format of a published journal article to fulfil the Pathway Two thesis requirements at AUT. The eight chapters of the thesis begin with a prelude detailing how each chapter links and subsequently build upon each other to ensure that the thesis is a unified body of work. This thesis is divided into eight chapters consisting of four thematic sections designed to answer the overarching question of whether BR training modalities can promote positive adaptations in athletic performance among male youth athletes. A schematic structure of the thesis is outlined in Figure 1.1.

Each chapter, with the exception of one and eight, have been submitted as a stand-alone publication to peer-reviewed journals within the area of applied strength and conditioning and sport and exercise science. The first section includes the introduction and a literature review. The introductory chapter provides the rationale, originality, and structure of this PhD while introducing the primary concepts used throughout this thesis (e.g. the importance of running speed, how it can be trained, and why BR may enhance FR in youth athletes). Chapter 2 is a narrative review of the literature describing the acute and training effects of BR on athletic performance compared to FR.

Section two consists of the first two acute experimental chapters of this thesis. These studies serve to understand how BR and FR compare and provide guidelines for how to overload unresisted and resisted BR during training. Chapter 3 is a reliability study examining the ability of youth athletes to run at prescribed intensities based on perceived effort. In it, comparisons are made between BR and FR at intensities commonly prescribed during warm ups, training, and return to play protocols following injury. This chapter aims to quantify whether young athletes can accurately and reliably achieve relative running velocities using autoregulated pacing strategies. In Chapter 4, the reliability of running velocity and the slope of the load-velocity curve during resisted BR and FR is analysed over multiple testing sessions. Within this chapter the relationship between resisted sprinting load and running velocity is established for both BR and FR.

Section three is comprised of the two training chapters. Chapter 5, a match-paired randomised control trial in which three groups (Control, BR and FR) of adolescent athletes performing either BR, FR, or traditional physical education (PE) curriculum over an 8-week period were compared. The BR and FR training groups followed protocols which systematically overloaded running intensity by progressively increasing matched sets, reps, intensity, and running distance; the only difference being running direction. Similarly, Chapter 6 used a match-paired randomised controlled trial to compare the training effects of 8-weeks of progressively overloaded resisted BR versus FR running on speed, lower body power, and stretch-shortening cycle characteristics of adolescent male athletes. Overload was achieved by increasing load (as a percentage of body mass), reps, and running distance.

The final section of this thesis consists of Chapter 7 and 8. Chapter 7 provides practitioners with an understanding of why BR may be used to enhance athleticism and how to integrate BR into an athlete's training programme. Finally, a discussion of the data reported throughout the thesis is provided in Chapter 8. The final chapter of this thesis serves as a synopsis which provides context on how the findings in this thesis add to the current body of research and finishes with conclusions, practical applications, and future recommendations for research.

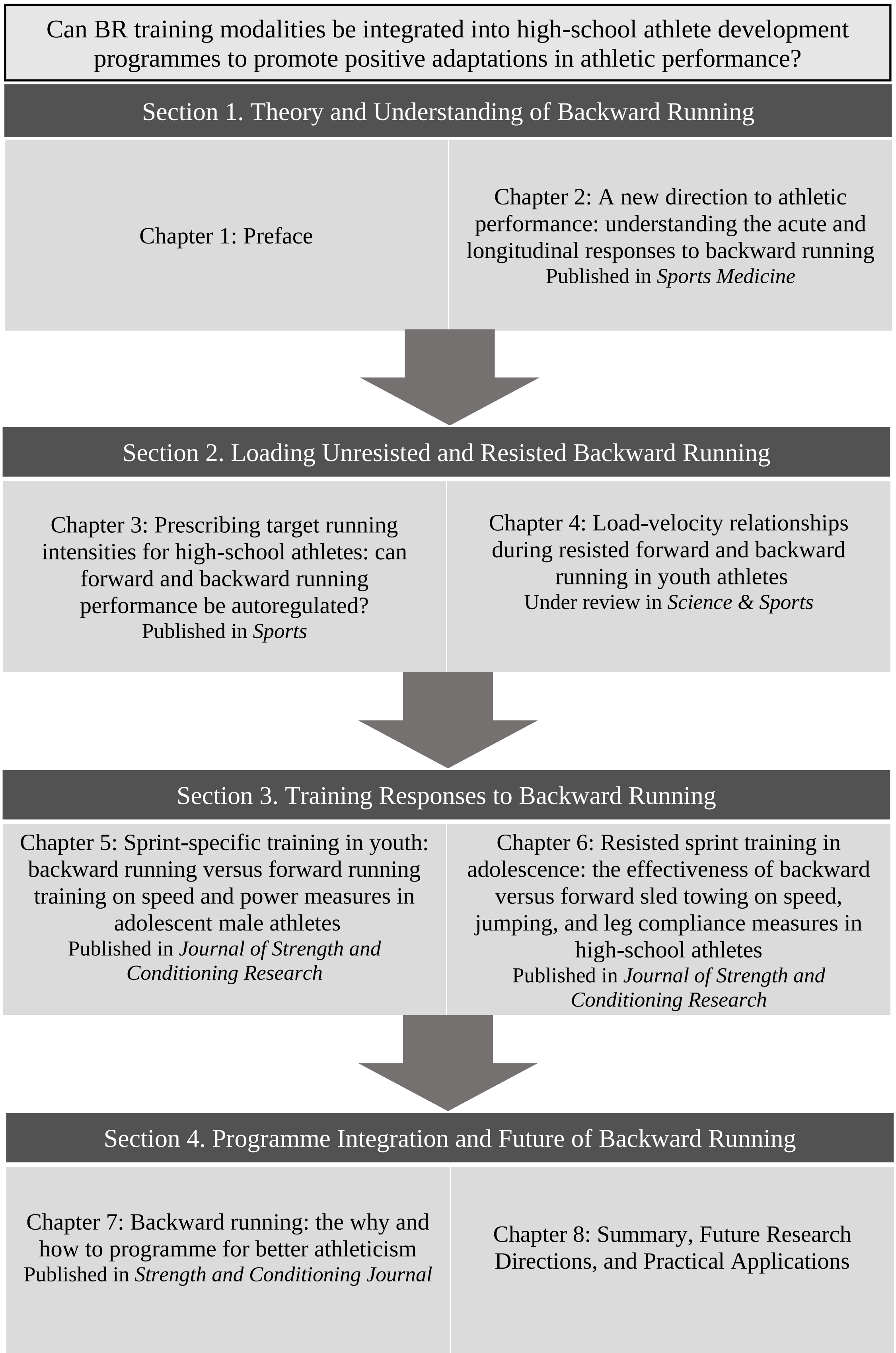

Figure 1.1. Thesis structure

CHAPTER 2. A NEW DIRECTION TO ATHLETIC PERFORMANCE: UNDERSTANDING THE ACUTE AND LONGITUDINAL RESPONSES TO BACKWARD RUNNING

2.0 Prelude

It has been identified that BR has a role in sports competitions, implications for injury prevention and performance enhancement due to the unique characteristics of this direction of running. The purpose of this chapter was to provide a comprehensive review of the literature pertaining to the acute and training adaptations to BR and compare these responses to FR. This review of the literature sets the foundation for the subsequent chapters by addressing the potential benefits and limitation of using BR to enhance components of athleticism. This chapter also identifies the gaps and limitations in the literature and provides justification for the research direction of this thesis.

This chapter comprises the following published paper:

Uthoff, A., Oliver, J., Cronin, J., Harrison, C., Winwood, P. (2018). A new direction to athletic performance: understanding the acute and longitudinal responses to backward running. *Sports Medicine, 48*(5), 1083-1096. doi: 10.1007/s40279-018-0877-5.

2.1 Introduction

It is understood that forward running (FR) is a propulsive form of locomotion characteristic of most overground sports. Running in humans is a method of terrestrial locomotion which can refer to a variety of speeds ranging from jogging to sprinting. Running is unique to other forms of terrestrial locomotion i.e. walking or skipping, as it is characterised by a single leg supporting the body for the duration of foot-ground contact and periods of time when both feet are in the air (28). Superior FR speed is considered an important component of success in most overground sports (69, 199, 217). Therefore, it is no surprise then that FR has received much attention from both scientific and coaching communities. Research on FR ranges from acute deterministic biomechanical studies (7, 17, 113, 151, 223, 247) to assessments of longitudinal training studies (53, 191, 210, 225). Descriptive research on acute variables that characterise superior forward distance running and sprint-running performances have helped inform training methodology designed to improve running velocity and running economy (38, 52, 66, 99). For example, specific and nonspecific training methods have been developed to enhance force production, power output, and movement velocity, which are known biomechanical determinants of FR performance in both youth and adult populations (42, 145, 209). However, while FR has received most of the attention, other directions of locomotion, such as backward running (BR), have been less well researched.

In the absence of any formal definition of BR in the literature, BR in the context of this paper is defined as any form of locomotion in a reverse direction where movement is accomplished via a single leg of support throughout foot-ground contact and both feet simultaneously in the air between contralateral foot strikes. BR, like FR, occurs for short periods of time during many overground sports (164). A fundamental difference between BR and FR is the visual perspective of the runner. During BR, an athlete must rely on alternative sensory information due to a lack of visual guidance experienced during FR (100, 148). BR and derivatives, such as backpedalling, are basic movement patterns utilised for agility actions in sports (109). BR provides athletes with a strategy to move in a desired direction and maintain a view of the ball or opposition (9), while reducing strain on the knee joint (65, 201, 226). It has also been recommended for use in sports training programmes to increase variability (230), prepare athletes for the demands of competition (12, 135), reduce injury rates (185, 203, 220) and enhance performance (64, 133, 229-231, 254).

Although BR may alter the normal visual orientation relative to FR, it is a strategy used by athletes of all levels. For example, elite soccer players spend approximately 3-4% of the match running backward (164). This is interesting when you consider that the same elite soccer players only spend between 0.9 and 1.4% of the match sprinting forward. In addition, top-class soccer players (ranked 1-10 on the official FIFA list) spend significantly more time ($p < 0.05$) running backward than moderately ranked soccer players (ranked higher than 20 on the official FIFA list) (164). This suggests that BR can be employed as a useful strategy among high performing soccer athletes.

Human locomotion is produced via central pattern generators i.e. an intraspinal network of neurons capable of generating a rhythmic output (79). It is generally accepted that forward and backward walking are products of the same central pattern generators (100), although some contention exists about which pathways are responsible for producing each direction of locomotion (36, 100). While limited evidence exists for whether this phenomenon extends to BR and FR (148), researchers have suggested that training adaptations from BR may transfer to FR (100). Although a shared neural circuitry might produce each running direction, BR velocities are known to be slower than FR velocities during maximal efforts (9, 243). In fact, maximal velocities which can be achieved during BR are approximately 70% of those which can be produced during FR (9, 243).

Although velocities achieved during BR are lower than those observed during FR, BR is found in warm-up programmes designed to reduce injury prevalence and improve athletic performance (135, 185, 203, 220, 254). The rationale for the inclusion of BR in the warm-up has not been documented to the knowledge of these authors, however, it may be due to BR's ability to demonstrate lower biomechanical strain on the knee joint than FR (65, 173, 201, 226) while also requiring higher activation in the leg muscles (64) or simply to warm up the muscles specific to the movement patterns encountered in the sport.

Currently, BR is a movement utilised as an injury prevention method and injury rehabilitation technique (77, 94, 114, 141), yet little is known about the athletic benefits of BR. Therefore, the purposes of this review are to (i) explore and compare the acute responses of BR to FR; (ii) examine the effects of BR training on aspects of athletic performance; (iii) discuss the possible merits of BR as a method to improve athletic performance; and (iv) provide future research recommendations into BR.

2.2 Search Strategy for Acute and Training Studies

From December 2016 to September 2017 a comprehensive search of seven electronic databases (MEDLINE [EBSCO], OVID, PubMed, ScienceDirect, SPORTDiscus, Web of Science and Google Scholar) was performed. The same databases were searched in January 2018 to identify more recent articles of relevance. The following keywords were used: 'backward', 'retro' 'running', 'backpedal'.

2.2.1 Selection Method and Criteria

Results were limited to human studies, academic journals, reviews, and dissertations. The bibliographies of all reviewed articles were hand searched and forward citation was used where applicable. All studies conducted on BR which were published in the English language were included. The study selection process involved removing duplicates, screening for relevance on title and then abstract and finally screening the full-text articles using the inclusion/exclusion criteria.

2.3 Acute Responses to Backward Running versus Forward Running

An acute response can refer to a range of biomechanical or physiological effects either during or immediately following a stimulus. To realise the potential long-term training effects of an exercise, it is important to understand the immediate overt and underlying outcomes associated with that movement. Running research has typically aimed to identify the influence of speed (8, 24, 139, 240) and resistance (6, 42) on acute responses, while generally overlooking the effect of running direction on these deterministic variables. Herein, acute energetic and biomechanical comparisons are drawn between FR and BR. Figure 2.1 provides a visual comparison between BR and FR over the stance phase of the gait cycle.

2.3.1 Energetics and cardiopulmonary responses

The energetic cost of running overground is determined by the volume of active muscle necessary to propel an athlete in their desired direction (251), the ability of muscle tendon units to store and utilise mechanical energy (118), and the rate at which force can be applied during foot-ground contact (162, 251). It is important to consider these factors when comparing how much energy is required during FR compared to BR.

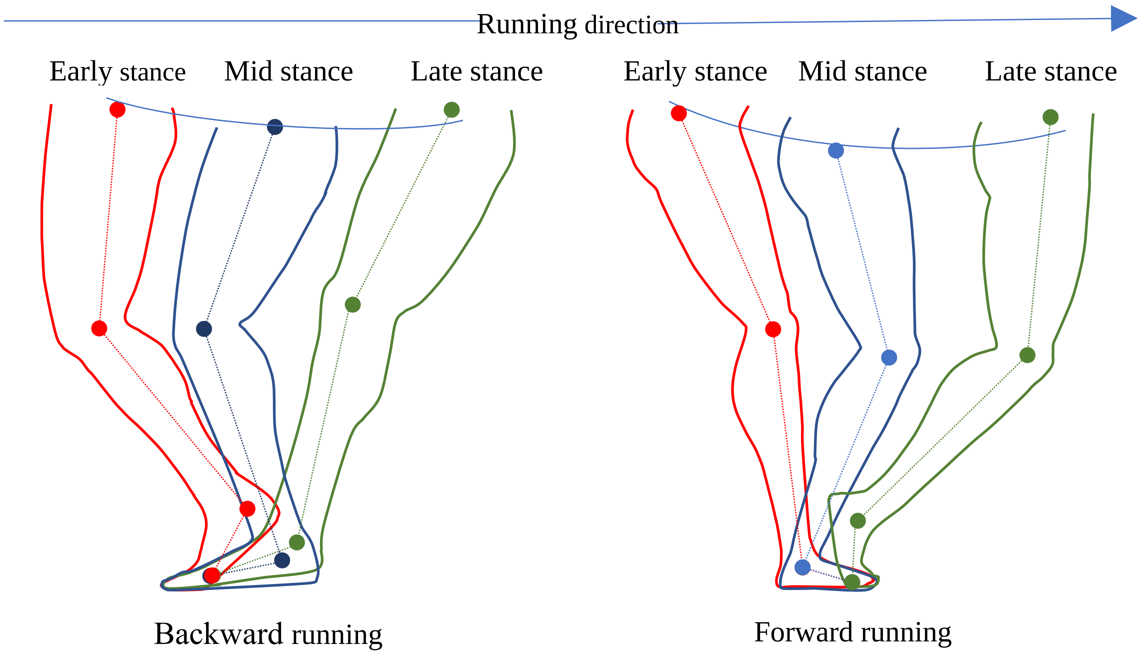

Figure 2.1. Stance phase of backward and forward running

It has been reported that BR places greater metabolic demands on the body than FR at relative and absolute velocities (3, 63, 251). Variables assessing energetic and cardiopulmonary responses include indirect calorimetry (41), oxygen consumption, heart rate, and blood lactate concentrates (3, 63, 251). Measurements of indirect calorimetry revealed that BR elicits 28% higher metabolic cost compared to FR at 2.24 m·s^{-1} (41). Oxygen consumption, heart rate and blood lactate have also been reported to be significantly higher during BR than FR at 2.68 m·s^{-1} (3, 63). This suggests that BR elicits a greater energetic demand and cardiopulmonary response than FR at a given speed.

Wright and Weyand (251) concluded that greater energetic demands exhibited during BR were a result of a 14% increase in average muscle force per unit of ground force exerted during BR versus FR. This resulted in 10% more muscle volume being activated to produce each unit of ground force during BR compared to FR. These findings are reported at relatively slow running speeds between 1.75 - 3.5 m·s^{-1}. Currently it is unknown whether comparisons of BR and FR at running speeds greater than 3.5 $m \cdot s^{-1}$ will result in similar reports of greater muscle volume being activated during BR.

Another suggestion for why BR requires greater energetic demands is that it is less reliant on the stretch-shortening cycle (29, 30). Cavagna et al. (29) concluded that BR relies less on eccentric work and more on concentric work because the muscle-tendon units are stretched more slowly during the braking phase at the beginning of foot-ground contact and shorten more rapidly during the push at the end of foot-ground contact compared to FR at similar absolute velocities. Accordingly, BR appears to be more reliant on the contractile components of the motor unit, which are known to require greater energy expenditure (96, 122). Therefore, BR is characterised by greater metabolic energy expenditure when muscles are exerting greater forces during concentric contractions and lower forces during eccentric contractions.

The time available for developing force is important for determining the energetic cost of a movement (92). A simple inverse relationship exists between the rate of energy used for running and the time a foot applies force to the ground during each stride (118). Wright and Weyand (251) concluded that the application of ground force during both BR and FR explains the energetic cost regardless of direction. Furthermore, they concluded that the rate at which force can be applied during foot-ground contact is higher during BR than FR (251). This finding has relevance to sporting applications because we know that rate of force development seems to be primarily determined by the capacity of motor units to produce maximal activation in the early phase of explosive contractions (first 50-75 ms) (134).

2.3.2 Kinematics

Running kinematics are biomechanical variables which describe motion of the body (e.g., angles, velocities and positions), without reference to the underlying forces that cause the motion (165). Detailing kinematics during running is useful as the information provides overt visual and quantifiable descriptions of movement. Typical kinematic measures of running include joint kinematics (e.g., location and orientation of body segments) and step kinematics (i.e. contact time, flight time, stride length and stride frequency). Empirical research pertaining to kinematic characteristics of FR and sprinting, and the influence of training on these variables, is plentiful (for review, readers are referred to the articles of: Mero et al. (151, 177), Novacheck (180)). Unfortunately, relatively little information is available on the kinematics of BR.

2.3.2.1 Joint kinematics

It appears that BR displays distinct differences (see Figure 2.2) in the displacement of the lower limbs compared to FR (9, 55, 65). Differences can be attributable to the reversal of movement direction and the location and magnitude of joint displacements over a stride cycle (55, 65).

2.3.2.1.1 Ankle range of motion

From the time a runner leaves the ground until mid-way through the flight phase of their stride, ankle kinematics display similar ranges of motion (ROM) for both FR and BR (55). However, differences appear moments before ground contact of the foot, characterised by a dorsiflexed position during FR and a second plantarflexion phase during BR (55). Mean ankle range of motion over a stride cycle has been reported to be 52 - 55° and 42 - 47° during FR and BR, respectively (9, 55). One possible explanation could be that the ankle is anatomically designed to produce forward propulsion (87). The foot is therefore functionally constrained in BR due to the angle of the ankle increasing, as opposed to decreasing before foot-ground contact in FR, limiting the overall ROM and propulsive potential of the joint (9).

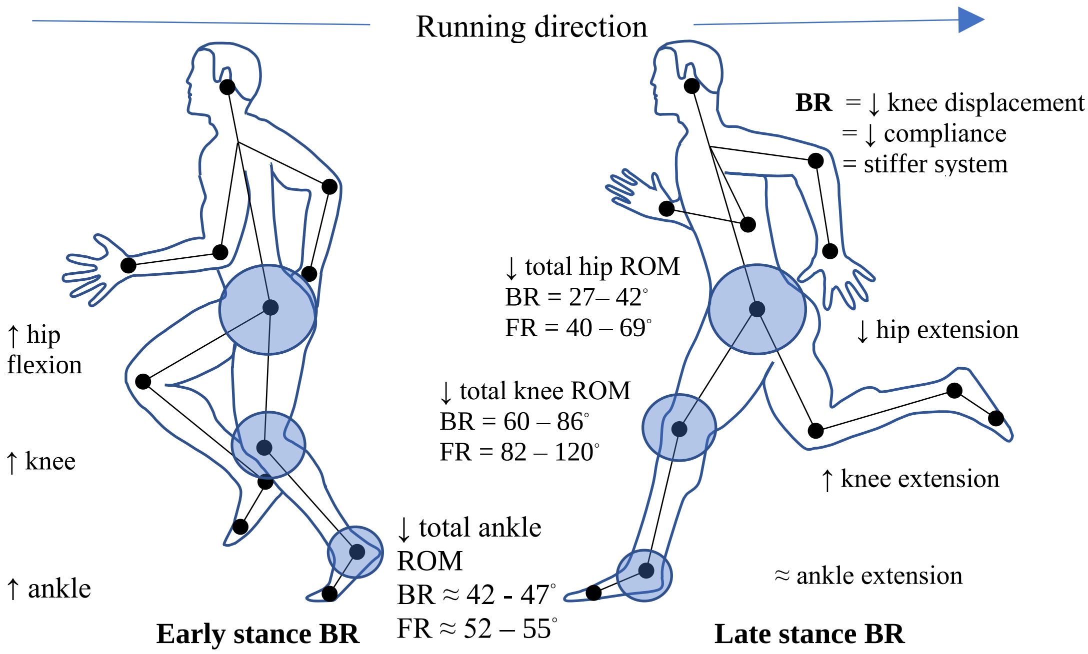

Figure 2.2 Joint kinematics of backward running in relation to forward running. The differences shown are relative to forward running.
N.B. ROM = range of motion; BR = backward running; FR = forward running

2.3.2.1.2 Knee Range of Motion

Knee ROM over the gait cycle has been reported to be greater during both the flight phase and stance phase of FR compared to BR at similar absolute and relative running speeds (14, 55, 65). BR is characterised by greater knee flexion during initial foot-ground contact and greater knee extension during late foot-ground contact compared to FR (55). Between early and late foot-ground contact the knee undergoes less flexion during BR than is experienced during FR (55). These findings indicate that the knee is less compliant during BR compared to FR at similar absolute intensities. A discovery from Cavagna et al. (30) that BR displays greater vertical leg stiffness compared to running at similar speeds forward supports this suggestion. Although it is unknown whether these characteristics are true when comparing BR and FR at similar relative intensities, several potential training adaptations could result from decreased knee ROM and increased vertical leg stiffness exhibited during BR. For example, increases in vertical leg stiffness may translate to greater utilisation of the stretch-shortening cycle (27) and reduce deformation of the lower extremities during FR and high velocity movements such as sprint-running and change of direction tasks (8). However, this posit has yet to be empirically tested.

2.3.2.1.3 Hip Range of Motion

Mean ROM between 27 - 42° and 40 - 69° have been observed at the hip for BR and FR, respectively (9, 55). Increasing running velocity results in concomitant increases in hip joint displacement for both FR and BR (9). Maximal hip flexion is rarely achieved during either FR or BR, yet maximal hip extension is only seen during FR (55). The lower ROM displayed during BR versus FR might be a result of anterior musculotendinous structures of the hip, knee and abdomen preventing overstretching during the flight phase of the stride cycle (105). This postulate seems logical, yet is currently untested.

2.3.2.2 Step Kinematics

Joint kinematics are known to be related to step kinematics during running (93). For instance, as running velocity increases joint ranges of motion become greater, which leads to concomitant changes in step kinematics i.e. longer stride length (24, 85). Step characteristics are variables that have been used by coaches and sports scientists to assess running performance for decades (52, 180). For example, optimal stride length has been recommended for submaximal and maximal phases of FR (7, 72, 107) and increases in stride frequency are thought to determine maximal sprint running performance (138, 171). To gain insights into the relationship between running direction and step kinematics researchers have analysed running performances at velocities ranging from 1.85 - 6.42 $m \cdot s^{-1}$ and 2.64 - 9.10 $m \cdot s^{-1}$ for BR and FR, respectively (9, 41, 55, 64, 231).

Running velocity is considered a result of the interaction between stride length and stride frequency (52), with greater speeds achieved through large ground reaction forces produced during short ground contact times (243). It has been reported that the distance between each ipsilateral foot-ground contact i.e. stride length, is significantly less during BR than FR (251), where matched absolute speeds have been reported to be 12% less (55, 63) and relative speeds 37% shorter (9, 243). Alternatively, stride frequency has been determined to be significantly higher for BR than FR (251), with matched absolute speeds being 12% faster (55, 63) and relative speeds showing 11% higher turnover (9, 222, 243). In BR, contact times have been found to be 19% longer at self-selected speeds (65), 9% shorter at matched absolute speeds (231) and 5% greater at relative speeds (243) compared to FR. Flight times, i.e. time that neither foot is in contact with the ground, have been shown to be lower for BR than FR by 9% and 25% when compared at matched absolute and relative running speeds, respectively (231, 243). These findings indicate that BR is characterised by increased contact times and decreased flight times which manifest as shorter stride lengths and higher stride frequencies across a range of speeds. Stride length and flight times appear to be influenced to a greater percentage when matched at relative running speed. This may be due to greater FR velocities being achieved, as we have seen that BR is on average 30% slower than FR (9, 243). FR appears to display advantageous step kinematics for producing higher running speeds than BR, although it is difficult to decipher the underlying determinants due to limited published studies in this area.

2.3.3 Function and Activation of Leg Muscles During Forward and Backward Running

As running speed increases, the need for greater forces to produce longer stride length and higher stride frequency appears to be controlled by increases in leg muscle activity

(115). The activation of leg muscles during human locomotion is the result of learned programming patterns generated via the central nervous system (56). The same neurological system stimulated by afferent muscle, joint and associated tissues is believed to produce both backward and forward locomotion (57, 83, 100, 248) and has been suggested to extend to BR and FR (148). This revelation has led to researchers investigating how the function and activation of musculotendinous structures of the lower limbs change with running direction (64, 231).

2.3.3.1 Muscle Function

The mechanical function of leg muscles is considered to have developed in humans to propel us forward (22, 142). The quadriceps and tibialis anterior primarily serve to attenuate eccentric braking force during early foot-ground contact while the plantar flexors, hamstrings and gluteal muscles assist in forward propulsion (139). The functional roles of lower limb muscles are interchanged between BR and FR, whereby the anterior muscles of the legs become the primary source of propulsion and posterior muscles absorb braking forces during BR (55). The findings of Flynn and Soutas-Little (64) support this notion with their discovery that the muscle firing patterns are unique to running direction. Specifically, BR velocity is achieved by large productions of activity during the shortening action of the quadriceps and posterior lower leg muscles. The pragmatic utility of this knowledge provides a method for reducing eccentric strain on desired musculotendinous structures of the leg, while potentially developing greater concentric contractile adaptations.

2.3.3.2 Muscle activation

If faster running velocities are related to increased muscle activity (115), FR could be expected to be characterised by greater activity than BR. However, the reality is that most lower limb muscles display greater total activation over an entire stride cycle during BR compared to FR (64, 222). The greatest differences are present in the leg extensor/hip flexor muscles with a range between 53.3% and 189.6% greater activity over the stride cycle reported during BR compared to FR at the same absolute speed (222). These findings are important because they are the driving force for some clinicians and researchers claiming that BR can be used to increase leg strength and power (111, 231) and restore muscle balance (64). In addition to greater muscle activation, the average muscle force per unit ground force has been shown to be substantially higher (14%) for BR than FR (251). The researchers suggested that this was a result of larger muscle forces at the ankle presenting during BR, which may manifest due to the average active muscle length being 4% shorter during BR than FR. This suggestion seems plausible as muscles of the lower leg have reported higher activation when length is decreased (179). Practically, even at matched absolute speeds this means that the muscle spent 4% more time in a concentrically contracted state over the stride cycle when the subject ran backward.

<u>2.3.4 Kinetics</u>

Kinetic variables (i.e. vertical and horizontal forces) have been shown to be important measures to determine running performance (24, 107, 151, 244). The ability to generate large forces in short periods of time characterises fast running speeds (243, 244). It is important to therefore quantify and compare how forces are expressed during BR and FR to understand the similarities and differences between running directions. Figure 2.3 illustrates some key kinetics associated with BR compared to FR.

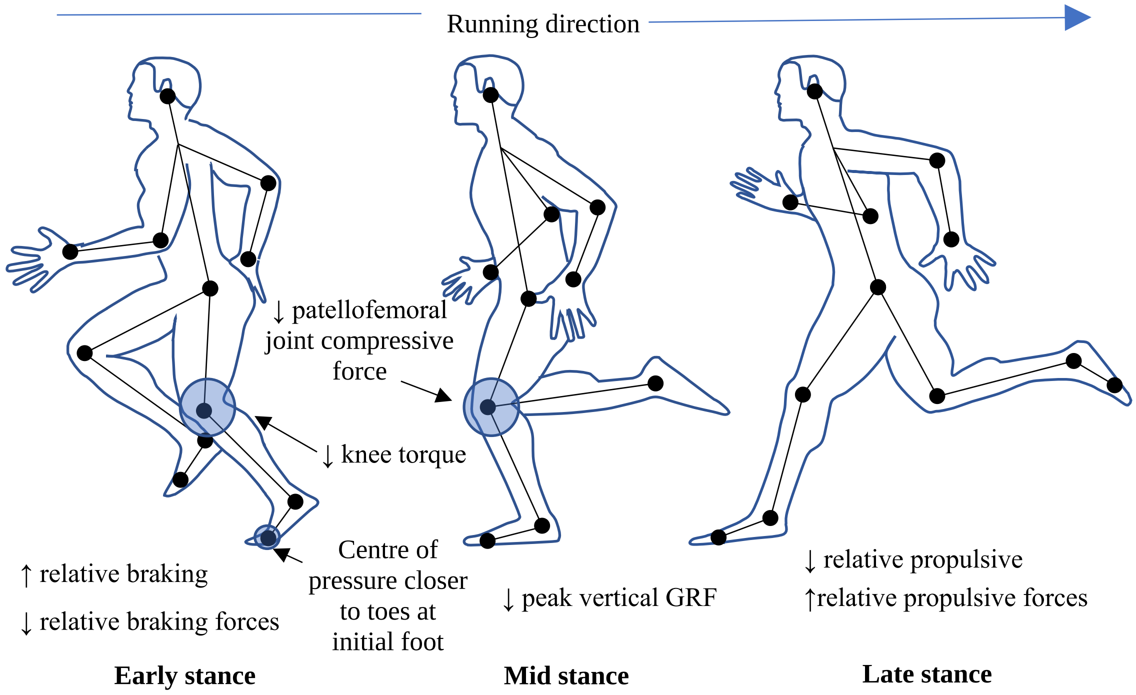

Figure 2.3: Kinetics of backward running compared to forward running.
N.B. GRF = ground reaction force

2.3.4.1 Patellofemoral Joint Compressive Forces

BR has been suggested for clinical purposes because it has been proposed to reduce the mechanical stress on the knee compared to FR at matched absolute submaximal speeds (65, 201, 226). Using mathematical models, researchers have calculated that the compression of the patella against the femur i.e. patellofemoral joint compressive force is on average 24% lower during BR than FR at relative and absolute running speeds (65, 201, 226). The general consensus is that patellofemoral joint compressive force is primarily influenced by knee extensor moments, which have been reported to be, on average, 72% higher in FR than BR (65, 201, 226). Knee moments are influenced by both the magnitude and location of the ground reaction force relative to the foot (201). Therefore, it is necessary to understand how and where forces are expressed during FR and BR to conceptualise the clinical and performance implications of each running direction.

2.3.4.2 Magnitude and Location of Ground Reaction Forces

Whilst patellofemoral joint compressive force is expressed to a lower degree in BR, the magnitude and orientation of the ground reaction force have been reported to be similar during both BR and FR (201, 231). These magnitudes at relatively low running speeds have been reported to be between 1.6 to 2.5 times body weight for BR and 2.5 to 2.7 times body weight for FR, respectively (47, 231). Weyand et al. (243) found that peak vertical ground reaction forces during BR and FR were 2.1 and 3.6 times body weight at maximal running speeds, respectively. The FR ground reaction forces found by Weyand and colleagues (243) are in agreement with other researchers who have determined that a sprinter exerts forces in excess of 3 to 4 times their body weight during FR (146, 151). Weyand et al. (243) explained that a possible reasoning for their finding was that running speeds at which the forces were obtained were 6.42 and 9.10 $m \cdot s^{-1}$ for BR and FR, respectively. In addition to the magnitude of force, knowing the location of force relative to the foot is useful for determining how the forces will act upon the body.

Although ground reaction force is distributed across the entire body, the foot is the only point of contact with the ground during running where forces are both attenuated and generated via the musculoskeletal system (54). The location of ground reaction force has been identified to be further forward on the foot at initial ground contact in BR versus FR (201). With the functional role of the knee and ankle muscles switching between BR and FR, the implications are that ground reaction forces may be attenuated more by the ankle and foot complex, resulting in a decreased moment arm between the ground reaction force vector and the knee joint in BR. This knowledge adds to our understanding of the magnitude and location of the peak force experienced during running, yet provides little information outside of a snapshot in time. Including information about how forces are expressed before and after peak ground reaction force is experienced may enhance our understanding of how FR and BR are generated.

2.3.4.3 Braking and Propulsive Forces

Kinetic variables such as braking and propulsive force expression and the rate at which force can be developed may serve strength and speed coaches with useful information when performance enhancement is the objective. Ground reaction forces during running change from being negative during early foot-ground contact (i.e. braking) to being positive during late foot-ground contact (i.e., propulsion) (29, 165). Measuring the duration and magnitude of braking and propulsive forces provides insights into the demands of muscle components (58, 86).

Running at a constant speed, the momentum lost during braking must equal the momentum gained during propulsion (31). The time the body undergoes braking forces has been shown to be shorter in BR compared to FR at constant speeds (29). Alternatively, the time generating propulsive forces has been found to be longer during BR than FR (29). The differences in time during braking and propulsion between BR and FR indicate that the mean force experienced while braking is greater in FR, while the mean force necessary for propulsion is greater during BR (30).

Expanding on the expression of force between BR and FR, Cavagna and colleagues (29, 30) discovered that the propulsive power during BR is, on average, greater than the braking power. Ultimately, the difference between backward and FR is due to a significant increase of the average propulsive power with a non-significant change in average braking power. This information suggests that compared to FR, BR may be less efficient at transferring eccentric energy to concentric energy via the stretch shortening cycle (29, 30), therefore indicating that FR is more reliant on the elastic components of the motor unit, while BR relies more heavily on the contractile component. If increasing contractile potential of lower limb motor-units is an objective, then BR may be a method to enhance these qualities.

2.3.4.4 Rate of Force Development

The speed in which the contractile elements of the muscle can develop force i.e. rate of force development (1), is an important determinant of explosive potential across a range of physical performance tasks differing in stretch-shortening cycle durations for both youth and adults (78, 120, 181, 219). Rate of force development during BR has been shown to be approximately 22% greater than FR across speeds ranging from 1.75 m/s to 3.5 m/s and was found to increase more rapidly with speed in BR compared to FR, with the greatest differences being realised at the highest speeds (251). The translation of these findings in a performance context is that BR is less reliant on the parallel and series elastic components of muscle, and appears to require greater recruitment of the contractile components, particularly at greater running speeds.

2.3.5 Acute Responses Summary

In summary, it seems BR provides a unique energetic and biomechanics profile compared to FR (see Figure 2.4). When comparing the acute responses, BR shows less efficient step kinematics and stretch-shortening cycle characteristics for producing high running speeds when compared to FR (9, 29, 30, 55, 65, 243). However, BR appears to display beneficial characteristics related to total muscle activation (64, 222), average muscle force per unit ground force (251), utilisation of the contractile element of the motor unit (29, 30), lower knee joint loads (65, 201, 226) and higher rate of force development (251) when compared to FR at matched absolute and relative speeds. While this information is promising for rehabilitation and performance purposes, most research has been conducted at relatively slow speeds where BR and FR were matched at absolute velocities. Knowing that maximal BR speed is approximately 30% slower than maximal FR speed (9, 244), further research is needed to conclude whether the available findings can be translated to comparisons at higher, relatively matched running speeds. Furthermore, as external resistance is known to influence biomechanical determinants during FR (6, 42, 129), the acute effects of adding resistance to BR is unknown.

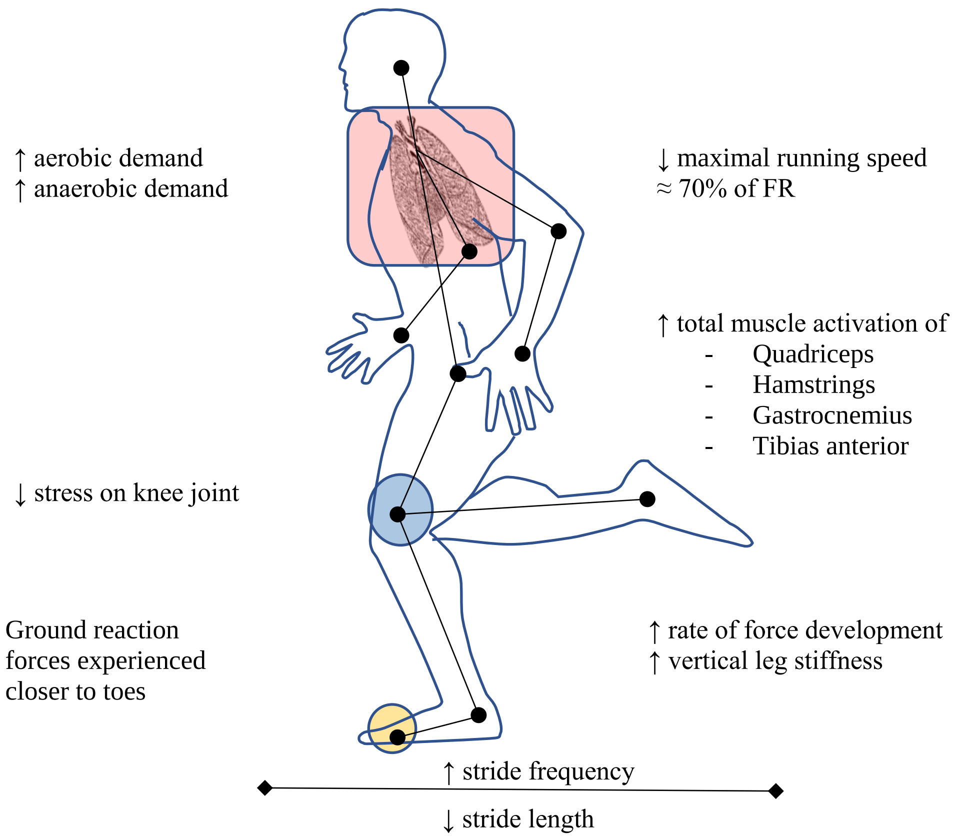

Figure 2.4. Key characteristics of backward running compared to forward running at relative and absolute speeds.
N.B. The differences shown are relative to forward running. FR = forward running

2.4 Longitudinal Responses to Backward Running

2.4.1 Warm-up Programmes to Reduce Injury and Enhance Performance in Athletes

An integral purpose of most sports training programmes is to prevent injuries and enhance athletic performance. Thus, warm-up protocols which include BR have been developed and researched in adult and youth populations (49, 220). The most notablepProgrammes include the FIFA 11+ (131, 220), FIFA 11+ Kids (203) performance enhancement and injury prevention (77), HarmonKnee (114) and Dynamic Warm-Up Programmes (4).

From a prevention perspective, these warm-up programmes have shown to statistically reduce lower limb overuse and injury prevalence (95). Additionally, it seems that these Programmes can significantly enhance quadriceps and hamstring strength (4, 49), hamstring flexibility, (4), sprint performance (12) and dynamic balance (50). Whilst the authors are aware that the warm-ups comprise of multiple movements and it is difficult to disentangle the contribution of each exercise to the researchers' findings, these results provide support for implementing warm-up programmes that includes BR.

2.4.2 Aerobic and Anaerobic Adaptations of Backward Running

Two research teams have examined the longitudinal effects of BR on physical and fitness adaptations (186, 229), although one must be cognisant that neither compared the effects to FR. Terblanche et al. (229) tested the effects of a BR programme on physical and performance components of fitness in 26 habitually-trained females. After training BR three times a week for six-weeks, the training group decreased body fat by 2.4% ($p = 0.01$), increased predicted maximal oxygen uptake (VO_{2max}) by 5.2% ($p = 0.01$), improved FR economy by 30.3% ($p = 0.01$) and decreased blood lactate concentration after submaximal FR by -17.1% ($p = 0.01$). The control group, which were not exposed to a training stimulus, did not show significant improvements in any of the tests. These findings provide some evidence that chronic BR can improve both physical and performance components of athletic fitness, however, whether it has any advantage over FR remains unclear.

In a group of highly-trained male runners, Ordway and colleagues (186) quantified the effects of a 5-week BR training programme on FR economy. The eight athletes completed two training sessions a week for five weeks, which resulted in significant improvements (2.54%; $p = 0.032$) in steady state FR oxygen consumption, i.e. running economy. This finding is of importance because it is comparable to improvements which have been reported after strength, plyometric, and altitude training interventions (161, 213, 214). Contrary to the findings of Terblanche et al. (229), Ordway and colleagues (186) did not find significant changes in VO_{2max} or body composition following BR training. The lack of improvement in VO_{2max} might be a reflection of the characteristics of the athletes, who were ranked above the 80th percentile in VO_{2max} at the pre-test. Something to consider is that the post-test results were compared to the post-familiarised results. While this is good scientific practice, readers must be cognisant that the five weeks of familiarisation and five weeks of training followed the same overload programme, differentiated in run training intensity by only 0.45 $m \cdot s^{-1}$ and fitness responses may have occurred during the first 5-weeks of familiarisation. The above findings support the hypothesis of previous researchers that aerobic capacity could be improved from BR training due to the relatively larger acute energetic costs and cardiopulmonary demands BR places on the body compared to FR (55, 63, 251). One may argue that increasing the speed of FR to impose higher aerobic and anaerobic demands would be a more specific form of training, however many field and court sports are not unidirectional (71, 110) and athletes may benefit from the reduced knee joint loading (65, 201, 226) and increased utilisation of shortening muscle actions (251) associated with BR. However, further research is needed to validate such views.

2.4.3 Strength Adaptations of Backward Running

To the authors' knowledge, only two research teams have published research examining the changes in maximal force production to BR training (227, 231). Swati et al. (227) examined the effects of BR training on maximal voluntary isometric contraction (MVIC) in a group of males between 18 and 25 years of age. Thirty participants were randomly allocated to either a backward walking (2.48 $m \cdot s^{-1}$), backward running (3.48 $m \cdot s^{-1}$), or a control group. The subjects performed their respective exercise three times a week for six weeks. It was found that the BR group significantly improved MVIC at 60° knee flexion by 10% in relation to the control group. These increases in isometric performance might be indicative of the isometric nature of BR, i.e. heavy reliance on contractile element with smaller range of motion (64). It should be noted that this study did not include a FR group, therefore direct comparisons between the effectiveness of BR versus FR on strength adaptations cannot be made from these findings.

Threlkeld and colleagues (231) compared the effects of an 8-week BR versus FR training programme on the isokinetic muscular torque production in a group of ten adult runners (6 males, 4 females). The runners were assigned to either an 8-week FR or BR training group. The FR group was instructed to continue their normal FR programme with no changes, whereas the BR group gradually included BR into their FR programme. Subjects were encouraged to set a 10-12 minute per mile pace (2.24 - 2.68 $m \cdot s^{-1}$) during BR. Improvements in knee extensor isokinetic muscular torque production were over two times greater in the BR group at $120° \cdot s^{-1}$ and over four-fold larger at $75° \cdot s^{-1}$ compared to the FR group. Additionally, the BR group showed significant improvements in ankle plantarflexor isokinetic muscular torque at 120 degrees per second, which were nearly ten times greater versus the changes in the FR group. The changes indicate that BR could be a technique for strengthening the quadriceps and plantar flexion muscles. This study is beneficial as it is one of the few to include a FR control group and provide direct insights into the utility of BR training versus FR training.

2.4.4 Linear Speed and Change of Direction Performance

Swati and colleagues (227) measured the effects of BR training on change of direction speed in a group of males aged 18-25 years compared to a backward walking and control group. The researchers found that BR and backward walking training three times a week for six weeks significantly improved change of direction performance by 3.86% and 2.38%, respectively, yet no significant changes were found for the control group who were not exposed to any training intervention (-0.66%). Change of direction performance from pre- to post-testing was found to be significantly different for the three aforementioned conditions, with the greatest difference between the BR group and control group ($p = 0.01$). This research highlights the ability of a six week BR training programme to improve change of direction performance in a group of male university aged subjects. However, this study did not compare the training effects of BR to FR.

One study compared the effects of BR training versus FR training on linear sprint-running and change of direction performance in 17 highly-trained female athletes (230). The BR and FR groups followed the same training programme biweekly for six weeks. The running was performed at maximum intensity with work-to-rest ratios between 1:5 and 1:3. Linear sprint-running performance did not differ from pre-training to post-training for the BR group, although the FR group showed declines in performance over 20 m, with significant ($p < 0.05$) decreases of 6.46% and 4.54% over 5 and 10 m, respectively.

Change of direction performance for the BR group showed significant improvements for all change of direction tasks, ranging from 2.99% for the 505-agility test to 10.33% in a ladder test. The improvements in the BR group were also found to be significantly greater than the FR group, which showed a range of improvements from 0.38% in the 505-agility test to 2.87% in the ladder test. These findings suggest that BR training may be used to improve change of direction performance and maintain linear forward sprint-running performance.

2.4.5 Training Responses Summary

The longitudinal adaptations to BR training appear to be beneficial for improving aerobic and anaerobic performance, isometric and concentric leg strength, and change of direction performance. These adaptations offer valuable insights into the possible applications of BR training in sports training Programmes.

Studies that have quantified the effects of BR on physical and physiological adaptations are few and typically carry a number of limitations e.g. lack of FR versus BR and/or lack of a training control group. From a practical perspective, this means that coaches and athletes wishing to use BR training do not have support for how to prescribe intensity or load to systematically overload training for their desired adaptations. It is unknown whether BR training is the panacea for injury prevention or performance enhancement. However, if BR is empirically investigated using robust methodological approaches, researchers and coaches may better understand the utility of implementing BR into a sports training programme.

2.5 Practical Application

Repetitive stress on musculoskeletal structures may lead to overuse injuries. Therefore, BR may be a method to increase training variability and reduce injury prevalence. From a performance perspective, exercises such as the start and acceleration phases during sprint running are known to require large isometric and concentric muscular forces. It may be hypothesised that BR could be used as a method to train such movements based on the knowledge that BR requires greater isometric and concentric demands of the musculotendinous structures of the legs to propel the body than constant speed FR at relative speeds. Furthermore, reductions in total lower limb ROM expressed during BR would allow the foot to be repositioned more rapidly and increase stride frequency. Higher stride frequency displayed during BR might help improve the neurophysiological functions of the body to increase maximal FR performance. This is further supported by the fact that greater vertical leg stiffness is associated with BR compared to FR. High vertical leg stiffness is known to be concomitant with greater maximal forward sprinting speed.

2.6 Conclusion and Research Suggestions

It appears that BR exhibits a unique energetic and biomechanical profile compared to FR. Whilst running speed may be limited by musculoskeletal function during BR, researchers have reported that the acute responses may be beneficial from both clinical and performance perspectives compared to FR. Energetics and biomechanics encompass a large portion of variables important for understanding the demands of a movement, yet only a small number of scientific investigations have researched these determinants in BR.

Empirical support exists for implementing warm-up protocols which include BR into sports training programmes to both fortify athletes against injury and improve performance. Additional evidence suggests that BR might be a training strategy to improve cardiovascular and neurophysiological functions necessary for optimising athletic performance. Whilst empirically supported reports are encouraging, longitudinal research on the training effects of BR is scarce. Currently, the training studies conducted on BR have been unresisted, therefore it is unknown how prolonged loading of BR may affect athletic performance. Additionally, most of these training studies are not designed to analyse the effects on trained athletes. Furthermore, none have analysed the effects on paediatric populations. Without knowledge in these areas, a dearth of scientific insight exists pertaining to BR training.

The biomechanics of BR are relatively well understood at slow running speeds, nevertheless little is known about how these determinants change with relation to running velocity or with various types of external resistance. Given this information, it is suggested that more empirical research should be conducted in this area. The findings of these investigations may allow for a more complete understanding of how BR may be implemented into sports training Programmes to achieve a desired training effect.

Until now, sports scientists have shown relatively little interest in developing BR training strategies that could improve athletic performance. The lack of research in this area means that coaches must make decisions concerning sport performance training without the support of empirical data. It is our recommendation that future research investigate the influence of speed and resistance on the acute and chronic effects of BR and FR. Additionally, we recommend that explorations be conducted in both youth and adult populations to understand whether BR is influenced by either maturation or training history.

CHAPTER 3. PRESCRIBING TARGET RUNNING INTENSITIES FOR HIGH-SCHOOL ATHLETES: CAN FORWARD AND BACKWARD RUNNING PERFORMANCE BE AUTOREGULATED?

3.0 Prelude

Chapter 2 highlighted a body of evidence describing the unique characteristics associated with BR, and subsequently, novel responses compared to FR. Evident from the previous chapter, BR has been investigated exclusively in adult populations with no literature attesting to the ability of youth athletes to perform this direction of running at any speed. It is common for coaches to programme sprint training using running intensities as a prescriptive method to promote desired training responses. However, there is currently little evidence to support that athletes are able to consistently achieve FR and BR performances at commonly prescribed intensities between training sessions. Therefore, the purpose of this chapter is to investigate athletes' ability to consistently achieve prescribed running intensities during overground unresisted BR and FR. This study will provide coaches with insights into autoregulation capabilities of high-school athletes during running and may assist with prescription for unresisted FR and BR training.

This chapter comprises the following published paper:

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C. (2018). Prescribing target running intensities for high-school athletes: can forward and backward running performance be autoregulated? *Sports*, *6*(3), E77. doi: 10.3390/sports6030077.

3.1 Introduction

It is common for coaches to prescribe targeted running speeds (e.g. half speed, three-quarter speed, or full speed), or intensities (e.g. a percentage of maximal running effort), during warm-ups (119), in training (19, 91) or for rehabilitation (94). Target intensities may range from relatively slower, submaximal efforts (190), to fast, maximal efforts (130), depending on the desired outcome of a session. Based on where and how target speed training is utilised in an athlete development programme, this training strategy may serve to prepare athletes for the rigours of competition, elicit desired training adaptations or help athletes return to their sport following injury. In the absence of sensory feedback, the capability of athletes to achieve target running intensities is facilitated by their ability to self-select their running velocity using auto-regulated strategies (2). Although it is common for coaches to prescribe target running intensities, there is currently little evidence to support that athletes are able to consistently achieve similar performances at these intensities between training sessions.

Submaximal target speeds (i.e. tempo running) have been programmed to improve running mechanics and promote aerobic adaptations (68, 73), while target speeds at maximal or near maximal sprint-running efforts are used in training to reflect biomechanical and physiological demands similar to those experienced by many athletes participating in field and court sports (10, 73). Maximal effort forward sprint-running over short distances (i.e. 20 m) have been reported to have high inter-day reproducibility in paediatric populations with coefficient of variations (CV) around 2% and high intraclass correlational coefficients (ICC) between 0.82 and 0.91 (70, 182), yet a paucity of information around reproducibility of submaximal speeds exists in youth. Moreover, no such information exists around the consistency of backward running (BR) training in youth.

Forward running (FR) and BR are sport-specific movements utilised by adults and adolescents during most overground sports (14, 84). However, the majority of scientific research has been on FR or forward sprint-running. This is interesting given that match analysis in youth football players has shown BR accounts for approximately 5% of total competition performance (198). Recently, BR has been proposed as a method for enhancing athletic performance given its unique acute and longitudinal adaptations relative to FR (235). Running speed during maximal efforts in adults have been reported to be approximately 30% slower during BR compared to FR (243), primarily as a result of shorter stride lengths and decreased reliance on the elastic components of the stretch-shortening cycle BR (148, 243, 251). At submaximal speeds, however, it is unknown whether similar decreases will be realised between the two running directions when asked to run at relative intensities. These biomechanical differences between FR and BR make them uniquely beneficial for inducing acute and long-term adaptations. Given BR's distinct biomechanical profile and the dearth of scientific literature on this running direction, empirical research is necessary to guide prescription strategies for BR.

Athletes use autoregulation to self-select targeted running speeds during both FR and BR in a variety of sports training situations, whether it be to prepare for the demands of competition or as a return to play protocol following injury (94, 239). However, the ability of high-school athletes to accurately self-select targeted running speeds, i.e. slow, moderate and fast, during either FR or BR, using auto-regulated strategies is unknown. Between session consistency has been reported for maximal effort forward sprint-running performance in youth athletes (70, 182), yet no information about the consistency of running speeds exists at submaximal intensities in youth. Additionally, no information regarding the ability of athletes to run at prescribed target speeds is available on BR in young athletes. Therefore, the primary purpose of this study was to determine the ability of youth athletes to run at prescribed target speeds during short overground efforts. An additional aim of this research was to establish and compare velocities associated with FR and BR at different prescribed intensities.

3.2 Methods

3.2.1 Participants

Thirty-four youth male athletes agreed to participate in this study. All participants were physically active and involved in summer sport(s) during the study duration, which generally consisted of two trainings and one competition game in a typical week. Maturity status was assessed using a non-invasive measuring technique recorded as age from peak height velocity (PHV), as predicted from anthropometric measures (163). The athletes were a mean age of 16.4 ± 0.9 years, with stature of 1.80 ± 0.05 m, body mass of 80.6 ± 12.6 kg and maturation of 2.8 ± 1.0 years from PHV. All parents/guardians provided written consent and assent from the participants were obtained prior to testing. The protocol was reviewed and approved by the Institutional Ethics Committee.

3.2.2 Measures

Running velocities associated with auto-regulated slow (i.e. 40-55% of maximal sprint performance), moderate (i.e. 60-75% of maximal sprint performance) and fast intensities (i.e. +90% of maximal sprint performance) served as the dependent variables. Double beam electronic photocell timing gates (Swift Performance Equipment, Australia), linked to an electronic timer, were used to determine sprint times of the running trials under each condition. Running times were then used to calculate average velocities between 0 –10 m and 0 –20 m splits for all running trials.

3.2.3 Design and Procedures

Testing was conducted on an outdoor turf field where weather conditions were consistently dry and runs were completed perpendicular to wind to ensure no tail or headwind. Wearing the same clothing and footwear, athletes were required to attend three consecutive testing sessions, seven days apart, at the same time of the day and under the same testing procedures. All participants attended a practice session prior to the first testing trial where they were familiarised with running at different target speeds via verbal feedback on their running times. Target speeds at slow, moderate and fast intensities were chosen to reflect running efforts at approximately half, three-quarters and near maximal speed (190). During each testing session, athletes completed 3 x 20 m repetitions at each intensity in both running directions (i.e. 18 x 20 m total runs). Running trials were randomised in the first experimental session and athletes were tested in the exact same order on all other occasions. To minimise potential fatigue there was at least two minutes of passive rest between 20 m runs. A standardised warm-up was conducted before the familiarisation and testing sessions. The warm-up consisted of progressively increased running intensities up to 90% of perceived maximal effort both forward and backward over 20 m, interspersed with dynamic stretching of the lower limbs.

Athletes started in a split stance with their leading foot on a tape 0.3 m behind the first gate and were prompted to run through the timing lights which were placed at the start, 10 m and 20 m marks. Timing gates were set at a height of 92.5 cm (top beam) and 68 cm (bottom beam) which corresponded closely with the approximate height of the athletes' centre of mass. A 20 m trial was chosen to reflect common distances covered during warm-ups (220), as well as typical sprint and BR distances as reported from match performance analysis (198). This research used a similar approach to Gabbett (70) who found youth produced reliable maximal FR efforts over 10 m and 20 m (ICC = 0.88 and 0.89, respectively). The averaged running velocities from 0 - 10 m and 0 - 20 m for each running intensity was used to assess absolute and relative consistency of FR and BR. The corresponding running intensities for FR and BR trials were compared to assess the relationship between intensities for each running direction.

3.2.4 Statistical Analysis

Assumptions of normality and descriptive variables were quantified using IBM SPSS statistics (V.23.0). Data is presented as means with 95% confidence limits (CL). Pairwise analysis of reliability was investigated using averaged data over the three running trials between the first and second testing sessions and between the second and third testing sessions for each dependent variable. To determine whether velocities differed between days, a one-way analysis of variance using repeated measures was conducted for each relative running condition. A Bonferroni pairwise comparison was used to determine whether differences occurred between the testing sessions one to two and two to three. Absolute consistency of BR and FR at slow, moderate and fast intensities was assessed while calculating both the percent change in mean and coefficient of variation (CV) with a specifically designed spreadsheet (104). Test-retest correlations were expressed as intraclass correlation coefficients (ICC's, absolute agreement) using a two-way random model and average measures (116). Typical error as a percentage was considered acceptable with CVs $\leq$ 10% (127). ICC classification was considered as follows: 'very poor' (< 0.20) 'poor' (0.20 - 0.49), 'moderate (0.50 – 0.74), 'good' (0.75 – 0.90) or 'excellent' (> 0.90) (25). Running velocities were compared between relative FR and BR intensities and distances using paired samples t-tests. To counteract the problem of multiple comparisons and the chance of a false positive, significance was accepted at the $p \leq 0.01$ level.

3.3 Results

For FR and BR at all speeds the change in the mean between pairwise trials revealed systematic bias between trials 1 - 2 but not between trials 2 - 3 (see Table 3.1). Between trials 1 - 2 mean change in velocity ranged from -6.15% to 5.59% and between trials 2 - 3 the change in mean velocity was between ± 2.18% for all conditions. For all target speeds and running conditions, the change in the mean was smaller in trials 2 - 3 compared to trials 1 - 2.

In terms of absolute consistency, CVs ranged from 1 to 12 %, with only slow forward running over 10 and 20 m > 10%. As can be observed from Table 3.1, greater variability was associated between Trials 1-2 (average CV across all measures = 6.92%) as compared to Trials 2-3 (average CV across all measures = 2.87%). It appears that variability decreased with increasing velocity for both forward and backward running. In terms of absolute agreement, ICCs ranged from 0.45 to 0.99. Lower absolute agreement was associated with Trials 1-2 (average ICC across all measures = 0.67) as compared to Trials 2-3 (average ICC across all measures = 0.93). In nearly all instances the magnitude of the improvement between consecutive pairs of trials for both the CV and ICC meant the confidence intervals from comparing trials 1 - 2 and 2 - 3 did not overlap. Both CV's and ICC's were comparable between FR and BR at all relative speeds and CV's were lower at faster speeds for both running directions.

Velocities for FR and BR showed similar trends of decreasing speed from the first to the second testing session at the slow pace (-4.86% and -3.98%) and increasing speed at moderate (4.72% and 5.43%) and fast intensities (0.77% and 2.26%), respectively. Averaged running velocity of participants over 0 – 10 m and 0 – 20 m are presented in Figure 3.1 and Figure 3.2, respectively. Significantly faster velocities were observed during FR at slow (26%), moderate (28%) and fast (26%) intensities compared to BR.

Table 3.1. Auto-regulated forward and backward running velocities over 10 m and 20 m and associated consistency data for slow, moderate, and fast intensities.

Variable	Day 1 (μ ± sd)	Day 2 (μ ± sd)	Day 3 (μ ± sd)	% Change in mean Day 1-2 (95% CL)	% Change in mean Day 2-3 (95% CL)	CV Day 1-2 (95% CL)	CV Day 2-3 (95% CL)	ICC Day 1-2 (95% CL)	ICC Day 2-3 (95% CL)
10 metres									
Slow forward ($m \cdot s^{-1}$)	2.70 ± 0.41	2.53 ± 0.41	2.54 ± 0.31	-6.15 (-11.3 to -0.75)	0.65 (-1.43 to 2.78)	12.0 (9.58 to 16.09)	4.33 (3.48 to 5.47)	0.45 (0.14 to 0.68)	0.93 (0.82 to 0.95)
Slow backward ($m \cdot s^{-1}$)	1.96 ± 0.33	1.87 ± 0.30	1.89 ± 0.29	-3.98 (-7.88 to 0.08)	1.07 (2.96 to 1.87)	8.75 (7.00 to 11.68)	3.82 (3.07 to 5.06)	0.75 (0.56 to 0.87)	0.94 (0.88 to 0.97)
Moderate forward ($m \cdot s^{-1}$)	3.70 ± 0.49	3.84 ± 0.36	3.80 ± 0.39	4.40 (0.41 to 8.54)	-1.25 (-3.04 to 0.57)	8.21 (6.57 to 10.94)	3.78 (3.06 to 5.00)	0.56 (0.28 to 0.75)	0.87 (0.76 to 0.93)
Moderate backward ($m \cdot s^{-1}$)	2.67 ± 0.32	2.81 ± 0.33	2.75 ± 0.30	5.27✧ (1.74 to 8.93)	-1.25* (-3.44 to -0.33)	7.16 (5.74 to 9.53)	3.26 (2.62 to 4.32)	0.67 (0.43 to 0.82)	0.92 (0.85 to 0.96)
Fast forward ($m \cdot s^{-1}$)	5.38 ± 0.28	5.45 ± 0.22	5.45 ± 0.20	1.49 (-0.23 to 3.24)	-0.13 (-0.74 to 0.50)	3.52 (2.83 to 4.66)	1.24 (1.00 to 1.64)	0.48 (0.18 to 0.70)	0.90 (0.81 to 0.95)
Fast backward ($m \cdot s^{-1}$)	4.02 ± 0.32	4.11 ± 0.28	4.13 ± 0.27	2.36✧ (0.95 to 3.78)	0.34 (-0.36 to 1.04)	2.85 (2.29 to 3.76)	1.42 (1.14 to 1.87)	0.87 (0.75 to 0.93)	0.96 (0.92 to 0.98)
20 metres									
Slow forward ($m \cdot s^{-1}$)	2.73 ± 0.41	2.62 ± 0.40	2.60 ± 0.31	-3.57 (-8.39 to 1.51)	-0.75 (-2.76 to 1.3)	10.95 (8.74 to 14.66)	4.24 (3.40 to 5.61)	0.52 (0.23 to 0.73)	0.91 (0.82 to 0.95)
Slow backward ($m \cdot s^{-1}$)	1.99 ± 0.35	1.94 ± 0.22	1.94 ± 0.25	-2.06 (-6.12 to 2.16)	0.20 (-1.54 to 1.98)	8.92 (7.14 to 11.91)	3.63 (2.92 to 4.81)	0.70 (0.48 to 0.84)	0.92 (0.85 to 0.96)
Moderate forward ($m \cdot s^{-1}$)	3.94 ± 0.57	4.12 ± 0.43	4.04 ± 0.47	5.05 (0.96 to 9.30)	-2.18 (-4.03 to -0.30)	8.38 (6.70 to 11.17)	3.63 (3.17 to 5.23)	0.63 (0.37 to 0.80)	0.89 (0.79 to 0.94)
Moderate backward ($m \cdot s^{-1}$)	2.83 ± 0.38	2.98 ± 0.37	2.92 ± 0.36	5.59✧ (2.06 to 9.24)	-2.18✧ (-3.64 to -0.70)	7.14 (5.72 to 9.50)	3.09 (2.49 to 4.09)	0.72 (0.51 to 0.85)	0.94 (0.89 to 0.97)
Fast forward ($m \cdot s^{-1}$)	6.23 ± 0.33	6.26 ± 0.28	6.26 ± 0.27	0.57 (-0.64 to 1.79)	-0.05 (-0.54 to 0.44)	2.48 (1.99 to 3.27)	1.00 (0.81 to 1.32)	0.76 (0.57 to 0.87)	0.95 (0.91 to 0.98)
Fast backward ($m \cdot s^{-1}$)	4.55 ± 0.40	4.64 ± 0.36	4.65 ± 0.35	2.16✧ (0.85 to 3.49)	0.15 (-0.32 to 0.64)	2.66 (2.14 to 3.51)	0.99 (0.80 to 1.30)	0.91 (0.82 to 0.95)	0.99 (0.97 to 0.99)

* Significant ($p \leq 0.05$), ✧ significant ($p \leq 0.01$) and † significant ($p \leq 0.001$) for between-day performances.

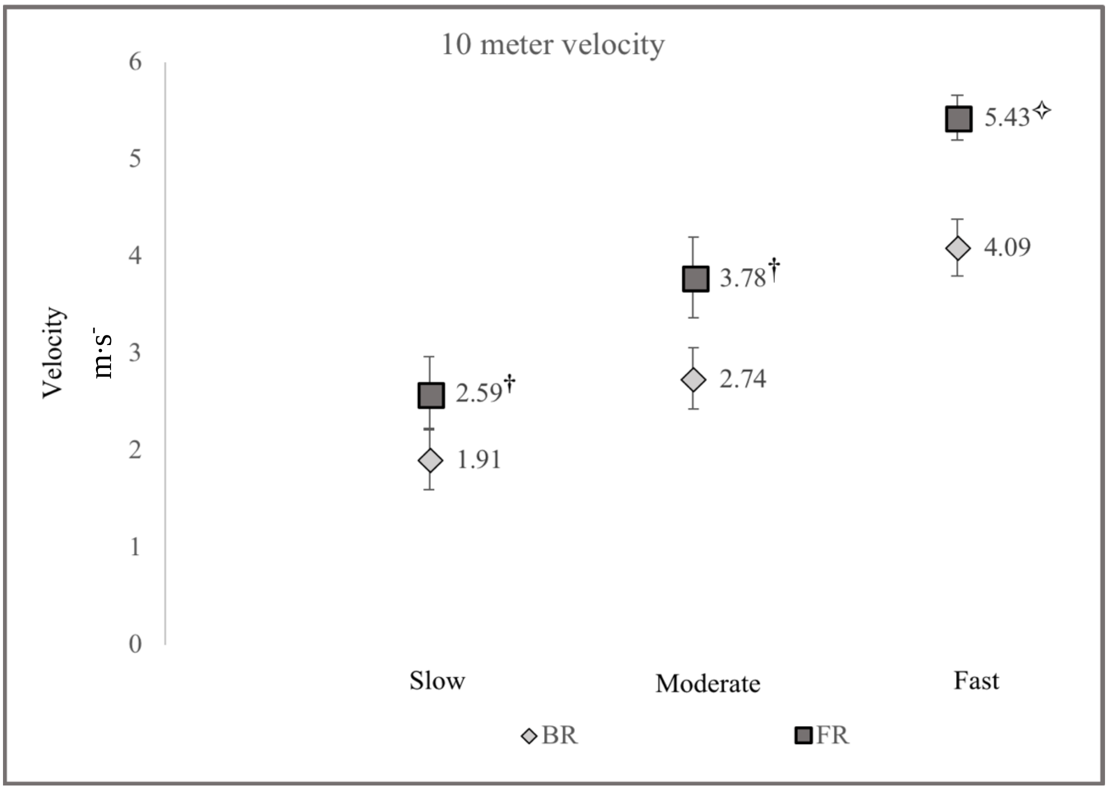

Figure 3.1. Comparison of averaged 10 m FR and BR velocities for athletes running at slow, moderate and fast intensities.
✧ = FR velocity significantly faster than BR velocity ($p \leq 0.01$)
† = FR velocity significantly faster than BR velocity ($p \leq 0.001$)

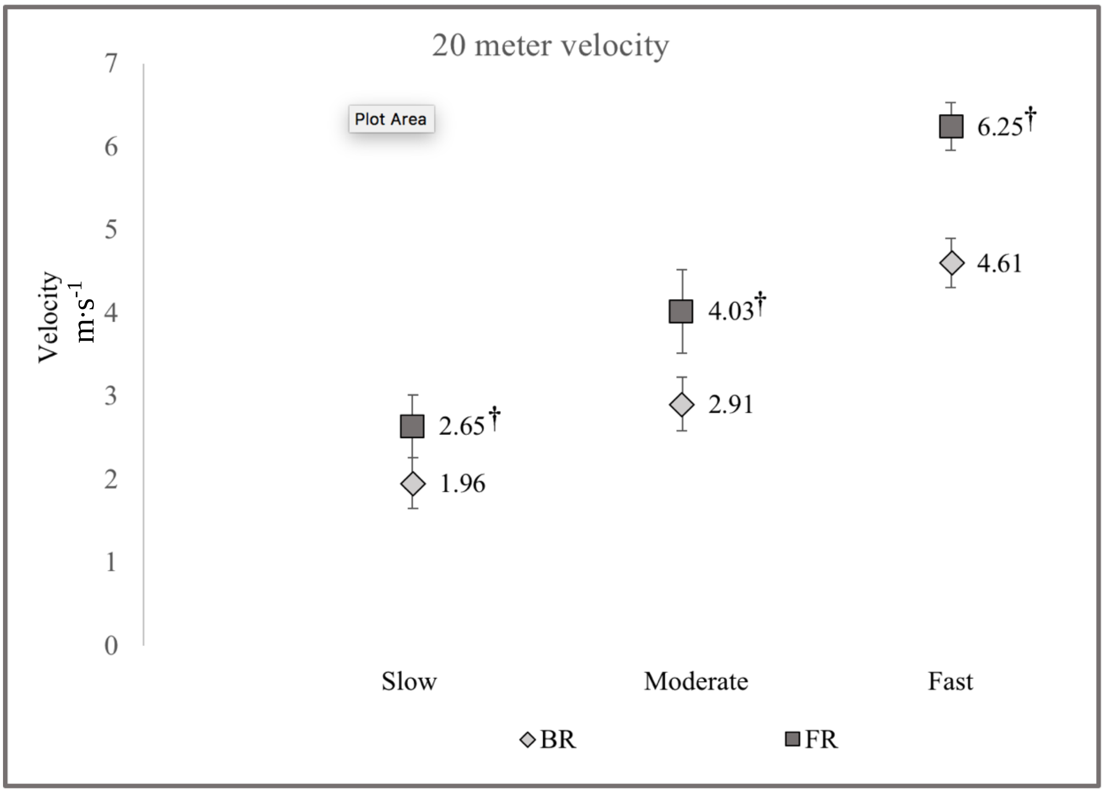

Figure 3.2. Comparison of averaged 20 m FR and BR velocities for athletes running at slow, moderate and fast intensities.
† = FR velocity significantly faster than BR velocity ($p \leq 0.001$)

3.4 Discussion

The ability to autoregulate running speed is important in terms of preparing the body for sports (i.e. warm-up and training) to induce specific physiological and mechanical adaptations. The present study sought to quantify the ability of adolescent athletes to consistently achieve targeted speeds using autoregulation during FR and BR. The main findings of this study were: 1) Change in the mean, CVs and ICCs indicate that there was a systematic change between the first two trials, with better consistency in results in the latter trials, indicating a familiarisation/learning effect; 2) that athletes can autoregulate forward and backward running velocity consistently with adequate familiarisation i.e. Trials 2 - 3 – change in the mean < 2.2%; CV < 5%; ICC > 0.87; 3) greater absolute consistency and agreement was associated with greater velocity; 4) averaged FR velocity was approximately 27% greater than BR across all prescribed target intensities, however, consistency and agreement of performance within the relative speed zones (slow, moderate, fast) was similar.

Improvements in the CV and ICC between trials 2 – 3 compared to trials 1 - 2 suggest that either a continued familiarisation, or a learning effect, was present for both FR and BR across all intensities in trial 1, but learning or familiarisations seized to continue in trials 2 and 3. The performance deviations reported in the present study are likely attributed to biological variations of the athletes since typical error associated with timing lights has been shown to be minimal (44). The time around PHV has been associated with temporary disruption in coordination (196) and youth performances have been shown to fluctuate on some athletic tasks, such as a countermovement jump (75).

Despite the presence of systematic bias between testing occassions, the present research demonstrated that with ample familiarisation, youth athletes can consistently attain prescribed submaximal and maximal target speeds during FR and BR using autoregulation. This is important as coaches who prescribe target running intensities or use target speeds as a testing method must be confident that their exercises are training or measuring the appropriate athletic qualities (101, 123). Given the presence of a potential learning effect, youth athletes may require multiple familiarisation sessions to become accustom to attaining consistent target running intensities via autoregulation. However, with an absence of literature on this topic, additional research is necessary to support this posit.

Interestingly, as velocity increased, so did consistency of auto-regulated performances. Running at the fastest velocities were associated with the lowest error between days compared to slow and moderate efforts. Reliability statistics at the fastest intensities agree with previous findings that youth athletes can reproduce FR sprinting performances (70, 182). The findings suggest that both maximal effort FR and BR may be used as performance assessment tools. While the present research provides promising information around the ability of youth to use autoregulation to attain target speeds and potential utilities around the findings, direct comparisons to previous findings are difficult due to a scarcity of published literature related to the consistency of running direction and/or intensity using autoregulation in youth populations.

Averaged FR velocity was approximately 27% greater than BR across all prescribed target intensities, however, consistency of selecting velocity within the relative speed zones (slow, moderate, fast) was similar. These velocity differences are in line with previous findings which demonstrated that submaximal and maximal running velocities during BR are, on average, 70% of FR velocity in adults (9). Differences in velocity may be expected between the two running directions as the human body has evolved to run forwards and the lower limb joints are mechanically constrained by skeletal and soft tissue (142). While BR appears to be less efficient at utilising eccentric energy during the stretch-shorten cycle (29), this does not explain the similar consistencies achieved between the two running directions. As both running directions corrected velocity at the slowest intensity by becoming slower and moderate and fast velocities became faster between trials 1 – 2, how the inconsistencies in movement were resolved appears dependent on the speed of movement, rather than the running direction. According to motor programming theories and posits by some researchers, each direction of movement is modulated by the same spinal neural network and modifications in one direction of locomotion may transfer to the other (148). Theories of control models may help explain the current findings, yet current models are incomplete and contention exists around how each direction of running is accomplished (100).

Auto-regulating running velocity appears to be an important method for achieving target running intensities in athletic populations (2). Understanding the consistency of performances between trials is essential for guiding exercise prescription and testing protocols. The present study identified that youth athletes can use autoregulation strategies to self-select a range of FR and BR speeds similarly in the absence of external cues. While the current study is limited to male athletes primarily post-PHV, it provides a focused understanding of gender- and maturity-specific performance for FR and BR at speeds used by practitioners and clinicians to prepare athletes for competition and progress back into their sport following injury. Knowing that greater differences in performance are experienced by less mature children when exposed to new stimuli compared to their more mature counterparts (e.g. adding resistance to FR) (205), scientists and practitioners would benefit from future investigations into the underlying mechanisms responsible for promoting motor control and the relationship between maturation and novel performance tasks in youth athletes.

3.5 Conclusion

This is the first study to investigate the ability of youth athletes to use autoregulation as a means to self-select running velocity based on prescribed target running intensities. Running at target intensities is an exercise method which can be used to enhance athletic performance or progress injured athletes back into their sport. Therefore, practitioners must be confident that athletes are capable of selecting the desired running intensities in the absence of external sensory feedback. The present research demonstrated that youth athletes are able to employ auto-regulated strategies to consistently attain prescribed target running intensities both forward and backward following ample familiarisation. The findings of this reasearch can be used to improve training or rehabilitation strategies, enhance adaptations and confidently track running performances at target intensities based on the needs of the athlete or demands of the sport. We suggest that the athlete's familiarity with using autoregulation to self-select running velocities be taken into account when prescribing target running intensities for high-school aged athletes.

CHAPTER 4. LOAD-VELOCITY RELATIONSHIPS DURING RESISTED FORWARD AND BACKWARD RUNNING IN HIGH-SCHOOL ATHLETES

4.0 Prelude

The main finding from Chapter 3 was that a common specific sprint prescription tool (i.e. running intensity) can consistently be used as a method to overload FR and BR for male high-school athletes. Another common training method for overloading specific sprint training is load in the form of resisted sled towing. Determining the load-velocity relationships during resisted sprinting (RS) can be used to assist load prescription. For example, determining decreases in velocity associated with loads can be used to establish optimal loading strategies based on the desired training responses. A scarcity of research is available detailing the load-velocity relationships during forward RS (FRS) in youth athletes, and no formal studies exist detailing the load-velocity relationship during backward RS (BRS). Further, it is unknown whether the load-velocity slopes, or running speeds, are consistent during FRS or BRS. Therefore, the purpose of this chapter was to explore the load-velocity relationships during FRS and BRS and determine the consistency of running performances. Findings from this study will help provide practitioners with guidance on how to determine loads for FRS and BRS and progressively overload this specific sprint training modality for high-school athletes.

This chapter comprises the following paper:

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C. (under review). Load-velocity relationships during resisted forward and backward running in high-school athletes. *Science and Sport.*

4.1 Introduction

Resisted sprinting (RS) towing weighted sleds has been used as a specific method to enhance sprinting ability in youth (205). To date, all RS studies in youth have been completed while running forwards (20, 204, 215). Interestingly, backward running (BR) has also been a locomotive strategy used to enhance athletic performance (235) due to its unique training stimulus compared to forward running (FR), yet the acute effects of loading this running direction is unknown in all populations including adolescents.

To determine optimal loading strategies, load-velocity profiles during RS have been used to assess percentage decreases in velocity (% V_{dec}) attributed to loads as a percentage of body mass (% body mass [BM]) compared to unresisted sprinting (46). In the only study detailing the load-velocity relationship during RS in youth, Rumpf et al. (205) concluded that for every 2.5% increase in BM when using loads up to 10% BM, RS times decreased by 2.4% in adolescent males. The ability to predict the percentage decrease in velocity associated with loads as a percentage of body mass is useful for determining optimal loads based on the desired training goals. However, there have been no formal studies, either to establish the load-velocity relationship during RS forwards (FRS) or backwards (BRS), nor the consistency of these RS conditions in boys. Therefore, the aims of this study were to quantify the load-velocity relationship during FRS and BRS and determine the consistency of this load-velocity data across multiple testing occasions in youth athletes.

4.2 Methods

4.2.1 Participants

Twenty-one male athletes (age, 13.6 ± 0.28 y; height, 1.7 ± 0.09 m; mass, 66.1 ± 8.2 kg; maturity, 0.57 ± 0.72 y from peak height velocity) agreed to participate in this study. Maturity status was assessed using an anthropometric measuring technique recorded as age from peak height velocity (PHV) (163). All guardians provided written consent and the participants provided assent prior to testing. The research protocol was approved by an Institutional Ethics Committee.

4.2.2 Study design

Participants attended a familiarisation session to determine their 20 m unresisted forward and backward sprinting performance. Thereafter, each athlete attended three testing sessions seven days apart in standardised conditions (i.e. time of day, running order, athletic clothing, starting position and testing environment). Following a warm-up consisting of progressively increased running efforts forward and backward, interspersed with dynamic stretching of the lower limbs, the athletes performed 12 x 20 m randomised FRS and BRS on an indoor wooden court. Athletes towed weighted sleds attached via a waist harness ranging from 25-76% BM (20, 30 and 40 kg) forwards and backwards twice on each testing occasion. Speed was calculated from sprint times measured via timing gates (Swift Performance Equipment, Australia), with athletes starting 0.3 m behind the first gate. Each participant was encouraged to run with maximal effort past a cone set 3 m after the last gate. Rest intervals between runs were ~180 seconds.

4.2.3 Statistical analysis

The data were analysed using Microsoft Excel (version 16.13; Microsoft, Seattle, WA, USA) and SPSS 24.0 for MAC OS (SPSS, Inc, Chicago, IL, USA). Data were presented as mean values and standard deviations. For each running condition, averaged performance data from each testing session was used for analysis. Trend lines and regression equations were fitted to the load-velocity relationship between sled loads for FRS and BRS, where loads represented percentage of BM, and velocity decrease, as a percentage of velocity decrease from unresisted 20 m sprinting performance. Coefficients of determination were used to show the goodness of fit for the load-velocity data along the trend line. The consistency of this load-velocity relationship across multiple testing occasions was quantified via three statistics; mean % change, coefficient of variation (CV) and intraclass correlational coefficients (ICC) for both FRS and BRS. Absolute consistency was considered acceptable with CV < 10% and the qualitative inferences for relative (ICC) consistency were 'poor' (< 0.50), 'moderate' (0.50 – 0.74), 'good' (0.75 – 0.90) or 'excellent' (> 0.90). Alpha was set at $p \leq 0.05$ and 95% confidence intervals were used.

4.3 Results

4.3.1 Load-Velocity Relationship

Mean load-velocity data, regression lines and equations are shown in Figure 4.1. Analysis of the trend lines for the plotted load-velocity relationships showed that loads of 31%, 46% and 61% BM resulted in 23%, 33% and 43% velocity decrease during FRS and 27%, 38% and 48% during BRS. These were found from the slope equations for FRS ($y = 1.43x - 0.60$) and BRS ($y = 1.25x - 1.14$). Additionally, load-velocity regression slopes were found to be linear but diverging for both RS directions.

4.3.2 Consistency

No systematic differences in FRS or BRS velocity were observed between consecutive days for any RS load, as can be observed in all changes in the mean falling below 3.1%. For all days and loads, CV's ranged from 2.3 - 4.7% during FRS and 3.8 - 7.2% for BRS. Across days and loads, relative consistency during FRS was moderate to excellent (ICC = 0.66 - 0.91) and moderate to good (ICC = 0.67 - 0.89) for BRS. Additionally, consistency of the load-velocity regression slope between consecutive days was found to be good during FRS (CV ≤ 7.2%, ICC ≥ 0.85) and good to excellent during BRS (CV ≤ 7.5%, ICC ≥ 0.83 - 0.91).

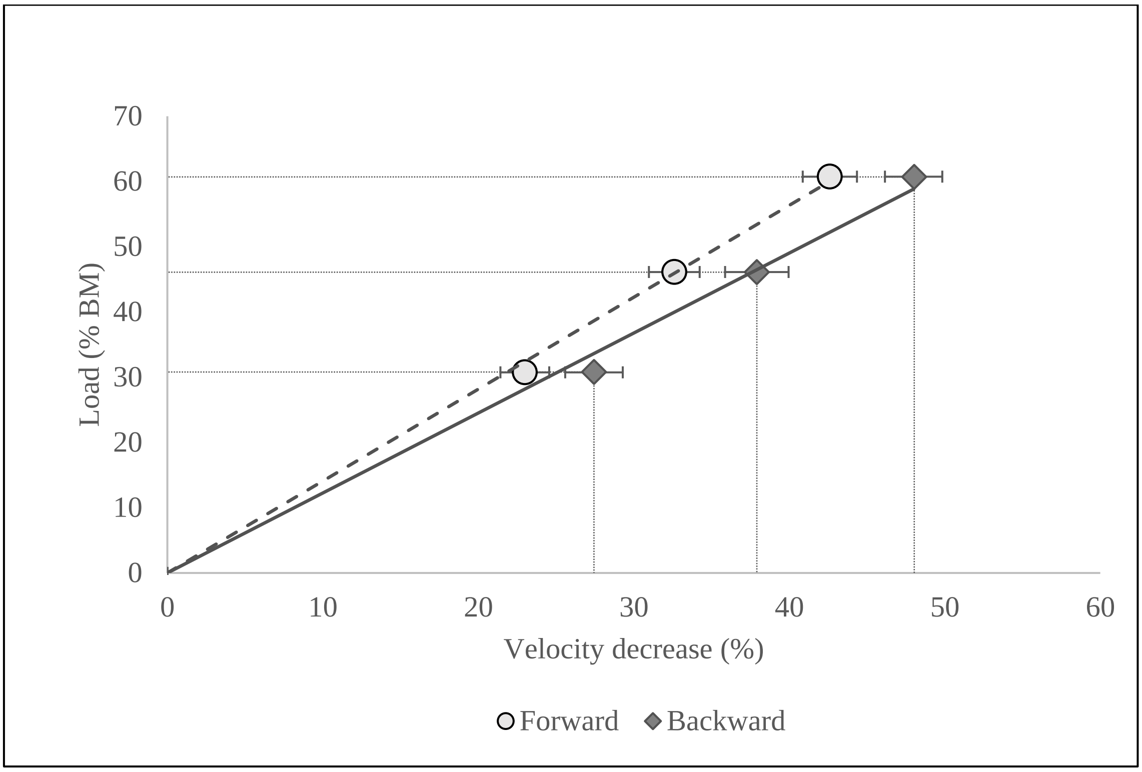

Figure 4.1. Load-velocity relationship of FRS and BRS.
FRS = forward resisted sprinting; BRS = backward resisted sprinting; BM = body mass

Table 4.1. Descriptive and consistency data during FRS and BRS.

Condition	Velocity Week 1 (mean ± SD)	Velocity Week 2 (mean ± SD)	Velocity Week 3 (mean ± SD)	% Change in mean Day 1-2 (95% CI)	% Change in mean Day 2-3 (95% CI)	CV Day 1-2 (95% CI)	CV Day 2-3 (95% CI)	ICC Day 1-2 (95% CI)	ICC Day 2-3 (95% CI)
20 kg FRS ($m \cdot s^{-1}$)	4.6 ± 0.34	4.5 ± 0.33	4.6 ± 0.27	-0.66 (-2.7 to 1.3)	0.70 (-0.66 to 2.1)	3.4 (2.6 – 4.9)	2.3 (1.7 to 3.3)	0.81 (0.57 to 0.92)	0.91 (0.78 to 0.96)
20 kg BRS ($m \cdot s^{-1}$)	3.1 ± 0.28	3.1 ± 0.25	3.2 ± 0.23	0.49 (-1.8 to 2.8)	2.4 (0.19 to 4.7)	4.0 (3.0 to 5.8)	3.8 (2.9 to 5.5)	0.81 (0.58 to 0.92)	0.77 (0.52 to 0.90)
30 kg FRS ($m \cdot s^{-1}$)	4.0 ± 0.38	4.0 ± 0.37	4.0 ± 0.24	-0.43 (-2.7 to 1.9)	-0.31 (-2.4 to 3.0)	3.9 (3.0 to 5.7)	4.7 (3.6 to 6.8)	0.84 (0.64 to 0.93)	0.66 (0.34 to 0.85)
30 kg BRS ($m \cdot s^{-1}$)	2.6 ± 0.32	2.7 ± 0.28	2.8 ± 0.21	3.95 (0.60 to 7.3)	0.20 (-3.5 to 3.9)	3.9 (3.0 to 5.7)	4.2 (3.2 to 6.2)	0.89 (0.75 to 0.95)	0.80 (0.57 to 0.91)
40 kg FRS ($m \cdot s^{-1}$)	3.4 ± 0.46	3.5 ± 0.37	3.5 ± 0.29	2.55 (-0.05 to 5.1)	-0.52 (-2.5 to 1.4)	4.6 (3.5 to 6.7)	3.3 (2.5 to 4.8)	0.87 (0.70 to 0.94)	0.89 (0.75 to 0.95)
40 kg BRS ($m \cdot s^{-1}$)	2.2 ± 0.29	2.3 ± 0.25	2.3 ± 0.19	3.1 (-1.0 to 7.2)	0.22 (-2.5 to 3.0)	7.1 (5.4 to 10.5)	4.7 (3.6 to 6.8)	0.67 (0.34 to 0.85)	0.79 (0.55 to 0.91)

FRS = forward resisted sprinting; BRS = backward resisted sprinting; SD = standard deviation; CI = confidence intervals.

4.4 Discussion

This study aimed to establish the load-velocity relationships during FRS and BRS and examine the consistency of running speeds and associated load-velocity regression slopes between sessions. The goodness of fit of load-velocity data along the trend lines were perfect ($r^2 = 1.00$) and nearly perfect ($r^2 = 0.99$) for FRS and BRS, respectively. Linear, yet divergent regression slopes were found for FRS and BRS. For each increase of ~15% BM (FRS) and ~13% BM (BRS), ~10% velocity decreases were observed. Previously, researchers have shown that boys mid-the PHV required 10% BM loading to decrease FR speed by 10% (205), however, those authors only used minimal resistance with the heaviest load being 10% BM. While individual force-velocity capabilities and maturation may impact the load-velocity relationship (46, 205), this research provides insights into the effect of loads on running velocity during a commonly used, and novel, sprint training method in youth around the time of peak height velocity.

The ability to consistently predict the percentage of BM load required for a given percentage decrease in velocity can be of great importance for practitioners interested in prescribing FRS or BRS for youth athletes. Running velocities and load-velocity regression slopes of both FRS and BRS were found to have moderate to excellent consistency (CV = 2.3 to 7.5; ICC = 0.67 to 0.91) for both RS directions across multiple testing occasions.

4.5 Conclusion

Backward running has been showed to offer a unique training stimulus compared to FR. Accordingly, it was important to determine how each form of running respond to resisted overload. The present study determined that the BRS load-velocity relationship was linear, but divergent to the FRS load-velocity relationship, indicating that running direction influences the magnitude of load needed for the same relative velocity decrease. Whether this finding affects adaptation is unclear and, therefore, requires future research. Practitioners can be confident in the consistency of load-velocity data in monitoring the force(load)-velocity capability of athletes in both running directions. Furthermore, such data allows better diagnostics to enable more targeted RS training e.g. athletes that need a speed-strength stimulus vs a strength-speed stimulus.

CHAPTER 5. SPRINT-SPECIFIC TRAINING IN YOUTH: BACKWARD VS. FORWARD RUNNING ON SPEED, JUMPING, AND STIFFNESS PERFORMANCE IN ADOLESCENT MALE ATHLETES

5.0 Prelude

In Chapter 3, the ability of athletes to achieve target speeds based on prescribed running intensities was established. The findings in Chapter 3 provide prescribed running intensities which may be used as a method to overload unresisted BR and FR for training purposes. The principle of specificity states that exercises that closely mimic athletic actions will have high transfer to performance. Interestingly, no research has investigated whether specific sprint training transfers to other athletic measures in youth athletes, such as jumping or leg compliance. Furthermore, it is unknown whether BR training leads to positive adaptations to FR sprinting performance in adolescent athletes. Therefore, the purpose of this chapter was to investigate and compare the effects of unresisted BR and FR training programmes on speed, jumping, and stiffness performance in high-school athletes. The findings of this study will inform strength and conditioning coaches of whether adaptations resulting from unresisted BR and FR training can transfer to specific and nonspecific athletic tasks.

This chapter comprises the following published paper:

Uthoff, A., Oliver, J., Cronin, J., Harrison, C., Winwood, P. (2018). Sprint-specific training in youth: backward running vs. forward running training on speed and power measures in adolescent male athletes. *Journal of Strength and Conditioning Research,* Published Ahead of Print. doi: 10.1519/JSC.00000000000002914.

5.1 Introduction

Sprint performance over short distances has been identified as a key characteristic of successful young athletes around the time of their adolescent growth spurt (132). Boys commonly experience their adolescent development between 12 and 16 years of age (16). Given the importance of sprint ability in sport and suggestion that speed development can be optimised during adolescence (125), it is no surprise that a myriad of specific and nonspecific training methods have been developed to enhance neural and structural characteristics associated with sprint performance in adolescents (60, 128). Sprint-specific training refers to free sprinting (i.e., straight line sprinting with passive recovery), resisted sprinting, or assisted sprinting, whereas nonspecific sprint training corresponds to other methods, such as strength, power, or plyometric training (209, 210). An abundance of research is available highlighting the benefits of nonspecific training methods on sprint performance and underlying determinants of speed, such as lower-body power and stiffness (15, 126, 170); yet, the optimal development of speed and power measures in adolescent male athletes using sprint-specific training methods requires further understanding.

Researchers have reviewed the effectiveness of sprint- specific training on boys' sprinting ability, concluding that free sprinting is a beneficial method for enhancing short-sprint speed up to 20 m with moderate to large effect (168, 209). From these two reviews, a total of six studies were identified, which measured the effects of straight-line free sprint training on running performance. Although the current re- views provide a comprehensive overview of the available scientific literature, the effects of anecdotal training methods yet to be empirically scrutinised remain unknown. For example, backward running (BR) has been used as part of specific training procedures in a variety of athletic sports (100, 235). However, to the authors' knowledge, the effects of BR on forward sprint performance in adolescent athletes are absent from literature.

Like forward running (FR), BR occurs in bursts during many overground sports (e.g., soccer, rugby, American football, and most racquet sports) (164). A recent review of BR by Uthoff et al. (235) highlights the immediate and long- term effects of BR on athletic performance. Sports warm-up programmes such as the "FIFA 11+,""Harmoknee," and "Prevent Injury and Enhance Performance" include BR to prepare adolescent athletes for the demands of competition, reduce injury rates (185, 220), and enhance performance (13, 178). The use of BR has been recommended in adult sports training programmes because of its ability to improve power output (231) while concomitantly reducing stress on the knee joint (201) compared with FR. Furthermore, it has been theorised that training adaptations from BR may transfer to FR tasks (100, 148). Evidence for this effect has been reported in adult populations (227, 230). For example, BR training (BRT) has been shown to improve change of direction performance (227, 230), increase foot speed in a ladder test (230), and maintain 20 m sprint performance times (230). Although previous findings are promising in adults, it is unknown how these types of training adaptations might transfer to adolescent athletes. Given that BR seems to be a method that promotes injury prevention, increased power output, and performance transfers to FR tasks, the lack of research attempting to quantify the effects of BR on these outcomes in adolescent athletes is surprising.

Most research into the trainability of speed and power in adolescent athletes has explored the effectiveness of nonspecific sprint training methods. Methods such as strength training and plyometric training have been shown to enhance speed and lower-body power and force characteristics (15, 126). Similarly, sprint-specific training methods are known to improve sprinting performances in adolescents (168, 209). Although, relatively few studies are available on the trainability of speed in young athletes using free FR training (FRT) or the effects of this type of training on lower-body power and force measures in paediatric populations. Furthermore, it is unknown whether BRT influences performance outcomes and whether these adaptations transfer to forward sprint ability in adolescent athletes. Therefore, the primary aim of the current research was to explore the effects of free BRT and FRT Programmes and quantify the potential training-related adaptations these methods promote on sprinting performance and underlying determinants of speed, such as leg stiffness and lower-body power in adolescent male athletes.

5.2 Methods

5.2.1 Experimental Approach to the Problem

A cluster randomised control trial was conducted to quantify the effects of 8 weeks of biweekly progressive running training, either forward or backward. To determine the effectiveness of the sprint-specific training Programmes on speed and power measures, sprinting ability, jumping performance, and vertical leg stiffness were tested before and after training. Boys enrolled in an athletic development programme at their school were divided into a BRT group (n = 26) and an FRT group (n = 17). A control (CON) group (n = 24) of the same age and physical characteristics was recruited from the school to assess the effects of natural growth on the selected performance measures. The CON group participated in their school's normal physical education (PE) curriculum, but not any structured training programme. Habituation sessions for the performance tests occurred in week one, baseline testing was administered in week two, supervised training was performed for the following eight weeks, and finally post-testing was concluded in week 11. Quantitative analyses were conducted to test scores from pre-training to post-training, while qualitative meaning of any observed changes in the independent variables were examined using inferential statistics.

5.2.2 Subjects

A group of 67 adolescent male athletes (aged 13-15 years) from a boys' high-school volunteered to participate in this study. Forty-three subjects were recruited from their school's athlete development programme and randomly assigned to either a BRT group (n = 26) or an FRT group (n = 17). The remaining subjects were recruited from a PE class, where they participated in their school's normal PE curriculum, serving as a control (CON; n = 24) to compare the training effects on the performance measures to those of normal maturation. The athlete development programme at the school was an option for students who wished to participate in organised training in place of their normal P.E class. Non-invasive anthropometric measurements were used to calculate maturity offset using an equation developed by Mirwald et al. (163). There were no significant differences between groups for physical characteristics or maturity offset. Table 5.1 outlines a summary of the subject's characteristics.

Table 5.1. Subject characteristics (mean ± SD).

Parameters	All Subjects (n = 67)	CON Group (n = 24)	BRT Group (n = 26)	FRT Group (n = 17)
Age (y)	14.61 ± 0.31	14.60 ± 0.31	14.59 ± 0.29	14.63 ± 0.35
Height (cm)	171.95 ± 9.68	170.10 ± 11.84	174.96 ± 8.27	169.96 ± 7.34
Body mass (kg)	62.24 ± 13.08	59.73 ± 13.65	64.84 ± 13.96	61.68 ± 10.66
Peak Height Velocity (y)	1.08 ± 0.76	1.02 ± 0.09	1.17 ± 0.67	1.05 ± 0.67

CON = control; BRT = backward running training; FRT = forward running training.

Subjects were included in this study if they were males between the ages of 13 and 15 years, enrolled in a public high-school, and free of any medical issues or injuries that may have compromised their participation or performance. Subjects were excluded if they did not meet the above criteria or failed to adhere to the training programme with above 80% attendance. After being informed about the benefits and risks of participating in this research, written consent was provided by all parents/guardians and assent was obtained from the boys. All procedures were reviewed and approved by the Auckland University of Technology Research Ethics Committee.

5.2.3 Procedures

Two baseline testing sessions and a post-training testing session were conducted at the same time of day, on the same wooden sprung floor, in the same indoor school gymnasium, using the same testing order for all performance tests. The participants wore the same clothing and footwear for each testing and training session, were asked to avoid any strenuous activity during the 12 hours preceding each session and maintain their normal dietary intake before and after each session. The subjects participated in two orientation sessions, separated by 3 days, to habituate themselves with the equipment, experimental procedures, and movements 2 weeks before the study commenced. The participants' anthropometric measurements (height, seated height, and body mass) were obtained during the first testing session. Thereafter, each participant performed a 15 minute standardised warm-up consisting of skipping, jumping, FR, BR, and sideways running progressively increasing in intensity over 20 m, interspersed with dynamic stretching of the lower limbs. Each testing session was used to determine the participants' 10 m, 10- to 20 m, and 20 m sprint times (s), countermovement jump (CMJ) height (cm), and vertical leg stiffness. Each performance test was completed twice by all participants in every group during each testing session. Five minutes of passive recovery was given between each test. Average performance data for each test were used for analysis. Baseline testing took place twice to establish the reliability of the variables with the examined population before the 8-week study. Coefficient of variation (CV) was computed to determine inter-day reliability of the 2 pre-test performances; 10 m sprint time (CV = 2.83%), 10- to 20 m sprint time (CV = 0.23%), 20 m sprint time (CV = 1.76%), vertical CMJ (CV = 4.24%), and hopping tests (CV = 4.34%).

5.2.3.1 Speed, Power and Stiffness Testing

Sprinting performance times over 20 m and splits from 0- to 10 m and 10- to 20 m were evaluated using SpeedlightV2 wireless dual-beam photocell timing gates (Swift Performance Equipment, Australia). Timing gates were placed 1.5 m apart at the start, 10- and 20 m distances, with photocell heights set at 92.5 cm (top beam) and 68 cm (bottom beam) to correspond with approximately the centre of mass of the participants. Participants were instructed to start in a split stance with their lead leg 50 cm behind the first timing gate and toes of the back foot in line with the heel of the front foot. No rocking or false steps were permitted before starting. Sprinting was encouraged to be completed with maximal effort for each trial. Sprint-running performance up to 20 m has shown good test-retest reliability in adolescence athletes (CV = 1.3–2.0%) (70).

Bilateral vertical CMJ height with full arm action was used to assess lower-body power. A Vertec vertical jump tester (Sports Imports, Columbus, OH, USA) was used to quantify jump height. The lowest vane was individually adjusted, so that it corresponded to within 0.5 cm of each participant’s maximal standing reach height (174). Participants were requested to use their dominant hand to displace the highest possible vane with an overhead arm swing at the highest point of their jump. Height was determined from the Vertec system as the number of vanes displaced above the original standing reach height to the nearest 1.27 cm. Jump height was then calculated by subtracting the standing reach height from the maximal jump and reach height determined from the highest displaced

Vertec vane (88). Between each attempt, all vanes were repositioned so that multiple trials could be recorded.

Leg stiffness was measured using a field based submaximal hopping test (127). Participants were asked to hop bilaterally for 20 consecutive hops on a portable contact mat (Fitness Technology, Australia) at a frequency of 2.5 Hz. Participants were instructed to minimise foot-ground contact time while hopping to an auditory signal produced via an electronic metronome. Ten consecutive hops closest to the designated frequency were used for analysis. Absolute leg stiffness (kilonewtons per metre; $K_N \cdot m^{-1}$) was calculated by modelling the vertical ground reaction force, based on the flight and contact time during hopping (48). The measures of body mass, contact and flight time were entered into an equation proposed by Dalleau et al. (48) in Equation 5.1, which has been shown to be a valid and reliable calculation in adolescents (127).

Equation 5.1.

$$\text{Vertical leg stiffness} = \left(\frac{M \times \pi(T_f + T_c)}{T_c^2\left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4}\right)}\right)/1000$$

Where M was the body mass and T_c and T_f were ground contact time and flight time, respectively.

5.2.4 Running Training Programme

Running training was conducted twice a week for 8-weeks on non-consecutive days. The running programme was conducted in place of the athletes' normal PE curriculum, and in addition to their regular sport training (i.e., typically two training sessions and one competition game a week). The running training programme involved participants performing linear running over a range of intensities either forward or backward utilising rest periods of three to five minutes between runs. Each training session was conducted after a standardised progressive warm-up resembling the one used during testing. Progressive overload principles were incorporated into the programme by increasing the overall intensity of the session through autoregulated running speed and running distance (see Figure 5.1). The intensities of slow, moderate and fast correspond to approximately 20 - 45%, 50 - 75% and ≥ 95% of maximal effort, respectively. These speeds were chosen to reflect common running intensities which young male athletes are capable of self-selecting using autoregulation (236). Table 5.2 outlines the repetitions by intensity over the prescribed distances for each training session. Equal volume and intensity were prescribed for both the BRT and FRT groups. A duration of 8-weeks was chosen for this study to exemplify how a running training programme can be implemented and assessed over a typical school term in a high-school athlete development programme.

Because of the novelty of high-speed BR, special attention was focused on correct BR technique by the means of demonstration and verbal feedback in the early sessions. Technical characteristics of BR stressed during training are presented in Figure 5.3. The FRT group also received specific technical instructions, such as; (a) “knee-up and toe-up”, (b) “drive your arms from cheek to hip”, (c) “strike the ground with the ball of your foot” and (d) “strike the ground under your hips and push back”.

Table 5.2. Eight-week BRT and FRT programme.

	Running intensity	Reps	Distance (m)	Distance per intensity (m)	Total session distance (m)
Week 1					
Session 1	Slow	3	15	45	225
	Moderate	4	15	60	
	Fast	8	15	120	
Session 2	Slow	3	15	45	225
	Moderate	3	15	45	
	Fast	9	15	135	
Week 2					
Session 1	Slow	2	15	30	225
	Moderate	4	15	60	
	Fast	9	15	135	
Session 2	Slow	2	15	30	225
	Moderate	3	15	45	
	Fast	10	15	150	
Week 3					
Session 1	Slow	1	15	15	225
	Moderate	4	15	60	
	Fast	10	15	150	
Session 2	Slow	2	15	30	225
	Moderate	2	15	30	
	Fast	11	15	165	
Week 4					
Session 1	Slow	1	15	15	225
	Moderate	3	15	45	
	Fast	11	15	165	
Session 2	Slow	1	15	15	225
	Moderate	2	15	30	
	Fast	12	15	180	
Week 5					
Session 1	Slow	3	20	60	300
	Moderate	4	20	80	
	Fast	8	20	160	
Session2	Slow	3	20	60	300
	Moderate	3	20	60	
	Fast	9	20	180	
Week 6					
	Slow	2	20	40	300
Session 1	Moderate	4	20	80	
	Fast	9	20	180	
Session 2	Slow	2	20	40	300
	Moderate	3	20	60	
	Fast	10	20	200	
Week 7					
Session 1	Slow	1	20	20	300
	Moderate	4	20	80	
	Fast	10	20	200	
Session 2	Slow	2	20	40	300
	Moderate	2	20	40	
	Fast	11	20	220	
Week 8					
Session 1	Slow	1	20	20	300
	Moderate	3	20	60	
	Fast	11	20	220	
Session 2	Slow	1	20	20	300
	Moderate	2	20	40	
	Fast	12	20	240	

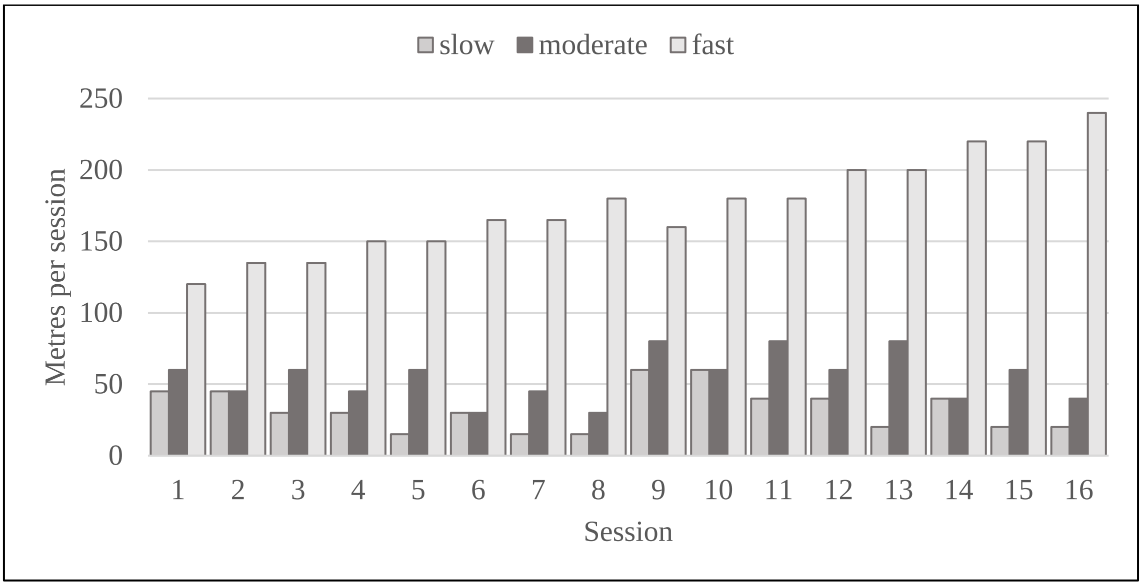

Figure 5.1. Volume by intensity per session for duration of running programme.

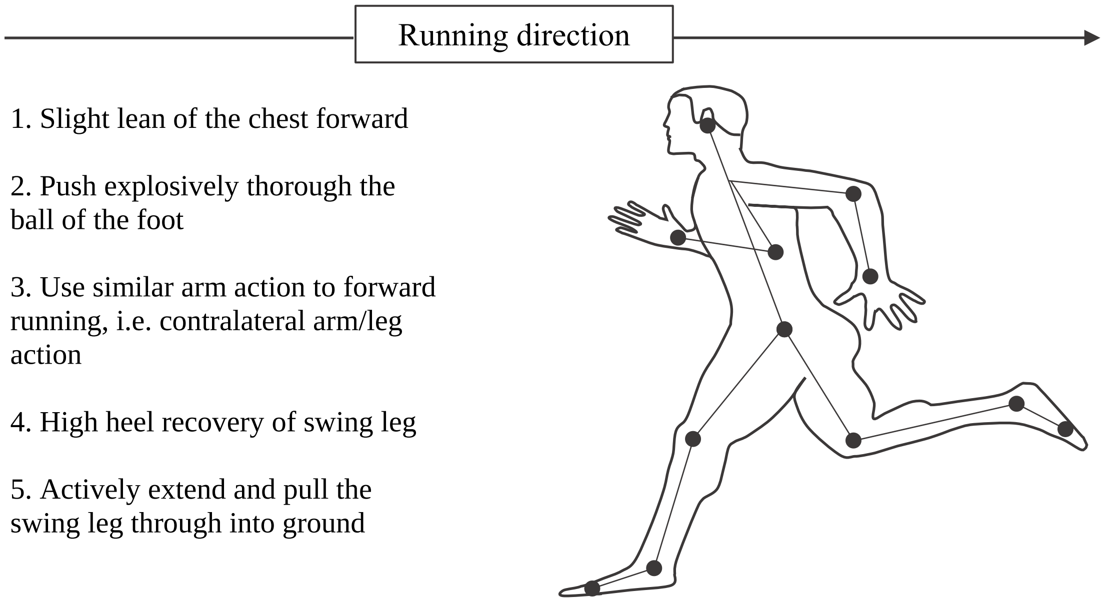

Figure 5.2. Technical cues for BR emphasised for the BRT group. BR = backward running; BRT = backward running training; Swing leg = the leg not in contact with the ground.

5.2.5 Statistical Analysis

The statistical analyses were performed using Microsoft Excel (version 15.28; Microsoft, Seattle, WA, USA) and SPSS 24.0 for MAC OS (SPSS, Inc, Chicago, IL, USA). The data were explored using histogram plots, and the normality of the distribution for all variables was tested using Kolmogrorov-Smirnov test. Homogeneity of variance was tested using the Levene's test. Thereafter, descriptive statistics were calculated and reported as mean values and SDs Within-group differences between pre-training and post-training for all performance variables were analysed using paired t-tests. Within-group percentage change and effect size (ES) were calculated to quantify the magnitude of the performance change in each group's performance tests. Within-group ES was calculated by dividing the difference between the mean performance change (i.e., post-training results – pre-training results) by the pooled sd for each performance variable (39). The smallest worthwhile individual change (SWC = 0.2 * sd) was calculated on the pooled SD of both pre-training session scores for all groups and converted to a percentage for each performance variable, where changes were deemed small (0.2 × SD), moderate (0.6 × SD) or large (1.2 × SD) (103). Training-related effects between groups were assessed using a one-way analysis of variance on the change score (mean difference from pre-training to post-training) for each performance variable, similar to Winwood and Buckley (249). Sidak post hoc comparisons were applied if a significant F value was observed to locate pairwise differences. The intervention ES was calculated by dividing the difference between groups' change scores by their pooled sd for each performance variable. Classification of ES was as follows: trivial (< 0.20), small (0.20 to 0.60), moderate (0.60 to 1.2) and large (≥ 1.2) (39, 102). Significance was accepted at the $p \leq 0.05$ level and 95% confidence intervals were used for all analyses.

5.3 Results

Performance testing data for the BRT, FRT and CON groups are presented in Table 5.3, including within-group changes from pre-training to post-training and between-group differences of the mean changes. The within-group analysis revealed that BRT elicited significant changes ($p \leq 0.01$) in sprint times, CMJ height and leg stiffness with improvements ranging from small to large from pre- to post-testing. Significant differences ($p \leq 0.05$) were reported after FRT for sprint times, CMJ performance, and leg stiffness, with beneficial effects ranging from small to large. The CON group reported mixed significant results, evident by small detrimental effects on sprinting performance ($p \leq 0.05$) over all distances and small beneficial effects on CMJ height ($p \leq 0.05$).

The BRT group had the highest relative number of individual responses above the SWC for 10 m-times (96%), 20 m times (96%), CMJ height (80%), and vertical leg stiffness (72%). The FRT group demonstrated the greatest relative number of responses above the SWC for 10- to 20 m times (56%). Performance gains in CMJ height were experienced in 58% of the CON group. Moderate to large gains were experienced in 96% of the BRT group for 10 m and 20 m performance and 53%–65% of the FRT group, respectively. More than half of the BRT (52%) and FRT (50%) groups experienced moderate to large gains in leg stiffness while just over a quarter were over the SWC threshold in the CON group (27%). Note that the SWC for sprinting performance is negative to reflect that decreases in sprint times are associated with improvements in performance. Figures 2 and 3 provide graphical references illustrating the individual percentage changes relative to the SWC detected for the BRT, FRT, and CON groups for sprinting performances and lower-body power and stiffness measures, respectively.

When the mean change scores between the groups were compared, statistically significant main effects were reported for all performance tests ($p \leq 0.001$). Compared with the CON group, significant differences ($p \leq 0.001$) were reported to be favourable for BRT on all performance tests, where large changes occurred for sprint times, and moderate changes were seen in CMJ height and vertical leg stiffness, respectively. The FRT group displayed significant improvements ($p \leq 0.01$) compared with the CON group in sprinting ability and vertical leg stiffness, where small to large effects were present for each performance test, respectively. Comparisons between training groups reported significant differences ($p \leq 0.05$) with small to moderate effects for 10 m and 20 m sprint times and CMJ height in favour of BRT over FRT.

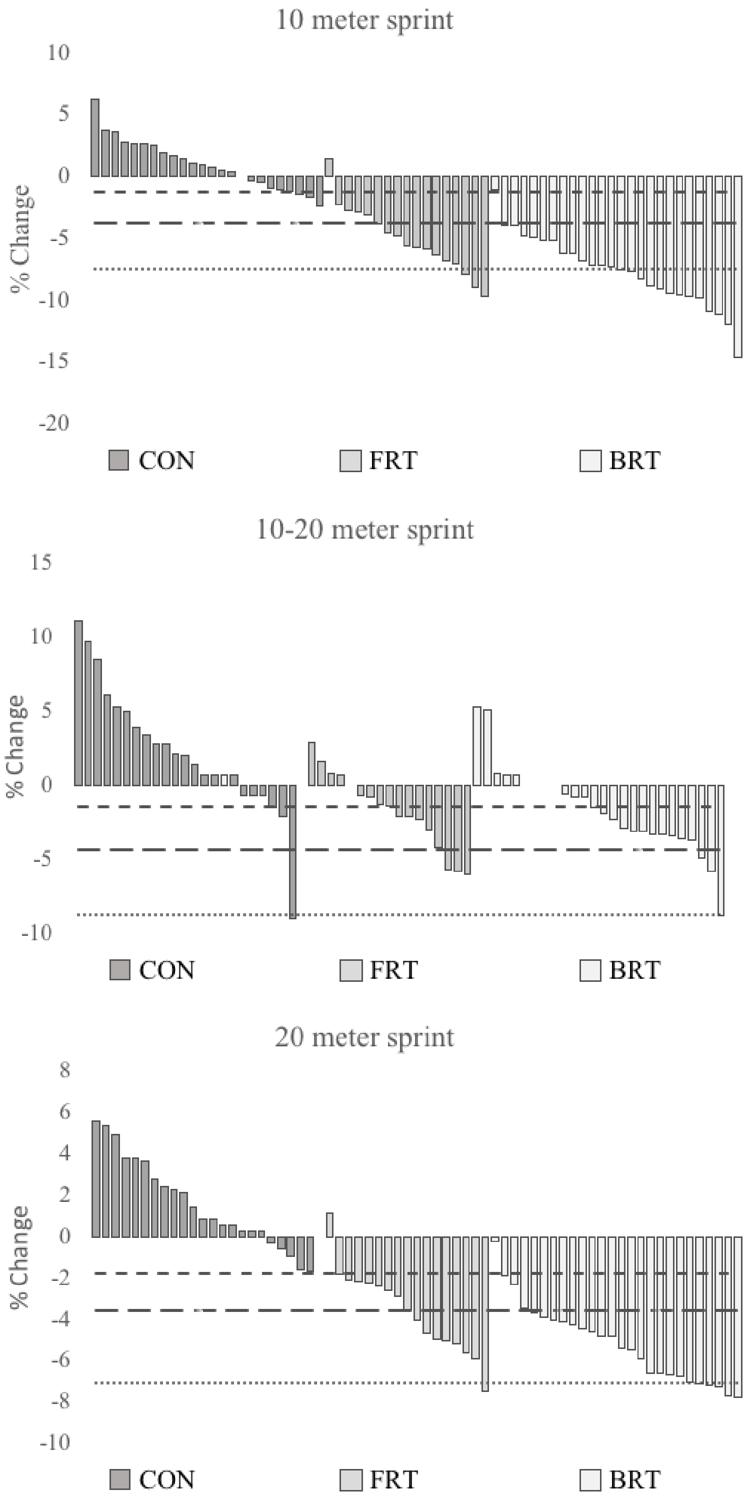

Figure 5.3. Graphical illustration of individual percentage change for sprinting performances over 10 m, 10-20 m and 20 m from pre-training to post-training by group. - - - Small response (SWC =0.2); — — moderate response (MWC = 0.6); ·········· large response (LWC = 1.2); FRT = forward running training; BRT = backward running training; CON = control; SWC = smallest worthwhile change; MWC = moderate worthwhile change; LWC = large worthwhile change.

Table 5.3. Descriptive performance testing results with for CON, FRT and BRT groups including within-group changes from pre- to post-training and between-group differences of the mean changes.

Performance Test	Group	Pre (mean ± SD)	Post (mean ± SD)	Performance change (%) (95% CI)-	Pre-post training effect (ES)	Diff FRT-CON (mean ± SE)	Effect size	Diff BRT-CON (mean ± SE)	Effect size	Diff BRT-FRT (mean ± SE)	Effect size
10m sprint (s)	CON	1.97 ± 0.11	1.99 ± 0.11*	1.10 (0.31 to 1.89)	0.20						
	FRT	1.94 ± 0.07	1.84 ± 0.09†	-5.03 (-6.34 to -3.71)	- 1.25	-0.12 ± 0.02†	-1.29[F]	-0.17 ± 0.02†	-1.59[B]	-0.05 ± 0.02✧	-0.54[B]
	BRT	1.97 ± 0.11	1.82 ± 0.08†	-7.47 (-8.65 to -6.28)	- 1.56						
10-20m sprint (s)	CON	1.43 ± 0.07	1.46 ± 0.09*	2.29 (0.54 to 4.04)	0.41						
	FRT	1.40 ± 0.09	1.37 ± 0.08✧	-1.71 (-2.95 to -0.47)	- 0.29	-0.06 ± 0.02✧	-0.45[F]	-0.05 ± 0.02†	-1.05[B]	0.00 ± 0.01	0.04
	BRT	1.40 ± 0.13	1.38 ± 0.11✧	-1.43 (-2.63 to -0.23)	- 0.24						
20m sprint (s)	CON	3.38 ± 0.15	3.43 ± 0.16✧	1.62 (0.74 to 2.50)	0.36						
	FRT	3.34 ± 0.15	3.21 ± 0.16†	-3.66 (-4.63 to -2.70)	- 0.79	-0.18 ± 0.03†	-1.20[F]	-0.22 ± 0.02†	-1.38[B]	-0.05 ± 0.02*	-0.29[B]
	BRT	3.37 ± 0.25	3.20 ± 0.21†	-5.01 (-5.78 to -4.24)	- 1.04						
CMJ (cm)	CON	45.19 ± 6.94	47.27 ± 7.18✧	4.93 (2.35 to 7.52)	0.30						
	FRT	54.08 ± 5.79	55.50 ± 5.48*	2.82 (0.54 to 5.11)	0.25	-0.66 ± 0.79	-0.10	4.57 ± 0.1.73†	0.63[B]	5.23 ± 1.75†	0.76[B]
	BRT	53.29 ± 8.20	58.50 ± 8.41†	9.88 (7.25 to 13.18)	0.83						
Stiffness (kN·m^{-1})	CON	30.74 ± 5.76	30.38 ± 5.92	-0.56 (-4.80 to 3.69)	- 0.07						
	FRT	29.73 ± 4.82	33.01 ± 4.37✧	12.37 (5.23 to 19.51)	0.71	3.64 ± 1.40✧	0.67[F]	3.83 ± 0.94†	0.65[B]	0.19 ± 1.28	0.03
	BRT	33.89 ± 6.00	37.36 ± 6.72†	10.59 (6.67 to 14.50)	0.54						

CI = confidence interval; CON = control; FRT = forward running training; BRT = backward running training; CMJ = countermovement jump. F Training effect toward FRT; B Training effect toward BRT.

* Significant ($p \leq 0.05$) for within- and between-group performances.

✧ Significant ($p \leq 0.01$) for within- and between-group performances.

† significant ($p \leq 0.001$) for within- and between-group performances.

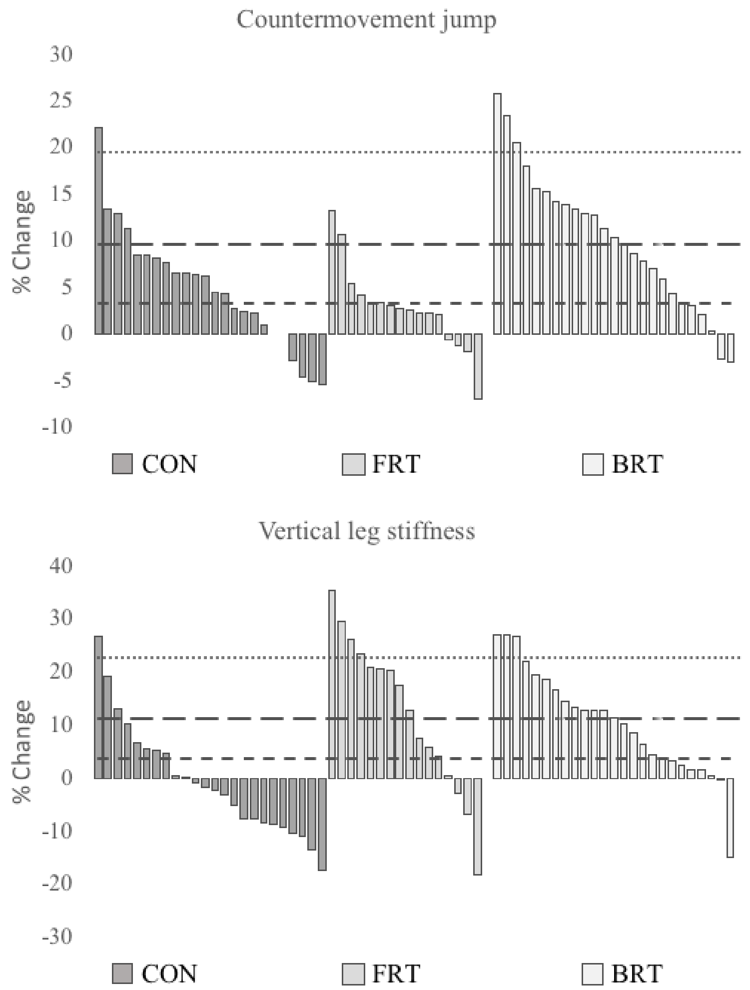

Figure 5.4. Graphical illustration of individual percentage change for countermovement jump height and vertical leg stiffness performance from pre- to post-training by group. Small response (SWC =0.2); moderate response (MWC = 0.6); large response (LWC = 1.2); FRT = forward running training group; BRT = backward running training; CON = control; SWC = smallest worthwhile change; MWC = moderate worthwhile change; LWC = large worthwhile change..

5.4 Discussion

The purpose of this research was to understand the effects of BRT and FRT programmes on speed and power measures in adolescent male athletes. This study is the first to investigate the effects of performing free BRT or FRT on short sprint speed and power measures in adolescent athletes. The major finding of this study was that individuals in both running groups improved sprinting performance and vertical leg stiffness compared with the individuals in the CON group who participated in normal PE curriculum.

Moreover, BRT seemed to provide the greatest performance benefits for CMJ height and 10 m and 20 m sprint times compared with the CON and FRT groups.

Findings from this study revealed training-related improvements in short sprinting performance up to 20 m for both FRT and BRT groups compared with the CON group. This is in agreement with previous reports that free sprint training enhances sprint performances up to 20 m more than natural development in adolescent male athletes (167). In addition, the current research found that BRT provided greater gains in sprinting performance over 10 and 20 m compared with FRT. This finding is in line with a previous study, which concluded that BRT was more effective at maintaining FR sprint ability than FRT in a group of 17 trained netball players (230). This is the first study to demonstrate that BR can be used as a training method to significantly enhance FR sprint performance. An explanation for this finding could be that both directions of locomotion are generated by the same basic neural mechanisms (83, 108, 148). Neurological adaptations are known to occur in response to periods of sprint training (202). By training one direction of running, neurological adaptations may result for both BR and FR (100, 148). Therefore, BR may be classified as a sprint-specific training method.

A higher number of participants in the BRT and FRT groups experienced adaptations greater than the SWC compared with the CON group, with all but one participant in the BRT group experiencing moderate to large gains in 10 m time. Although improvements in 10- and 20 m sprint performance were reported after both the BRT and FRT Programmes, it is important to distinguish that gains in 20 m performance were primarily a result of increased speed over the first 10 m. This is especially true for the BRT group, who increased performance more over 10 m than 20 m compared with the CON and FRT groups. Although, this study demonstrated that improvements in 10 m sprint performance have subsequent benefits over longer distances up to 20 m. It seems that sprint-specific training, either forward or backward, increases early acceleration over 10 m to a greater extent than late acceleration, or performance over 20 m, based on the relatively larger effects identified from pre-training to post-training. As BR is known to be achieved through higher step frequencies and lower step lengths compared with FR (235), increases in sprinting performance may be a result of alterations in step kinematics, which are representative of early accelerative sprinting (245), i.e. 0-10 m. However, further research using floor level optical timing systems or video are required to substantiate this posit.

The current study revealed that BRT yielded moderate effects for CMJ performance (↑9.9%), whereas FRT had a small effect on jumping ability (↑2.8%). Moreover, more than half of the BRT group demonstrated a moderate to large worthwhile change in CMJ height. The larger increase in CMJ height displayed in the BRT compared with FRT group in the present study contradicts a previous report by Terblanche and Venter (230) which found female netball athletes aged 19-20 years improved CMJ performance more after FR training (↑2.61%) compared with sport-specific BR training (↑0.25%). Differences between this study and those of Terblanche and Venter (230) could be related to either the technical running model used or the amount of work performed during training. Terblanche and Venter (230) applied maximal effort BR in a sport-specific programme, mimicking FR drills, with limited mention of BR technique, distance, or speed. This study, in contrast, used principles of overload to progress BR up to maximal intensity, as a specific training drill where biomechanical components were emphasised through a combination of demonstration and verbal feedback. Therefore, the effect of BRT may be influenced by the quality and attention to direction-specific running mechanics. Ultimately, training BR seems to have favourable transfer to FR and movements related to lower-body power, i.e., CMJ height.

The significant improvement in vertical leg stiffness after BRT (↑10.6%) and FRT (↑12.4%) observed in the current study demonstrates the ability of free sprint-specific training methods to enhance stretch-shortening cycle function in adolescent male athletes. These results are comparable with previous reports that leg stiffness in paediatric populations is enhanced by up to 8% after nonspecific sprint training (i.e., plyometrics) (126). This is important considering increased leg stiffness has been associated with higher maximal sprinting speeds in adolescents (35). This study demonstrated that both running programmes were equally effective at inducing performance gains in stiffness when compared with the CON group. This finding is promising because it provides evidence that BR and FR increase vertical leg stiffness more than a traditional PE curriculum in adolescent athletes. Given the relationship between stiffness and maximal velocity sprinting, it can be postulated that either direction of sprint-specific training may be used to increase the maximal sprinting speed in young athletes.

Readers should be cognisant that the participants were performing a variety of sport trainings outside of school, which were not quantified and may have had some influence on the training adaptations observed in this study. Nevertheless, this study demonstrates that BR and FR training can be implemented twice a week in a high-school athlete development programme intended to improve physical performance in adolescent male athletes. The training gains from BR for sprint performance, leg stiffness, and CMJ ability were comparable with, or greater than, FR. These findings suggest that BR is similarly beneficial to other modes of sprint training for improving sprinting and lower-body performance measures and may be classified as a sprint-specific training method. However, future research should consider using dual energy X-ray absorptiometry scanning to determine body composition changes and help give more insight into the nature of adaptations that take place over periods of BRT. Although this study is limited to male athletes' mid-PHV, it provides a snapshot of sex- and maturity-specific adaptations from sprint-specific training programmes compared with a traditional PE curriculum in adolescent boys. Such findings are important considering the lack of published data related to the effects of BR and specific FR sprint training in boys. With the recent upsurge in scientific attention aimed at optimising sprint speed in young athletes, additional training studies are necessary to understand the mechanisms responsible for adaptations related to free and resisted BR and FR in paediatric populations.

5.6 Practical Applications

Progressive high-speed BR is recommended as a safe and effective training method for improving athletic performance in adolescent male athletes following sufficient practice and instruction. Speed and strength coaches aiming to optimise the athletic potential of adolescent athletes should consider the following points when implementing sprint-specific training into the training programme of their athletes:

1. Training adaptations from BR transfer to FR sprint ability and underlying determinants related to fast FR speeds in mid-adolescent boys.
2. Both BRT and FRT can be used to improve sprinting performance, jumping height, and leg stiffness in adolescent athletes.
3. Implementing BR into a training programme provides a novel stimulus that seems particularly beneficial for improving performance tasks heavily reliant on concentric strength and power.
4. Regardless of running direction, coaches should pay particular attention to the technical demands of running movements and be cognisant that effort and intensity may moderate training responses to sprint-specific training methods.

CHAPTER 6. RESISTED SPRINT TRAINING IN YOUTH: THE EFFECTIVENESS OF BACKWARD VERSUS FORWARD SLED TOWING ON SPEED, JUMPING, AND LEG COMPLIANCE MEASURES IN HIGH-SCHOOL ATHLETES

6.0 Prelude

In Chapter 4, the load-velocity relationships during resisted FR (FRS) and resisted BR (BRS) were determined, and consistency of these performances established. In Chapter 5, it was concluded that unresisted BR and FR both improved forward sprinting performance, jumping height, and vertical leg stiffness in high-school athletes, though BR had the greatest transfer to sprinting and jumping performance. With the loading prescription established and utility of unresisted FR and BR training determined, the next logical step was to understand the sprinting, jumping, and stiffness responses following FRS and BRS training. Therefore, the purpose of this research was to examine and compare the training effects of FRS and BRS programmes on speed, jumping, and stiffness performance in high-school athletes. The findings of this study will inform strength and conditioning coaches of whether adaptations resulting from FRS and BRS training can transfer to specific and nonspecific athletic tasks.

This chapter comprises of the following published paper:

Uthoff, A., Oliver, J., Cronin, J., Winwood, P., Harrison, C., Lee, J. (2019). Resisted sprint training in youth: the effectiveness of backward vs. forward sled towing on speed, jumping, and leg compliance measures in high-school athletes. *Journal of Strength and Conditioning Research.* Published Ahead of Print. doi: 0000000000003093

6.1 Introduction

Talent identification, team selection, and successful competitive outcomes for many youth athletes are dependent on their ability to sprint quickly over short bursts (78, 159, 207). Fast sprinting performance is facilitated by a combination of lower-body power and rapid stretch-shortening cycle function (183, 208). Running speed and the ability to produce force quickly naturally improve due to growth and maturation (183, 207); however, the development of speed and its underlying determinants may be further enhanced through specific and nonspecific training methods (168, 209). Specific-sprint training (i.e. resisted and unresisted sprinting) has been shown to be more effective than nonspecific training methods (i.e. resistance training and plyometrics) for developing sprinting speed in youth (209). Following the principle of specificity, specific sprint training methods aim to promote neurological and musculoskeletal adaptations, which are velocity and task dependent (43). Furthermore, novel sprint training methods such as backward running (BR) have resulted in greater improvements in speed, jumping height, and leg stiffness than more traditional forward running (FR) programmes in youth athletes (238). This is important as increased jumping height is related to improved strength qualities (40), and leg stiffness is essential for force transmission during sprinting (208).

The training principle of specificity is considered critical for maximising the benefits of speed and power training in youth (59). Resisted sprinting (RS) towing weighted sleds is a training method often used by speed and strength coaches because its technical and mechanical demands are similar to unresisted sprinting (191). It is believed that RS improves an athlete’s ability to apply propulsive forces more effectively and leads to adaptations in sprint acceleration ability (112). This specific sprint training method has been shown to be particularly beneficial for midpubescent and postpubescent youth (20, 204, 215). For example, six to weeks of RS training using loads ranging from 2.5 to 20%

body mass (BM) has resulted in small to large increases in propulsive force production (204) and sprinting performances over 20 m (215) and 30 m (20, 204). Although these findings are promising for practitioners wishing to implement RS with youth, these results are limited to 3 known studies using RS towing weighted sleds up to 20% BM as a training stimulus (20, 204, 215). This is important because it has been recognised that loads >20% BM and up to 96% BM are most beneficial for improving peak power and acceleration performance in adults (45, 166, 191), yet the chronic influence of towing relatively greater loads has not yet been examined in youth.

Another specific sprint training method that has been identified as a means to improve athletic performance is BR (227, 230, 238). Backward running is a novel training stimulus that has been shown to increase lower body musculotendinous functions, jumping performance, and sprinting ability in adults and youth (64, 230, 235, 238). Uthoff et al. (238) reported that progressively overloading unresisted BR biweekly over 8 weeks resulted in improvements in 10-m and 20-m sprint times (7.47 and 5.01%, respectively), countermovement jump (CMJ) height (9.88%), and leg stiffness (10.6%) in youth male athletes. These findings were found to be similar to or better than a group performing an equal volume and intensity of FR training. Inclined BR training has also been recommended as a means to increase quadriceps functional strength while simultaneously reducing knee joint stress (97). Despite the recent evidence for integrating BR into athletic performance programmes, this training method has received little empirical attention compared with FR training. Although researchers have begun to understand the utility of unresisted BR, explorations into the prolonged effects of adding external resistance to BR have yet to be scientifically tested in youth or adults.

Given that sprinting is an essential movement for many sports (183, 208), understanding the most effective methods to enhance speed and musculotendinous functions in youth athletes is imperative. Specific sprint training methods of RS forward and unresisted BR have proven beneficial for enhancing midpubescent and postpubescent athletes' ability to produce force and sprint quickly (204, 238). However, research to date has only established the effectiveness of using forward RS training loads up to 20% BM. Moreover, the effects of resisted BR training have yet to be investigated. It is unknown whether using RS loads >20% will lead to positive adaptations in sprinting and musculotendinous performances in youth or whether these adaptations may also be realised after backward RS. Therefore, this study aimed to assess the efficacy of performing forward and backward RS towing loads from 20 to 55% BM on sprinting, jumping, and stiffness measures in youth male athletes. It was hypothesised that forward RS would be the most beneficial for improving sprinting ability, and that backward RS would be the most beneficial for improving jumping ability and leg stiffness.

6.2 Methods

6.2.1 Experimental Approach to the Problem

A cluster randomised control trial was used to examine the effects of an 8-week progressively overloaded RS training programme, either forwards or backwards, in high-school-based physical education (PE) classes. The independent variables of interest were tested before and after training and included sprinting ability, jumping performance and leg stiffness. Boys enrolled in a PE programme at their school were matched for maturity and cluster randomised to a control group or two experimental groups. The boys in the control group (CON = 35) followed the usual PE programme curriculum comprised of 50 minutes of various modified sporting games such as touch rugby, cricket, soccer, or basketball which included periods of running and sprinting interspersed with active and passive recovery, whereas the boys in the training groups performed either backward resisted sprinting (BRS = 45) or forward resisted sprinting (FRS = 34) biweekly. The 8-week training programme was implemented during a 10 week academic term. Baseline testing was administered in the 1st week, supervised training was performed for the following eight weeks, and post-testing was completed in week 10. Quantitative analyses were conducted using Frequentist statistics to test scores from pre-training to post-training, whereas Bayesian and inferential statistics were used to examine the qualitative meaning of any observed changes in the independent variables.

6.2.2 Subjects

A group of 115 boys volunteered to participate in this study. Boys were matched for maturity and cluster randomised to either a backward resisted sprinting group (BRS; n = 46), forward resisted sprinting group (FRS; n = 34), or a control group (CON; n = 35). A summary of the subject's pre-training descriptive characteristics is outlined in Table 1. Maturity offset, measured as age from peak height velocity (PHV), was calculated using equation 1 developed by Mirwald et al. (163) using non-invasive anthropometric measurements. No significant differences between groups were observed for physical characteristics or maturity offset. Subjects were included in this study if they were boys between 13 and 15 years of age, enrolled in a PE programme at a public high-school, played a sport for their school or local sports team, were free of any medical issues or injuries that may have hindered their participation or performance, and adhered to the training programme with above 80% attendance. After being informed of the risks and benefits of participating in this study subjects provided a signed assent form and a parental informed consent form signed by a parent or guardian before participation in this study. The procedures for this research were reviewed and accepted by the Auckland University of Technology Research Ethics Committee.

Table 6.1: Subject characteristics (mean ± SD).

Parameters	All Subjects (n = 115)	CON Group (n = 35)	FRS Group (n = 34)	BRS Group (n = 46)
Age (y)	14.3 ± 0.49	14.4 ± 0.52	14.0 ± 0.27	14.4 ± 0.51
Height (cm)	168.9 ± 8.9	168.6 ± 10.1	170.2 ± 7.9	168.4 ± 8.8
Body mass (kg)	58.4 ± 11.1	56.3 ± 9.9	58.7 ± 10.8	59.5 ± 12.2
Maturity offset (y)	0.53 ± 0.92	0.53 ± 1.0	0.47 ± 0.90	0.58 ± 0.86

CON = control group, BRS = backward resisted sprinting group, FRS = forward resisted sprinting group.

Equation 6.1.

Maturity offset = -9.236 + 0.0002708 × leg length and sitting height interaction – 0.001663 × age and leg length interaction + 0.007216 × age and sitting height interaction + 0.02292 × weight by height ratio
.

6.2.3 Procedures

Testing sessions at baseline and post-training were conducted under the same experimental conditions i.e., on the same indoor gymnasium wooden sprung floor, at the same time of day, by the same testers, using the same randomised testing order. In addition, subjects wore the same school-issued clothing and personal footwear for each testing and training session, were advised to refrain from any strenuous activity in the 12 hours prior to each session and told not to make any changes in their normal dietary intake for the duration of the study. To habituate themselves with the experimental procedures and training protocols, all subjects took part in 2 familiarisation sessions 2 weeks before baseline testing at the end of the preceding school term.

At the beginning of the pre-training test session, subjects' anthropometric measurements i.e., height, seated height, and BM were determined. Following the collection of anthropometric data, participants performed a 10 minute standardised warm-up consisting of a combination of skips, jumps, FR, BR, and sideways runs progressively increasing in intensity over 20 m, interspersed with lower limb dynamic stretching. Pre-and post-test were used to determine sprinting ability, jumping performance, and lower limb compliance as assessed by 10 m, 10 to 20 m and 20 m sprint times, CMJ height, and leg stiffness, respectively. Each performance test was completed twice by all participants in each group during each testing session, with 3 minutes of passive recovery provided between attempts. Analysis was conducted on the average performance data for each test.

6.2.3.1 Speed, Jump, and Stiffness Testing

Sprint times over 0-10 m, 10-20 m, and 0-20 m were measured using SpeedlightV2 wireless dual-beam photocell timing gates (Swift Performance Equipment, Australia). Photocell heights were set at 92.5 cm (top beam) and 68 cm (bottom beam) and timing gates were placed at the start, 10 m, and 20 m distances creating a 20 m x 1.5 m wide running lane (238). Before to starting, subjects assumed a split stance lining up with the toes of their lead foot 50 cm behind the first timing gate and toes of the back foot in line with the heel of the front foot. Rocking and false starts were not permitted before starting. Sprinting was encouraged to be completed with maximal effort for each trial. Sprinting performance over 20 m was chosen because of youth athletes' having shown good test-retest reliability up to this distance (coefficient of variation [CV] = 1.3 – 2.8%) (70, 238).

Vertical countermovement jump (CMJ) performance off two feet using full arm action was assessed using a Vertec vertical jump tester (Sports Imports, Columbus, OH, USA). After adjusting the lowest vane so that it corresponded to within 0.5 cm of each participant's maximal standing reach height (174), participants were instructed to jump and land in the same place while striking the highest possible vane using an overhead arm swing with their dominant hand at the peak of their jump. Jump height was calculated as the difference between the standing reach height and the maximal jump and reach height determined from the highest vane reached on the Vertec system (88). All vanes were placed in their original position between attempts to allow for multiple trials to be recorded. Jumping performance using the Vertec system similar to this study has been reported reliable in youth male athletes (CV = 4.24%) (238).

Lower limb compliance was assessed by calculating leg stiffness (k_N) through a field based submaximal hopping test, which has been identified as a valid and reliable (CV = 4.3-7.5%) method in youth athletes (127, 238). Subjects performed 20 consecutive bilateral hops on a portable contact mat with their hands on their hip (Fitness Technology, Australia). Subjects were instructed to minimise foot-ground contact time and keep in rhythm with a designated audio frequency of 2.5 Hz produced through an electronic metronome. The first and last five hops were excluded and the middle ten consecutive hops were used for analysis. Using BM, and flight and contact times during submaximal hopping, vertical ground reaction force was modelled to provide an estimate of absolute leg stiffness using equation 2 (48).

Equation 2.

$$K_N = \left(\frac{M \text{ x } \pi(T_f + T_c)}{T_c^2\left(\frac{T_f + T_c}{\pi} - \frac{T_c}{4}\right)}\right)/1000,$$

Where K_N is leg stiffness (N m^{-1}), M is body mass (kg), T_f is flight time (s) and T_c is ground contact time.

6.2.4 Running Training Programme

The training programmes consisted of 8-weeks of biweekly progressively overloaded RS towing weighted sleds either forward or backward for a total of 16 sessions during the athletes' competitive winter sports season. This duration was selected to show how a RS programme can be applied and monitored over a typical high-school term. The RS intervention was conducted in place of the athletes' normal PE curriculum and was implemented on non-consecutive days. The same standardised warm-up routine used during the testing sessions was performed before each training session. Custom made sleds weighing 8 kilograms in conjunction with waist harnesses from XLR8 (Speed Power Stability Systems Ltd, Christchurch, New Zealand) and weightlifting plates were used to provide the training stimulus during RS training. The RS programme used six to nine sprints over 15-m, separated by three to five minutes, with undulated progressive overload to increase the training stimulus from 20 to 55% BM. The training programme progression can be observed in Table 6.2.

Table 6.2. Eight-week resisted sprinting programme for BRS and FRS groups.

Week	Session	Load (% BM)	Reps	Distance (m)	Distance per Session (m)	Weekly Distance (m)
1	1	20	6	15	90	180
	2	30	6	15	90	
2	3	25	7	15	105	210
	4	35	7	15	105	
3	5	30	8	15	120	240
	6	40	8	15	120	
4	7	35	9	15	135	270
	8	45	9	15	135	
5	9	30	6	15	90	180
	10	40	6	15	90	
6	11	35	7	15	105	210
	12	45	7	15	105	
7	13	40	8	15	120	240
	14	50	8	15	120	
8	15	45	9	15	135	270
	16	55	9	15	135	

BRS = backward resisted sprinting group; FRS = forward resisted sprinting group; BM = body mass.

Because towing weighted sleds adds an additional component of risk as a result of being a relatively novel task and absence of visual guidance, particular attention was dedicated to performing BRS with appropriate technique. See Figure 1 for the technical components used for the BRS for this study. To ensure both groups received similar training stimuli, the FRS group also received specific coaching instructions where they were encouraged to (a) “drive their arms”, (b) “punch their knees through”, and (c) “push maximally during each step”.

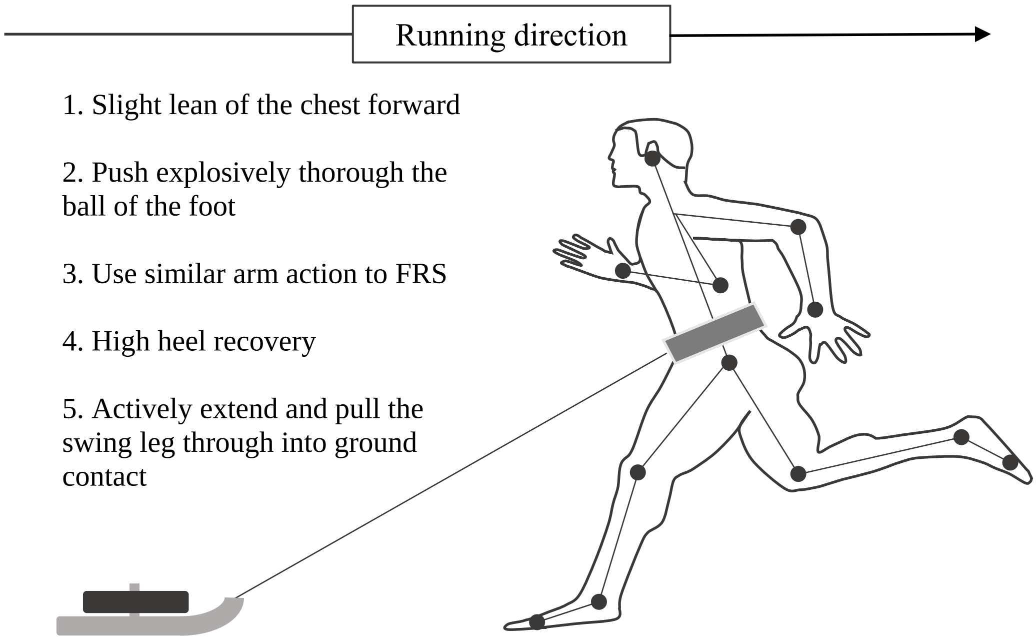

Figure 6.1. Technical cues emphasised for the BRS group. FRS = forward resisted sprinting; swing leg = the leg not in contact with the ground.

<u>6.2.5 Statistical Analyses</u>

The statistical analyses were performed using Microsoft Excel (version 15.28; Microsoft, Seattle, WA, USA) and SPSS 24.0 for MAC OS (SPSS, Inc, Chicago, IL, USA). The data were explored using histogram plots and distribution estimation, and normality of the distribution for all variables was tested using Kolmogrorov-Smirnov test in order to determine any obvious effects and estimate the distribution of the data. Homogeneity of variance was tested using the Levene’s test. Taking a frequentist approach training-related effects within and between groups on pre- and post-test performances were assessed using a 2-factor mixed design analysis of variance (ANOVA). If a significant F value was observed Bonferroni post-hoc comparisons were applied to locate pairwise differences between groups. To quantify the magnitude of the performance change in each group's performance tests within-group percentage change and effect sizes were calculated. Effect sizes (ES = mean change/pooled standard deviation of the sample scores) were calculated to quantify the extent of the performance changes from pre- to post-testing within- and between-groups (39). Effect sizes (ES) of >1.2, >0.6 to <1.2, >0.2 to <0.60, and <0.20 were classified as large, moderate, small, and trivial, respectively (39, 102). Alpha was set at $p < 0.05$ and 95% confidence intervals (CI) were used for all analyses. Taking a Bayesian approach, mean parameter estimates were quantified to determine the average relative change from pre-test to post-test for the performance variables (post-test – pre-test/pre-test). Given all performance variables were symmetric around their median, a Gaussian distribution was chosen to model relative changes on performance rate (149). Using the Jeffery's prior on the parameter estimates, posterior probability of performance improvements for each group along with their 95% credible intervals was computed using the Markov Chain Monte Carlo method (74, 149).

6.3 Results

No injuries were reported as part of the training programme. Within-group changes from pre- to post-training and between-group differences in the performance testing data for the BRS, FRS and CON groups are presented in Table 6.3. Significant main effects ($p < 0.05$) for time were found for all performance variables. The within-group analysis revealed that BRS elicited significant changes ($p < 0.01$) in sprint times at all distances, CMJ height, and K_N (-2.4 to 26.3%; ES = -0.22 to 0.79). Significant differences ($p < 0.05$) were reported after FRS for 10-20 m and 20 m sprint times, CMJ height, and K_N (-0.90 to 19.3%, ES = -0.13 to 0.90). No significant improvements were reported in the CON group for any performance test.

Table 6.3. Descriptive performance testing results with for CON, FRS, and BRS groups including within-group changes from pre-training to post-training and between-group differences of the mean changes.

Performance Test	Group	Pre (mean ± SD)	Post (Mean ± SD)	Performance change (%) (95% CI)	Post-pre training effect (ES)	Diff FRS-CON (mean ± SE)	Effect size	Diff BRS-CON (mean ± SE)	Effect size	Diff BRS-FRS (mean ± SE)	Effect size
10m sprint (s)	CON	1.94 ± 0.09	1.92 ± 0.10	-1.1 (-2.0 to -0.13)	-0.09						
	FRS	1.90 ± 0.10	1.89 ± 0.10	-0.65 (-1.5 to 0.19)	-0.13	0.01 ± 0.01	0.09	-0.03 ± 0.01	-0.28[B]	-0.03 ± 0.01	-0.36[B]
	BRS	1.92 ± 0.09	1.87 ± 0.10†	-2.4 (-3.3 to -1.5)	-0.49						
10-20m sprint (s)(s)	CON	1.48 ± 0.07	1.47 ± 0.08	-0.50 (-1.8 to 0.76)	-0.10						
	FRS	1.42 ± 0.10	1.40 ± 0.11*	-1.2 (-2.6 to 0.23)	-0.18	-0.01 ± 0.01*	-0.11	-0.01 ± 0.01*	-0.15	0.00 ± 0.01	-0.03
	BRS	1.43 ± 0.09	1.41 ± 0.08✧	-1.4 (-2.3 to -0.49)	-0.22						
20m sprint (s)	CON	3.42 ± 0.15	3.39 ± 0.17	-0.80 (-1.6 to 0.05)	-0.18						
	FRS	3.32 ± 0.19	3.29 ± 0.20*	-0.90 (-1.8 to 0.00)	-0.16	0.00 ± 0.02	-0.02	-0.04 ± 0.02*	-0.24[B]	-0.04 ± 0.02	-0.20[B]
	BRS	3.34 ± 0.17	3.28 ± 0.17†	-2.0 (-2.7 to -1.3)	-0.39						
CMJ (cm)	CON	45.6 ± 7.3	46.0 ± 7.0	1.7 (-2.2 to 5.6)	0.05						
	FRS	48.5 ± 7.0	51.6 ± 6.8†	6.8 (4.2 to 9.4)	0.45	2.7 ± 0.96✧	0.38[F]	4.5 ± 1.0*	0.67[B]	1.8 ± 0.89	0.27[B]
	BRS	46.1 ± 6.2	51.0 ± 7.6†	10.8 (7.8 to 13.9)	0.79						
Stiffness ($kN \cdot m^{-1}$)	CON	27.0 ± 8.6	27.2 ± 5.6	4.5 (-1.1 to 10.1)	0.02						
	FRS	29.2 ± 5.8	34.4 ± 7.4†	19.3 (11.7 to 26.8)	0.90	5.1 ± 1.3†	0.69[F]	6.8 ± 1.4†	0.94[B]	1.8 ± 0.89	0.29[B]
	BRS	28.3 ±6.0	35.1 ± 8.8†	26.3 (17.7 to 35.0)	0.79						

CMJ = countermovement jump; CON = control; FRS = forward resisted sprinting; BRS = backward resisted sprinting; ES = effect size; SE = standard error; CI = confidence interval. F = Training effect towards FRS; B = Training effect toward BRS.
* Significant ($p < 0.05$) for within- and between-group performances.
✧ Significant ($p < 0.01$) for within- and between-group performances.
† significant ($p < 0.001$) for within- and between-group performances.

Significant main effects ($p \leq 0.05$) for group × time were found for the jumping and leg compliance tests, but not for sprinting performance. Compared with the CON group, significant favourable differences ($p \leq 0.05$) were reported for the BRS group for 10-20 m and 20 m sprint times, CMJ, and K_N (ES = -0.15 to 0.94). The FRS group displayed significant improvements ($p \leq 0.01$) compared with the CON group for 10-20 m sprint times, CMJ, and K_N (ES = -0.11 to 0.69). No significant differences were reported between the training groups.

As seen in Figure 6.2 and Figure 6.3, the BRS group had the highest relative number of individual beneficial responses for all performance tests i.e. 10 m times (85%), 10-20 m times (65%), 20 m times (74%), CMJ height (85%) and K_N (85%). The mean parameter estimates in Table 6.4 signify that the average relative improvement is in favour of the BRS group compared with the FRS and CON groups for all performance tests. The mean parameter estimates for sprinting performance are displayed as a negative to suggest that decreases in sprint times are associated with performance improvements. The mean estimated posterior probability of performance improvements for each test variable along with their 95% credible intervals is shown in Table 6.4. The probability of improving sprinting performance is generally higher after BRS (66 to 73%), whereas BRS and FRS show similar probabilities of improving CMJ height (75% and 79%) and K_N (80% and 81%), respectively.

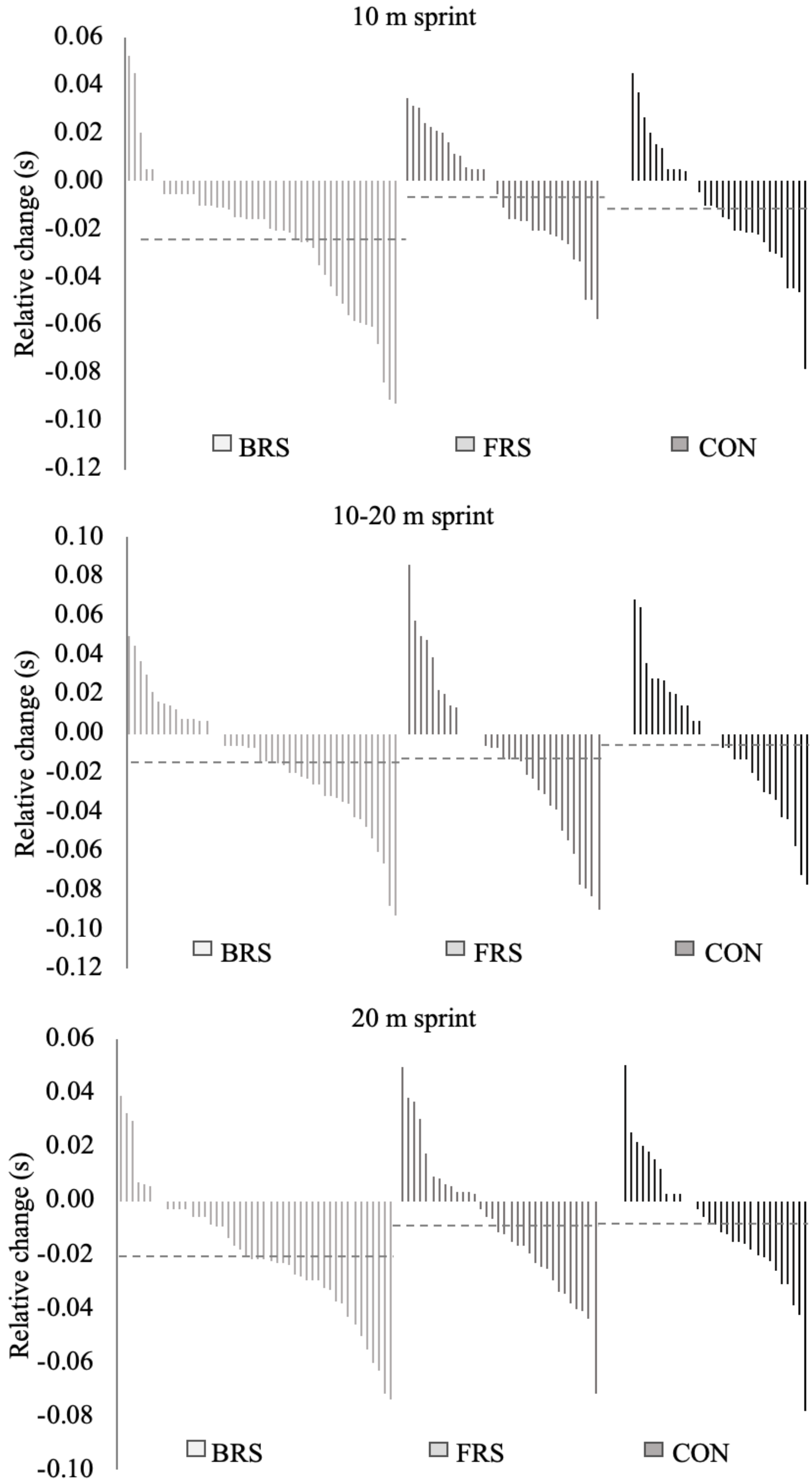

Figure 6.2. Individual relative change from pre- to post-test for sprint performances by group. — — denotes the average relative change (post-test – pre-test/pre-test) for each group. BRS = backward resisted sprinting group; FRS = forward resisted sprinting group; CON = control group.

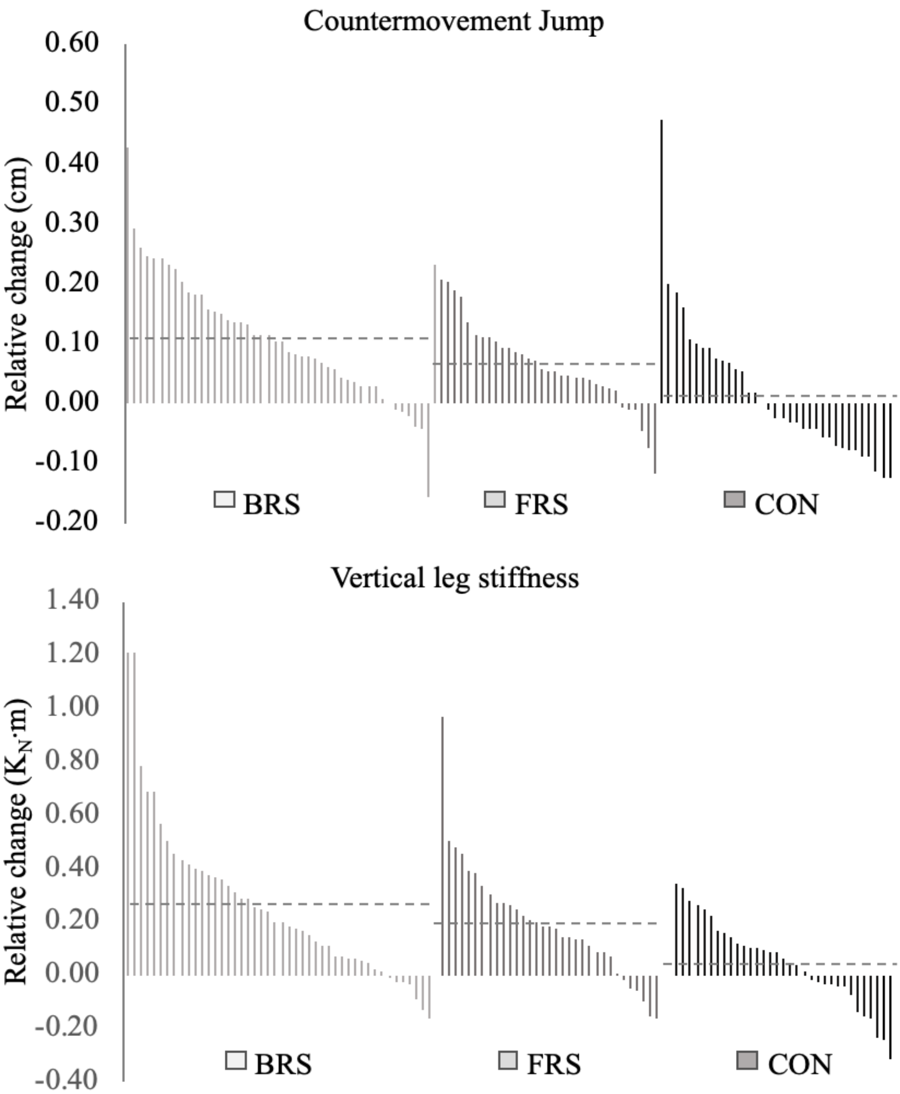

Figure 6.3. Individual relative change (post-test – pre-test/pre-test) for countermovement jump and vertical leg stiffness performances by group.— — denotes the average relative change for each group. BRS = backward resisted sprinting group; FRS = forward resisted sprinting group; CON = control group.

Table 6.4. Posterior probability of improving sprinting, jumping, and stiffness performance for each group.

Performance variable	Group	Probability (95% credible intervals)
10 m	CON	0.65 (0.51, 0.78)
	BRS	0.73 (0.61, 0.82)
	FRS	0.56 (0.42, 0.68)
10-20 m	CON	0.55 (0.41, 0.69)
	BRS	0.66 (0.55, 0.77)
	FRS	0.60 (0.47, 0.73)
20 m	CON	0.63 (0.48, 0.76)
	BRS	0.68 (0.56, 0.78)
	FRS	0.59 (0.45, 0.72)
CMJ	CON	0.55 (0.42, 0.68)
	BRS	0.75 (0.65, 0.84)
	FRS	0.79 (0.67, 0.89)
Stiffness	CON	0.61 (0.48, 0.73)
	BRS	0.80 (0.69, 0.88)
	FRS	0.81 (0.68, 0.90)

CMJ = countermovement jump; CON = control group; FRS = forward resisted sprinting; BRS = backward resisted sprinting.

6.4 Discussion

This research was the first to explore the chronic training adaptations associated with BRS vs. FRS on proxies of speed, jumping performance, and leg compliance capabilities in male youth. The main findings of this study were that sprinting performance improved the most after BRS, BRS and FRS resulted in similar improvements in CMJ height and K_N, and the training effects of BRS and FRS did not significantly differ for any performance metric. Our hypotheses were partially reinforced in that BRS was found to be effective for increasing CMJ height and K_N, although the postulate that FRS would be the best method for improving sprint performance was not supported. These results are important for researchers and practitioners given the dearth of published data on the effects of BRS and relatively heavy (e.g. >20% BM) FRS in boys.

The BRS group showed the greatest improvements in sprint performance over all distances (1.4% to 2.4%), albeit trivial to small compared with the FRS and CON groups.

However, not only was the average relative change the highest after BRS for all distances, but the relative number of participants who benefitted from BRS training was, on average, 20% higher than the FRS group and 29% more than the CON group when all distances were considered. The significant improvements from pre-training to post-training for all sprint times in the BRS group signify the transfer of an 8-week training block of loaded BR to improve unresisted forward sprinting in youth athletes. These findings correspond to previous research into BR in youth (238). Uthoff et al. (238) reported that eight weeks of unresisted BR training had a moderate to large beneficial effect on 10 m and 20 m sprint times, which was significantly better than unresisted FR training. Although the training adaptations after BRS and FRS did not significantly differ in this study, the small beneficial effects toward BRS over 10 m and 20 m indicate that BRS may provide a unique training stimulus especially useful for enhancing short sprint abilities in youth athletes. This is highlighted by the probability that approximately 70% of new runners are expected to get faster after BRS, which is on average, ~10% and ~8% greater than the number of new runners expected to get faster if assigned to FRS and CON groups, respectively.

Curiously, our results and those of Uthoff et al. (238) both found that improvements in 20 m speed after BRS and unresisted BR primarily occur over the first 10 m. For example, our results show that 83% of the changes in 20 m performance (↓ 0.06 seconds) occurred over the first 10 m (↓ 0.05 seconds). It seems that BRS is particularly helpful for improving boys' early acceleration performance (i.e., 10 m), which consequently benefits performance up to 20 m. These reports are based on relatively few studies in youth populations and more research is needed to substantiate such observations.

Youth CMJ height has been shown to improve following plyometric, strength, and unresisted sprint training (128, 170, 238). To our knowledge, this is the first study in youth to quantify the effects of RS, either forward or backward, on vertical jumping ability. We found that CMJ height improved after BRS (↑10.8%; ES = 0.79) and FRS (↑6.8%; ES = 0.45). The meaningfulness of these results for practitioners can be translated from the posterior probabilities, which indicate that if the intervention was repeated with a similar population, 75% and 79% of new athletes would expect to improve CMJ performance after 8-weeks of BRS and FRS training, respectively. As CMJ height and lower body strength qualities are known to have a strong relationship in youth (40), using BRS and FRS could be a means to improve lower body strength capabilities. Furthermore, the longer ground contact times associated with towing heavy sleds (42) may rely more heavily on the contractile and parallel elastic elements and promote adaptations specific to the CMJ task. However, as this study did not measure the musculotendinous adaptations directly it is difficult to say if performance changes were a result of neural, muscular, or tendinous modifications.

Leg stiffness has been proposed as a critical characteristic for achieving high sprinting velocities in youth athletes (208). Herein, it was observed that BRS and FRS resulted in ↑26% (ES = 0.79) and ↑19% (ES = 0.90) in leg stiffness, respectively, over the course of 8-weeks. Our findings differ from those of Rumpf et al. (204) who concluded that 6-weeks of FRS with loads ranging from 2.5% to 10% significantly reduced relative leg stiffness by 45% (ES = -2.2) in fourteen mid-PHV to post-PHV boys. It was postulated that chronic kinematic adaptations of longer ground contact times associated with increased sled loading (42) lead to greater vertical displacement (204) and, subsequently, a more compliant lower limb. However, with the use of relatively greater loads (i.e., 20-55%), our findings indicate that ~80% of new athletes are expected to decrease limb compliance by developing stiffer, more reactive, lower body capabilities after BRS and FRS. It should be noted that making direct comparisons between studies is problematic because leg stiffness was measured using a hopping test in this study, whereas Rumpf et al. (204) calculated stiffness using a non motorised treadmill. Although quantifying leg stiffness on a non motorised treadmill allows for the measurement during the actual performance task (i.e., sprinting), the speeds that were achieved by the boys in the study by Rumpf et al. (204) were slower than typical speeds reached during overground sprinting (238). Performance appears to be influenced by youth athletes' ability to overcome the resistance of a non motorised treadmill (206, 207), in which case Rumpf et al. (204) was measuring stiffness in a slower stretch-shortening cycle movement. Therefore, further research using the same leg stiffness calculation methods is required to understand the chronic influence of BRS and FRS on lower-limb compliance in boys mid-PHV and post-PHV.

In regards to loading intensity, for adults, it has been suggested that loads < 20% BM should be used to reduce disruptions in natural sprinting technique (5), loads > 20% should be used to improve acceleration (191), and loads between ~20 and ~80% should be used to maximise power output (45, 166). On the other hand, minimal loading with sensible upper limits of 10% BM have been recommended for youth (184). Although suggestions have been made to limit RS loads to 10%, it has been shown that training with loads up to 20% results in improved force capabilities and sprinting performance in boys (215). In addition, findings from this research demonstrate that towing weighted sleds ranging from 20 to 55% BM can safely be used to overload BRS and FRS, minimise negative adaptations, and cause meaningful changes in a variety of athletic tasks in mid-PHV to post-PHV boys. If RS, either forward or backward, is used as a resistance exercise rather than a technique exercise, then resistance training guidelines, which state that youth benefit most from working at higher loads (i.e., 80-89% of 1 RM) (121), should be considered when loading RS.

The results of this study demonstrate that BRS training is most beneficial in improving athletic performance in youth boys. Although previous studies using FRS training programmes have reported improvements in sprinting performance using loads ≤ 20% BM (20, 204, 215), the aim of this study was to evaluate the effects of using loads ≥ 20% BM and compare them with a novel training stimulus (i.e., BRS). The findings that BRS improved forward sprint performance and that relatively heavy FRS improved vertically oriented tasks (i.e., CMJ height and leg stiffness) indicate a transfer effect for specific sprint training methods exists. Furthermore, the dynamic leg extension action characterised by BRS may help facilitate neurological and structural adaptations to the knee extensors and subsequently develop both contractile and elastic elements of muscle-tendon units. However, the true nature of the musculotendinous adaptations resulting from chronic BRS and FRS training is unknown. Therefore, investigations using different jump testing strategies (e.g., squat jump versus CMJ vs. drop jump) and ultrasound scanning technologies are required to understand the muscle mechanical and structural responses to BRS and FRS training in youth populations.

6.5 Practical Applications

Progressively overloading BRS and FRS using relatively heavy loads up to 55% BM are recommended as safe and effective training methods for improving performance in a variety of athletic tasks in pubescent and post-pubescent boys. Anyone interested in using RS as a method to enhance athletic performance in youth athletes should consider the following points:

1. Eight weeks of BRS leads to adaptations that transfer to forward sprinting.
2. Although RS has been developed as a specific sprint training method, adaptations from both BRS and FRS also transfer to vertically-oriented athletic tasks.
3. BRS is the recommended method to improve early acceleration.
4. With the probability of a new athlete improving jumping and stiffness by 75-80% after BRS and 79-81% after FRS, practitioners can be confident that implementing RS methods will lead to positive adaptations in jumping ability and enhanced stiffness capabilities in youth athletes.

CHAPTER 7. BACKWARD RUNNING; THE WHY AND HOW TO PROGRAMME FOR BETTER ATHLETICISM

7.0 Prelude

In the preceding chapters, a review of the literature was presented, methods for prescribing unresisted and resisted FR and BR were established, and the effectiveness of unresisted and resisted BR training on athletic measures of sprinting, jumping, leg stiffness were determined. Evident from the review and training studies, BR is a method that may be incorporated into athletes' training programmes to improve components of athleticism. These findings provide snapshots of the adaptations a novel training method such as BR may provide, yet guiding principles for how to integrate BR into wider strength and conditioning programmes is still required. Therefore, the purpose of this chapter was to provide programming considerations on why and how to integrate BR to improve athleticism. Documenting the benefits of BR and providing programming consideration will help speed and strength coaches design and facilitate BR in a safe and progressively overloaded fashion for youth and adult athletes alike.

This chapter comprises of the following paper:

Uthoff, A., Oliver., J., Cronin, J., Winwood, P., Harrison, C. (Accepted on January 29th, 2019). Backward running; the why and how to program for better athleticism. *Strength and Conditioning Journal.*

7.1 Introduction

In the pursuit of optimal performance, athletes typically participate in a variety of training methods designed to reduce injury and enhance athletic outcomes. Backwards running (BR), which has been used to prepare athletes for competition demands (12, 135) and as a return to play protocol for injured athletes (94), is one such method. Although a formal definition of BR has yet to be adopted in the scientific community, Uthoff et al. (235) defined BR as "any form of locomotion in a reverse direction where movement is accomplished through a single leg of support throughout foot-ground contact and both feet simultaneously in the air between contralateral foot strikes". Backward running is different than other forms of backward locomotion such as backward pedalling – the crouched technique often used by defensive backs in American football. Figure 7.1 provides an example of different backward running gaits. Backward running, for the purpose of this chapter, more closely emulates forward running (FR) with an upright running posture and contralateral arm swing (238). Figure 7.2 highlights the technical models adopted over the gait cycle during maximum velocity BR and FR.

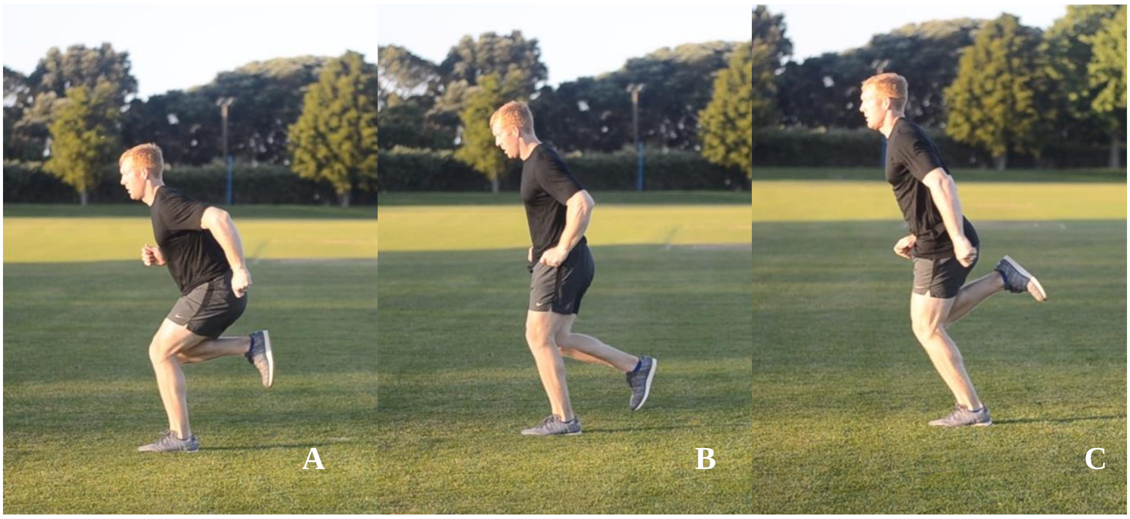

Figure 7.1. Backpedal (A), backward shuffle (B), and backward run (C) during mid-stance phase of gait.

A recent review examining the acute and trained responses to BR found that running in reverse had a unique energetic and biomechanical profile useful for enhancing a range of athletic performance measures from running economy to change of direction ability (235). Given the recent developments in literature pertaining to the use of BR for athletic enhancement in both youth and adult populations (230, 235, 237, 238), this chapter aims to examine why BR has made a resurgence in the literature and provides practical recommendations for how to integrate BR into athlete training programmes.

7.2 The Why: The Role of Backward Running in Sports and Training

Backward running is a form of locomotion which, like FR, is utilised by athletes in most overground sports (14, 164). Running itself is defined as a form of gait which is characterised by a single support phase and double flight phase (28). While both directions of locomotion are thought to be generated by the same neural pathways (100), BR is unique in that visual feedback is altered and greater demands are placed on alternative sensory systems to maintain positional awareness (100, 148). The ability to run backwards with an altered visual orientation may give athletes a tactical advantage. For example, being able to run backward at high speeds while maintaining a view of the ball or opposition will allow athletes to make more informed decisions (9). This is particularly important when you consider rugby league players BR an average of 3.6-5.4 m after each tackle (218), BR comprises of 3.4% of total distance covered by professional handball athletes during competition (160) and that elite soccer players cover 3-4% of the entire match distance running backward (164).

Outside of game play, BR is commonly included in injury prevention and rehabilitation programmes (77, 94, 114). Backward running is also part of many warm-up protocols which prepare the body for specific movements encountered during the sport and enhance athletic performance (185, 203, 220, 254). Additionally, BR has been used as a training tool by coaches to increase qualities of aerobic and anaerobic fitness (186, 229), vertical jump height (238), change of direction performance (227, 230), and sprinting speed (238). It is important that strength and conditioning professionals understand the body's immediate response to BR and the efficacy of training using this modality so they can better integrate BR in their practice.

7.2.1 Acute Responses to Backward Running

The immediate physiological or biomechanical adaptations to a stimulus provide a snapshot of the potential long-term effects of an exercise. A number of researchers have studied the energetic, kinematic, and kinetic responses to BR, and compared these to FR. Table 7.1 provides an overview of the acute responses of BR versus FR at similar relative intensities (i.e., BR at ~70% of FR speed).

As identified in Table 7.1, researchers have shown that, at the same relative, or matched, intensity (e.g., maximal velocity or BR at 70% of FR velocity), BR is characterised by greater energetic expenditure (55, 63, 251), lower running speed (9, 237) and overall joint ROM (9, 64), unique step kinematic interactions (41, 64, 243), decreased lower limb compliance (29, 30), reliance on isometric and concentric muscle actions (29, 30) greater leg muscle activation (64, 222) reduced knee joint stress (65, 201), modified ratios of braking and propulsive forces (29, 30) and greater rates of force development (251) compared with FR. The unique physiological and biomechanical responses to BR indicate that it may provide a different training stimulus to FR, which may serve to reduce injury risk, enhance metabolic functions, and improve muscular capabilities. Furthermore, including BR into a programme while following the principles of variability, specificity and overload may serve as a conjugate method to combat training monotony.

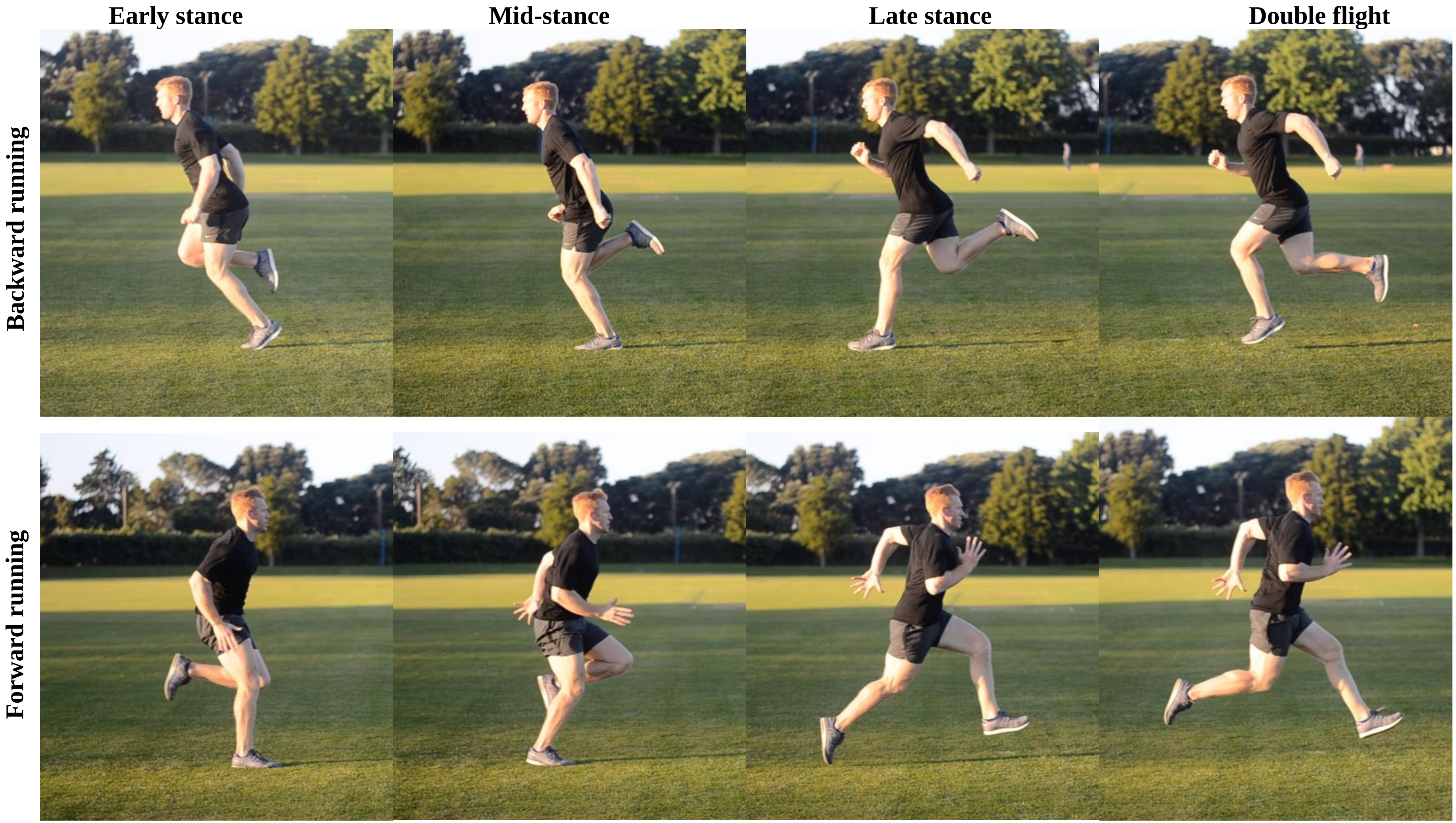

Figure 7.2. Gait cycle of backward running and forward running.

Table 7.1. Comparison of acute characteristics of forward versus backward running at matched relative running speeds

Variable	**Study**	**BR in relation to FR**
Cardiopulmonary		
Oxygen consumption	(3, 63, 251)	↑
Heart rate	(3, 63)	↑
Blood lactate	(3, 63)	↑
Kinematics		
Velocity	(9, 237)	↓
Ankle ROM	(55)	↓
Knee ROM	(55, 65)	↓
Hip ROM	(55)	↓
Stride frequency	(9, 55, 243)	↑
Stride length	(9, 243)	↓
Contact time	(243)	↑
Flight time	(243)	↓
Lower limb muscle activity	(64, 251)	↑
Eccentric muscle action	(29, 30)	↓
Isometric muscle action	(29, 30)	↑
Concentric muscle action	(29, 30)	↑
Kinetics		
Vertical leg stiffness	(29)	↑
Knee joint force	(65, 201)	↓
Vertical GRF	(243)	↓
Braking/propulsive force	(29, 30)	↓/↑
Braking/Propulsive time	(29, 30)	↓/↑
Rate of force development	(251)	↑

BR = backward running; FR = forward running

7.2.2 Backward Running as an Injury Resistance Tool

The primary goal of any strength and conditioning programme is to reduce the likelihood of injury and ensure athletes are healthy for competition (124, 228). Along these lines, BR is included in programmes specifically designed to minimise injury risk in athletes of all ages (49, 77, 220). In particular, warm ups such as FIFA 11+ (131), FIFA 11+ kids (203), HarmonKnee (114), Performance Enhancement and Injury Prevention (77), and Dynamic Warm-Up (4) provide exercise variation and progression to reduce the likelihood of sustaining an injury to the knee and ankle ligaments and thigh muscle strains. Warm up programmes including BR have been found to be particularly beneficial for reducing the amount of overuse and severe injuries in athletes between 13-20 years of age (77, 114, 220).

One rationale for including BR early into a warm up protocol or pre-season programme is that reductions in joint ROM of the lower limbs (55) while concomitantly adopting an increased stride frequency will reduce the load on lower body joints (65, 93, 201). Chronic reductions in lower limb joint loading may lead to fewer impact related musculoskeletal injuries. Further, functional reversal of the leg muscles during BR may provide a means to reduce stress on the posterior chain and reduce repetitive strain injuries (94). This is particularly important in adolescent athletes who are undergoing rapid hormonal and anthropometric changes where their training increases (124) and they must be able to withstand greater forces (157). Coaches may use BR to improve neural and musculotendinous properties of the lower limbs, while adding variety into a programme, and attenuate stress placed on the lower limbs.

7.2.3 Backward Running to Enhance Muscular Functions

The nature of athletic tasks determines the reliance on components of musculotendinous functioning. Forward running is often understood in terms of a spring mass model by which muscles are stretched and eccentric energy is absorbed and converted to propulsive energy through the tendons and connective tissue (18). Alternatively, BR more closely reflects a pendulum action whereby the muscle and tendon length remains relatively constant upon foot-ground contact and propulsion is produced primarily through a contractile movement (29, 30). Concentric-dominant exercises offer a potentially useful training tool, which may negate or mitigate muscle damage, soreness, fatigue, and inflammation associated with eccentric movements (106). The specific isometric and concentric nature of BR has led clinicians and coaches to use BR as a tool to return players back from injury (94, 141) and increase quadriceps strength (64, 227) while concomitantly reducing knee joint stress (65, 201).

Training BR leads to preferential adaptations in movements which are dependent on the concentric muscle functioning of the quadriceps, such as vertical countermovement jumps and early accelerated sprinting (238). Adolescent athletes around the time of their growth spurt seem to respond particularly well to BR, where their vertical jump ability has been found to increase by 9.9% (ES = 0.83) and their sprint performance over 0-10 m and 0-20 m improved by 7.5% (ES = 1.56) and 5.0% (ES = 1.04), respectively following training twice a week for 8-weeks. The dynamic leg extension action produced during BR may provide a method to train the anterior muscles of the thigh and hip to produce concentric force at relatively high velocities. Therefore, if the demands of a sport depend on acceleration ability or an athlete needs to improve their ability to produce concentric force, BR may provide a means to develop this component of athletic performance.

In addition to linear sprinting, BR has also been identified as a method to increase vertical leg stiffness (238) and change of direction ability in athletes (230). Uthoff et al. (238) found that 8-weeks of BR training improved vertical leg stiffness similar to equal volume and intensity training in a group of high-school male athletes (10.6% and 12.4%, respectively). Additionally, Terblanche and Venter (230) concluded that netball specific training using BR was more beneficial than equivalent FR training, with 505 agility, Agility T, and ladder tests improving between 3.4-10.3% (ES = 0.85 – 1.44) in a group of highly trained female netball athletes. These findings indicate that BR is not only a contractile stimulus, but can promote positive adaptations to fast stretch-shortening cycle tasks (234) and movements which have a large eccentric component (33) for athletes of varying ages and experience levels.

7.2.4 Backward Running as a Metabolic Stimulus

From an energetics standpoint, BR places a greater metabolic demand on individuals than FR at similar relative intensities (3, 63, 251). Essentially, this means that an athlete can perform BR at the same absolute volume and relative intensity as FR, yet expect to expend approximately 28% more energy (41). Therefore, when repeatedly exposed to BR training, athletes are able to improve their running economy between 2.5-33% (186, 229) while also improving their peak oxygen consumption capabilities by 5.3% (229). The exact mechanisms underpinning these adaptations are ambiguous and require further exploration, however, the variability of performing a novel athletic task (148) along with increased demand on the concentric functioning of muscles have been postulated to influence the specific metabolic responses to BR (29, 30). Practically, this means that athletes who are either injured, or under a high training load, can include BR into their programme to stimulate metabolic responses similar to FR with fewer repetitions.

7.3 The How: Integrated Programming

Given the highlighted research into why a strength and conditioning coach may wish to implement BR as an acute or chronic training stimulus for athletes, it is important to understand how BR may be integrated as an effective training practice. To minimise the effects of accommodation, subsequent training stagnation, the principle of variation should be applied (253). Appropriate variation is important to stimulate continued adaptations over multiple training phases (117) and is concerned with appropriate manipulation in exercise selection, speed, volume, and intensity (224). Similarly, when an athlete is learning a new skill, there needs to be a sequence of progressions that allow them to become habituated with the movement and master the basics at lower intensities before advancing to higher intensity or more complex movements (186). Therefore, we recommend that coaches use BR as a method to vary exercise selection and it should be progressed in order of running speed, absolute and relative volume, and finally, by adding external resistance. The following sections provide recommendations for how to progressively integrate different modes of BR into an athlete's training programme. Please note that while it is important to consider exercise selection, speed, volume, and appropriate resistance for both purposes of injury rehabilitation and athletic performance, the following programme suggestions are focused on healthy, uninjured, athletes. However, we recommend any coach wishing to use BR as a return to play protocol to adhere to the principle of variation and confer with their physiotherapist or team physician for programming considerations.

7.3.1 Phase 1: Progress Backward Running Speed

Due to the increased coordination demands (148) and modifications to sensory inputs during BR (100, 148), running backwards at speed should be introduced gradually into an athlete's training programme and, where possible, be performed on soft surfaces such as grass. This is especially important if an athlete is young or has limited training history with BR as they may have more variable coordination ability (62, 200). The programme presented in this section is designed to habituate an athlete to high-speed BR at commonly used speed ranges of 40-55%, 60-75% and +90% of maximum running velocity (237).

Table 7.2. 2-week introductory backward running programme.

Training phase	**General preparation**			
Speed emphasis	Familiarisation			
Progression emphasis	Speed			
Week	1		2	
Training session	1	2	3	4
	Repetitions	Repetitions	Repetitions	Repetitions
Slow (40-55%)	10	8	6	5
Moderate (60-75%)	5	5	6	6
Fast (90+%)	0	2	3	4
Distance (m)	15 - 20	15 - 20	15 - 20	15 - 20
Total volume (m)	225 - 300	225 - 300	225 - 300	225 - 300
Cue	High	Moderate	Low	None

An introductory programme such as that detailed in Table 7.2 may be conducted over a microcycle of two weeks with training conducted biweekly. As running speed is increased, special attention should be given to the technical running model using ability appropriate cues similar to those found in Table 7.3 and feedback on running times. As speed is progressed, the amount of feedback on running times may be reduced to allow athletes to autoregulate their speeds. Based on our previous work (237), it takes male athletes between the ages of 15-18 years of age approximately three sessions to become accustomed to self-selecting BR and FR speeds consistently between sessions. Overload in this manner serves to both enhance proficiency and confidence in performing high-speed BR, and refine autoregulatory capabilities of athletes.

Table 7.3. Cues for backward running technique

1. Slight flexion at the hip
2. Push explosively through the ball of the foot on the ground
3. Use similar arm action to forward running, i.e. contralateral arm/leg action
4. High heel recovery of the swing leg
5. Extend the swing leg behind by kicking and reaching rapidly

7.3.2 Phase 2: Progress Backward Running Volume

Once an athlete is familiar with BR at high intensities and can accurately selfselect running speeds with minimal to no external feedback, the second phase is to overload BR by modifying either relative or total running volume. Respectively, this means a speed or strength coach can either manipulate the distance travelled at each intensity, or the sum of all intensities for total session load. Based on current evidence from both youth and adult research, free, or unresisted, sprint programmes should be performed 2-3 times a week for >6 weeks and comprise of approximately 16 runs over ~15-30 m per session (168, 210). These programming guidelines have also been found to lead to positive adaptations after BR (238). Therefore, the training programme presented in this section is designed to improve performance and lower body stretch shorten cycle function by progressively increasing both forms of volume (238).

Table 7.4 exemplifies how an 8-week programme can be structured during a transition from the general preparatory phase into the specific preparatory phase with an emphasis on developing speed-strength. To standardise the programme, lower intensity runs are performed before higher intensities. Volume is progressed first by increasing the number of moderate and fast repetitions over the course of the first 4-weeks while maintaining the same total session volume. Second, using a similar relative loading scheme to the first

Table 7.4. Sample off-season unresisted backward running programme

Training phase	**General preparation**								**Specific preparation**							
Speed emphasis	Speed strength															
Progression emphasis	Relative and absolute volume															
Week	1		2		3		4		5		6		7		8	
Session	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Repetitions Slow (40-55%)	3	3	2	2	1	2	1	1	3	3	2	2	1	2	1	1
Repetitions Moderate (60-75%)	4	3	4	3	4	2	3	2	4	3	4	3	4	2	3	2
Repetitions Fast (+90%)	8	9	9	10	10	11	11	12	8	9	9	10	10	11	11	12
Distance (m)	15	15	15	15	15	15	15	15	20	20	20	20	20	20	20	20
Session volume (m)	225	225	225	225	225	225	225	225	300	300	300	300	300	300	300	300

4-weeks, running distance is increased by five metres for each run, which leads to an increase in total session volume for weeks 5 - 8. To ensure the acute expression of muscular power is maintained, fast repetitions (+90% max effort) should include rest intervals of three to five minutes (51). Understanding how BR can be progressed using volume manipulation is useful to strength and conditioning professionals and provides a foundation for adding external load to BR in the form of resisted runs.

7.3.3 Phase 3: Progressive Backward Running Using Resistance

Once an athlete has undergone training phases progressing BR speed and volume, external load can be added in the form of resisted sled towing. Resisted sled towing is a form of unilateral strength training (130) which adheres to the principle of specificity to improve sprinting performance and lower body power (45, 191). Inclusion of unilateral movements is essential given that when athletes perform linear running or change of direction movements, they will predominantly be in a single-leg support during the action (221). Furthermore, variable unilateral multidirectional movements have been shown to improve change of direction ability and multidirectional jumping ability compared to traditional bilateral exercises (81).Therefore, integrating backward sled towing into an athlete's training programme is recommended as a means to aid metabolic and neuromuscular functioning (195, 242).

The programme in Table 7.5 demonstrates how an 8-week resisted BR programme can be structured during the transition from a specific preparatory phase into a pre-competition phase with an emphasis on developing strength-speed for accelerated sprinting. The programme follows the recommendations that resisted sprint training focused on acceleration performance should be conducted 2 – 3 times per week for >6 weeks with loads >20% body mass (191). As resisted sprinting maximal expression of muscular power, interset rest of three to five minutes is recommended to ensure maximal motor unit activation and maintenance of training intensity (51). The use of daily undulated loading is used to add novelty and variability to the programme (89), whereas the principle of progressive overload is adhered to by increasing resistance each week. The concentric muscle demands of sled towing (195) in combination with BR provide a method to strengthen contractile muscle function.

7.3.4 Backward Running as Part of a Total Performance Plan

Although the preceding programmes have been recommended for improving running, jumping, and hopping performance in athletes (238), by no means are they the only way to integrate BR into an athlete's training programme. By understanding the underpinning mechanisms of BR, an informed coach/clinician can adapt the programmes any number of ways to meet the demands of the sport or requirements of the athlete. Similar to any other training method, BR should not be performed in isolation and instead as part of a wider strength and conditioning programme that includes a range of training modalities. It is therefore recommended that strength and conditioning coaches include strength, multi-directional running, and ballistic movements because these combinations will provide concurrent training adaptations to muscle force capabilities, stretch-shortening cycle functioning, and metabolic fitness (192). Furthermore, BR may be implemented into regular warm-ups as a time effective method to reduce injury and enhance performance, or into a traditional FR sprint programme on acceleration days as a conjugate method to increase movement variability. Although further research still needs to be performed to identify the optimal application of BR, when it is included as part of a youth athlete development or sport-specific training programme it may reduce injury risk and promote beneficial adaptations across a wide variety of athletic performance tasks dependent on lower body power, speed, and metabolic fitness (77, 186, 230, 238).

Table 7.5. Sample off-season resisted backward running programme.

Training phase	**Specific preparation**								**Pre competition**							
Speed emphasis	Strength speed															
Progression emphasis	Load relative to body mass															
Week	1		2		3		4		5		6		7		8	
Session	1	2	3	4	5	6	7	8	9	10	1	2	3	4	15	16
Repetitions	6	6	7	7	8	8	9	9	6	6	7	7	8	8	9	9
Load	20%	30%	25%	35%	30%	40%	35%	5%	30%	40%	35%	45%	40%	50%	45%	55%
Distance (m)	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
Distance per session (m)	90	90	105	105	120	120	135	135	90	90	105	105	120	120	135	135
Weekly distance (m)	180		210		240		270		180		210		240		270	

7.4 Conclusion

Given the rigours of sport, coaches are constantly looking for effective training strategies to improve their athletes' performance while concomitantly minimising joint loading. As evidenced previously, BR could be a means of aerobic, anaerobic, and neuromuscular training that does not overload tendons and ligaments as much as FR. Importantly, this chapter is not intended to understate the importance of training FR, nor is BR a panacea for injury prevention or athletic performance, but rather a method in a practitioner's toolkit. Similar to other forms of strength and speed training, BR should be practiced and progressed appropriately. Depending on the competence and goals of the athlete and current training phase, different BR modalities may be used to apply the principles of variation, specificity, and overload. Integrating BR as part of a holistic athlete development programme may provide a novel stimulus which brings physiological and physical adaptations that compliment an athlete's ability, serves to increase training variability, and stave off the monotony of traditional training.

CHAPTER 8. SUMMARY, FUTURE RESEARCH DIRECTIONS, AND PRACTICAL APPLICATIONS

8.1 Summary and Discussion

Specific sprint training in the form of linear unresisted and resisted sprinting are often used by coaches to improve sprinting performance in youth athletes, yet literature on the effectiveness of these sprint training methods in boys around the age of their adolescent growth spurt is limited to two studies (167, 204). Further, BR is a locomotive strategy used by most overground athletes of all ages and levels, yet little scientific evidence is available on the training benefits of BR. Given that the period around adolescence appears to be an important time for the natural development of speed in boys (67, 176, 194, 241), it was necessary to understand if specific sprint training methods, whether forwards or backwards, can promote adaptations which are as, or more, effective than those of maturation alone.

This PhD served to answer the overarching question: “can BR training modalities promote positive adaptations in athletic performance among male youth athletes”? This purpose was considered based on gaps identified in the literature. Specifically: 1) no reviews on the acute or trained responses to BR existed in the literature; 2) no study had determined the consistency of self-selecting running speed during BR and FR using autoregulation; 3) no study had established the load-velocity relationship during resisted BR, nor established the consistency of load-velocity relationships during resisted BR and FR; 4) no study had investigated the training effects of unresisted BR on FR speed, jumping ability, or stiffness performance in adolescent athletes; 5) no study had investigated the training effects of resisted BR on FR speed, jumping ability, and stiffness performance in adolescent athletes; and, 6) no programming considerations had been proposed for integrating BR into athletic training programmes. Consequently, bridging these gaps in the literature provided the focus for the thesis. This chapter provides a synopsis of the main findings for each aim in this thesis. Subsequent discussion on the practical applications and limitations of each aim are presented and directions for future research are offered.

8.1.1 Aim 1: Review and understand the differences in acute and chronic performance, neuromuscular and metabolic responses to BR vs FR.

Anecdotally, BR has been used by clinicians and coaches to return players to sport and prepare athletes for competition; however, there was little synthesised scientific evidence into the acute and trained responses to BR compared to FR. This literature review investigated the energetic and biomechanical adaptations associated with BR both acutely and following training. The major takeaways from this review were as follows:

1. The metabolic cost of BR is 28% greater than during relative speed FR.
2. Maximum BR speed is, on average, ~70% of FR maximum velocity.
3. Step length and flight time is decreased during BR compared to FR; whereas, stride frequency is increased and contact time remains relatively unchanged.
4. The functional role of lower limb muscles is interchanged between BR and FR, whereby the anterior muscles of the legs become the primary source of propulsion and posterior muscles absorb braking force.
5. BR is predominantly a contractile stimulus which is less reliant on the stretch-shorten cycle.
6. Leg extensor and hip flexor muscles display 53% and 190% greater activity during BR compared to FR, respectively.
7. Decreased mechanical stress on the knee joint, in the form of lower patellofemoral joint compressive forces and vertical ground reaction forces, is a product of BR versus FR.

8. Six to eight weeks of BR training leads to increased adaptations in maximum voluntary isometric contractions and isokinetic muscular torque production capabilities of the leg extensors in trained populations.
9. Six weeks of BR training is useful for maintaining linear sprint performance and vertical jumping ability, yet increases change of direction performance in both untrained and trained populations.

From the review, it was concluded that the acute and trained response to BR are not the same as FR. While sports scientists have previously shown relatively little interest in developing BR training strategies that could improve athletic performance, this culmination of literature offered the first overarching review of BR and provided insight into the potential training related adaptations of BR.

8.1.2 Aim 2: Investigate athletes' ability to consistently achieve prescribed running intensities during overground unresisted backward and forward running.

Speed and strength coaches commonly prescribe target running intensities (e.g. ~50%, ~75% and +95% of maximum effort), during warm-ups, in training, or for rehabilitation; however, there was limited scientific data suggesting that athletes are capable of reliably self-selecting running speeds to achieve these target intensities forwards, and no research on these capabilities during BR. Therefore, the purpose of this study was to determine the ability of 34 high-school athletes to perform BR and FR at prescribed target intensities consistently over 0-20 m across multiple sessions, and compare these velocities between running directions. Major findings included:

1. The change in mean velocity between consecutive trials was smaller between the 2nd and 3rd session (-2.0 to 0.22%) compared to the 1st and 2nd session (-3.3% to 5.3%) for both BR and FR at all prescribed intensities.

2. Absolute consistency was better between the 2nd and 3rd session (CV = 0.99% to 3.6% and 1.0% and 4.2%) compared to the 1st and 2nd session (CV = 2.7% to 8.9% and 2.5% to 11.0%) for BR and FR, respectively.
3. Absolute consistency was found to be the best over the fastest intensity for both running directions.
4. For sessions 2 and 3, relative consistency during BR and FR was higher (ICC = 0.92 to 0.99 and 0.89 to 0.95, respectively) than that between session 1 and 2 (ICC = 0.67 to 0.91 and 0.52 to 0.62, respectively).
5. The fastest prescribed intensity was found to have the highest relative consistency for both BR and FR.
6. Running speed during BR was observed to be between 72% and 74% of FR speed across all prescribed intensities.

It would seem although a learning effect was apparent given the systematic changes in the mean between the first two trials, athletes were able to self-select BR and FR velocity consistently between the 2nd and 3rd trials. These findings provided coaches with the first insights into the ability of athletes to self-select speed consistently to achieve prescribed target running intensities both backwards and forwards. Self-selecting running speed using autoregulation strategies could prove to be an effective strategy for overloading running intensity during training.

<u>8.1.3 Aim 3: Explore the load-velocity relationships during resisted backward running and forward running and determine the consistency of running performance.</u>

Understanding load-velocity relationships can be used to determine optimal loading prescription during resisted sprinting to produce the desired training effects. However, the load-velocity relationships of resisted BR and FR had not been studied, and the consistency of these performances had yet to be established. Therefore, the purpose of this study was to determine the load-velocity relationships of 21 high-school athletes during resisted BR and resisted FR and explore the consistency of the load-velocity data across multiple testing sessions. The primary findings included:

1. During resisted BR and resisted FR, loads of 31%, 46%, and 61% BM resulted in 27%, 38%, and 48% and 23%, 33%, and 43% decreases in running speed compared to unresisted maximum effort BR and FR, respectively.
2. No systematic differences in velocity were found between consecutive sessions for any load during either resisted BR or resisted FR.
3. Absolute consistency of resisted BR and resisted FR was determined by CV ≤ 7.5% and 7.2%, respectively.
4. Relative consistency of resisted BR and resisted FR was found to be good to excellent (ICC ≥ 0.83 – 0.91).
5. The absolute and relative consistency of resisted BR and resisted FR load-velocity slope was moderate to excellent (CV = 2.3 to 7.5; ICC = 0.67 to 0.91).

The results of this study provided coaches with the first load-velocity description of resisted BR and how this relationship compares to resisted FR at relative loads. Increasing resisted BR and resisted FR by ~13% and ∼15% body mass respectively, consistently results in ∼10% decreases in running velocity compared to unresisted maximal effort velocities during both BR and FR in high-school athletes. Essentially, this data showed that the slope is reliable and practitioners could choose to load at any point on the slope and expect to get accurate velocity decrements associated with that loading. Furthermore, this research provided practitioners with more informed diagnostics to enable targeted resisted sprint training depending on the desired training responses e.g. athletes which require greater force or velocity capabilities.

8.1.4 Aim 4: Investigate and compare the effects of backward running and forward running training programmes on speed, jumping, and stiffness performance in high-school athletes.

Unresisted sprint training is widely used by coaches and can result in moderate to large improvements in forward sprinting ability in adolescent athletes. However, whether this method of training may be used to enhance other athletic characteristics, such as jumping and lower limb stiffness, was unknown. Further, BR training is a promising method for promoting physiological and neuromuscular adaptations which transfer to FR in adults, yet it was unknown whether these adaptations transfer to adolescent athletes. Therefore, the purpose of this training study was to investigate and compare the effects of BR training and FR training programmes on sprinting, jumping, and stiffness performance in 67 male high-school athletes. The primary findings included:

1. Training responses from BR transferred to FR sprint ability.
2. Unresisted BR training was the most effective method for improving sprinting ($p \leq 0.01$; ↑5.0% to 7.5%) and jumping performance ($p \leq 0.001$; ↑9.9%). This is further indicated by the 95% CI on the ES changes within-groups ranging from small to very large for 10 m, 20 m and CMJ performance in Appendix 2 Table A.1.
3. The BR training group had the highest relative number of individual responses above the SWC for 10 m times (96%), 20 m times (96%), CMJ height (80%), and vertical leg stiffness (72%).
4. The FR training group demonstrated the greatest relative number of responses above the SWC for 10 to 20 m split times (56%).
5. Moderate to large worthwhile gains were experienced in 96% of the BR training group for 10 m and 20 m performance and 53% and 65% of the FR training group, respectively.

6. Vertical leg stiffness improved similarly for both BR training ($p \leq 0.001$; ↑10.6%) and FR training ($p \leq 0.01$; ↑12.4%).
7. Over half of the BR training (52%) and FR training (50%) groups experienced moderate to large worthwhile gains in leg stiffness while just over a quarter were over the SWC threshold in the CON group (27%).
8. Compared with the CON group, BR training was found superior ($p \leq 0.01$) for all performance tests, where large effects occurred for sprint times, and moderate effects were seen in CMJ height and vertical leg stiffness, respectively.
9. The FR training group displayed superior magnitudes of improvement ($p \leq 0.01$) compared with the CON group in sprinting ability and vertical leg stiffness, where small to large effects were present for each performance test, respectively.
10. Between training groups comparisons were found to differ significantly ($p \leq 0.05$), with small to moderate effects for 10 m and 20 m sprint times and CMJ height in favour of BR training over FR training. Although, readers should be cognisant that 95% CI on the within-group ES for FR training and BR training overlap for every performance variable. Indicating that that there is some change that the true effect is insubstantial.

The findings from this study suggest that unresisted BR training and FR training can be used to improve sprinting ability, jumping height, and leg stiffness in adolescent athletes, although BR training appears to result in superior responses for sprinting and jumping performances. Previously, unresisted FR sprint training had been found improve sprint performance at similar rates to normal soccer training in mid-PHV boys (167). Considering that 10 m sprint performance is expected to improve by 3.1%, or 0.05 seconds annually (246), the respective 7.5% and 5.0% increases following BR training and FR training indicate unresisted sprint training, either backwards or forwards, can lead to greater adaptations than might be projected due to natural development during boys' adolescent growth spurt. However, the preferential adaptations to sprint acceleration and CMJ performance seen herein may be attributed to the findings that anterior leg muscle activity can be up to 189.6% greater (223) and lower limb muscles may spend up to 4% more time in a concentrically contracted state over the stride cycle during BR compared to FR (179), consequently resulting in more total work being performed and theoretically improving leg strength and power. Coaches may use this information to better understand how running speed and volume can be progressed effectively to moderate training responses to unresisted BR and FR.

8.1.5 Aim 5: Examine and compare the training effects of resisted BR and resisted FR programmes on speed, jumping, and stiffness performance in high-school athletes.

Resisted sprinting is a common training method used to increase sprinting ability in athletes. However, only loads up to 20% BM had been empirically explored in athletes under 18 years of age, and no research had investigated the effectiveness of resisted BR training. Therefore, the purpose of this training study was to examine and compare the training effects of resisted BR and resisted FR programmes with loads ranging from 20-55% BM on speed, jumping, and stiffness performance in 115 male high-school athletes. The main findings of this research were as follows:

1. Eight weeks of resisted BR led to the greatest improvements in forward sprinting performance ($p \leq 0.01$; ↑1.4 to 2.4%).
2. Athletes who performed FRS did not improve sprint ability (↑0.65 to 1.2%) over the CON group athletes ($p > 0.05$) who participated in their normal PE class (↑0.50 to 1.1%).
3. The likelihood of a new athlete improving sprinting performance was the highest for resisted BR (66-73%).

4. Resisted BR training was moderately effective for increasing CMJ ability ($p \leq 0.001$; ↑10.8%).
5. Moderate improvements in CMJ performance ($p \leq 0.001$; 6.8%) were found following resisted FR.
6. Following resisted BR training, vertical stiffness was found to improve ($p \leq 0.001$) by 26.3% with moderate effectiveness.
7. Resisted FR training was observed to have a moderate effect on vertical stiffness, with improvements of ↑19.3% ($p \leq 0.001$).
8. Regardless of running direction, resisted sprinting was more effective ($p \leq 0.05$) than traditional PE curriculum for increasing jumping and stiffness capabilities.
9. 75-80% of new athletes are expected to improve jumping and stiffness performance following resisted BR training.
10. The probability of a new athlete improving jumping and increasing stiffness following resisted FR training is between 79-81%.
11. There were no statistically significant differences ($p > 0.05$) observed between the training groups for any performance test.

This study provided practitioners with the first insights into the effectiveness of resisted FR training on athletic tasks outside of linear sprinting, and provides the first empirical understanding into the utility of resisted BR training for athletes of any age. The improvements in 20 m performance following resisted BR and resisted FR were similar and lower, respectively, compared to previous findings in resisted FR for 20 m (2.76%) (215) and maximal velocity (5.76%) (204) performance in youth mid-PHV to post-PHV. However, the 10.8% and 6.8% gains in CMJ height from resisted BR and resisted FR, respectively, support that these resisted sprinting methods may be used to promote larger responses than might be expected from annual natural development (i.e. 6.9%) (246). The increased CMJ ability following resisted BR and resisted FR in this study were similar to what has been found following combined and plyometric training in youth of similar age (61, 126, 169). Moreover, the improvements in stiffness resulting from resisted BR and resisted FR were what might be expected to occur over longitudinal transitions between different stages of maturation (208). While resisted sprinting in either direction may be used to improve jumping and stiffness capabilities in athletes similar to other nonspecific training methods the reversal of muscle functions occurring during resisted BR may lead to particular adaptations to the anterior muscles of legs preferentially enhancing early acceleration and vertical displacement capabilities. These findings are meaningful for practitioners because they show that although resisted sprinting was designed for the purpose of developing sprinting ability, it may also be a means used as a nonspecific training method which enhances other athletic capabilities, such as jumping and stiffness. Additionally, the quasi-isometric nature (64) and approximately 22% faster speed at which the contractile elements of the muscle can develop force (251) during BR compared to FR may lead strength coaches, sports scientists and clinicians to believe that BR may be predominantly used to improve the functioning of contractile tissues

8.1.6 Aim 6: Provide programming considerations on why and how to integrate backward running to improve athleticism.

Coaches are endlessly in the pursuit of training methods which enhance athletic performance in a safe and effective manner. However, before novel exercises are incorporated, it is necessary to understand the benefits of using such methods, and useful to know how these methods fit into the greater athlete development programme. Therefore, the purpose of this chapter was to examine why BR may be considered as a method to improve components of athleticism and provide practical recommendations for how to integrate BR into athlete training programmes. The main considerations from this chapter are as follows:

1. Since visual feedback is altered during BR, the use of alternative sensory systems is increased to maintain positional awareness.
2. An athlete's ability to run backward at high speeds may allow them to maintain view of the playing field and provide them opportunities to make informed decisions during competition.
3. Many warm-up protocols for both youth and adults include BR as part of a sport-specific preparation to enhance performance and decrease the likelihood of injury.
4. When used as a training tool, BR can improve qualities of aerobic and anaerobic fitness, vertical jump height, change of direction ability, and linear sprinting performance in youth and adult athletes.
5. When introducing athletes to BR, it is important to use a sequence of progressions to familiarise them with the movement at lower intensities before advancing to maximum effort attempts.
6. Progressing running speed over several training session may be used to habituate athletes to high speed running during the general preparatory phase.
7. Once athletes are used to high-speed BR, manipulating absolute and relative running volume can be used to facilitate speed strength responses at either the end of a general, or beginning of a specific, preparation phase.
8. Progressively overloading resisted BR may serve as a method to develop strength-speed for accelerated sprinting when transitioning from a specific preparatory phase into a precompetition phase.

This chapter highlighted why BR could benefit athletes and provided strength and conditioning coaches with practical considerations for how to integrate BR into athlete development programmes. Coaches are encouraged to use the information in this chapter and adapt BR to fit the competency of their athletes and promote the desired training outcomes.

8.2 Practical Applications

Strength and conditioning practitioners are constantly looking for safe and effective methods to enhance their athletes' sprinting and jumping ability, but may be limited by time or resources. This thesis was intended to provide strength and conditioning practitioners or speed coaches who may not have access to advanced monitoring or training equipment a simple, evidence-based, method for prescribing BR and FR training to enhance athletic characteristics. Resulting from the findings in this body of work, the following applications/recommendations are offered:

1. Relatively novice athletes can consistently self-select BR and FR velocities based around commonly prescribed target running intensities in as few as two sessions.
2. Regardless of running direction, as running intensity increases, so does the consistency of self-selected running velocity.
3. Using percentage of body mass or velocity decrement, resisted sprinting loads can be accurately determined for both BR and FR in relatively novice athletes with the load-velocity relationships being near perfect to perfect for the respective running directions.
4. When determining resisted sprinting loads for high-school athletes using weighted sleds on indoor hardwood courts, running velocity can be consistently expected to decrease by ∼10% when loads are increased by ~13% and ∼15% body mass for BR and FR, respectively.
5. Progressive high-speed BR is recommended as a safe and effective training method for enhancing sprinting, jumping, and stiffness capabilities in high-school athletes.

6. Progressively overloading resisted BR and resisted FR using relatively heavy loads up to 55% BM is recommended as a safe and effective training method for male high-school athletes.
7. Although resisted sprinting has been developed as a specific sprint training method, adaptations from both resisted BR and resisted FR appear to have the greatest transfer to vertically oriented athletic tasks.
8. Adaptations following unresisted and resisted BR training transfer to improvements in forward sprinting ability.
9. If the goal of an athlete's programme is to improve early sprint acceleration capabilities, BR, whether unresisted or resisted, is recommended over FR.
10. Regardless of running direction, coaches should pay particular attention to running technique and be cognisant that speed, volume, and external load may moderate training responses to sprint specific training methods.
11. When integrating BR into an athlete's training programme we recommend that coaches progress it in order of running speed, absolute and relative volume, and finally, by adding external resistance.

8.3 Limitations

It is important for the reader to be cognisant of the following limitations when interpreting the results of this thesis.

1. The design of this thesis to understand loading considerations and training effects of BR may be considered unique given that the mechanical determinants of BR are vaguely understood in adults and unknown in adolescent populations. However, the overt performance effects identified within this thesis provide a foundation for future research to understand the underpinning mechanisms for these adaptations.

2. The resisted sprinting load-velocity relationships established in Chapter 4 were only concluded for hardwood surfaces, making the generalisation of these findings challenging for surfaces with differing coefficients of frictions (e.g. grass, field turf, synthetic track).
3. The control groups in the training studies (Chapter 5 and 6) were active controls, matched for age and maturation, participating in their normal PE classes. Their activity was not quantified and may have influenced the responses, or lack thereof, observed in these groups. However, due to the active nature of young athletes, active controls are commonly used when researching training effects in adolescent athletes (158, 212, 250).
4. The training study durations were limited to 8-weeks and only two training sessions a week due to term time, school and class constraints. Long-term training studies may provide a more comprehensive understanding of the longitudinal training effects of both BR and FR modalities. However, the training studies reflected how training programmes could be implemented within the length of a typical school term. While longer study durations would have been ideal, we only had one school term with these athletes before they were enrolled in a new class. The length of these studies are within the recommended guidelines for sprint specific training in youth (168, 209).
5. The studies in this thesis are de-limited to male athletes' mid-PHV to post-PHV. Generalising the findings of this research to females, less mature youth, or adults should be done with caution. However, this thesis offers a snapshot of sex- and maturity-specific responses to BR and FR, and provides detailed information on how these methods may be utilised for this population.

6. Participants were performing a variety of sports outside of school/training, which were not quantified and may have had some influence on the responses observed in this thesis.
7. Similar to other unresisted and RS training studies in youth, we only measured performance directly pre-training and post-training (167, 204). Therefore, it is unknown whether there is a supercompensatory effect, nor the nature of detraining, following training cessation.
8. The methodological procedures of this thesis were, for the most part, only concerned with the development of sprint acceleration and therefore only a small part of the athletes' sprint performance. While BR modalities seem to be particularly beneficial in the acceleration phases over the first 10 m, analysis of other phases of sprint performance, such as maximal velocity, might have resulted in different findings.
9. Improvements in athletic performance following BR training may have been a result of neural and/or structural adaptations. However, this thesis did not measure the musculotendinous responses directly, making it difficult to decipher if performance changes were a result of neural, muscular, or tendinous transformations.
10. Although BR is primarily believed to be a contractile stimulus, this thesis did not measure specific changes in isometric, concentric, and eccentric muscle strength. Therefore, the contractile reliance posit is currently unexplained.

8.4 Future Research Directions

This thesis aimed to assist strength and conditioning professionals with understanding whether BR training could be a tool for improving athletic performance and to determine how to prescribe BR training to achieve their desired goals. Considering the findings and limitations of this thesis, the following recommendations can be offered for future research:

1. Given the training effects, it is clear that the nature of BR results in beneficial performance responses. However, knowledge into the underlying determinants responsible for promoting the observed training adaptations is currently scarce. Acute studies using floor-level optical measurement systems or series of in-ground force platforms would help sports scientists and strength and conditioning coaches understand BR step variables over different phases, or under different loading conditions. These insights may help shed light on why BR may be a useful method for enhancing athletic potential.
2. The result of this project determined that BR modalities can improve sprint acceleration capabilities and lower limb stiffness. While accelerated sprinting is essential for many sports, and lower limb stiffness is a determinant of maximal velocity sprinting, it is unknown whether adaptations to BR training transfer to maximal velocity sprinting. Therefore, future research examining the effects of BR on maximal velocity sprinting would enhance our understanding of BR as a forward sprint training method.
3. Empirical training studies commonly include pre-training and post-training performance measurements. However, only quantifying performances at these two points may not consider the necessary time for adaptations to manifest due to supercompensation, nor does it determine how long responses will last following training cessation. Therefore, in order to improve exercise prescription and maximise training responses to unresisted and resisted BR, we suggest that future research should attempt to quantify periods of supercompensation and detraining.
4. Given that the improvements following BR and FR training in this thesis are almost exclusively better than what might occur as a result of natural development, longitudinal research is required to understand whether these adaptation rates may exist over prolonged training periods.

5. The benefits of BR training can be observed from performance tests, yet these outcomes are insufficient at explaining the exact nature of the adaptations (e.g. neural, muscular, or tendinous). Future research should adopt additional mechanistic techniques such as electromyography, dual energy x-ray absorptiometry, and ultrasound scanning technologies to understand neural and structural responses associated with BR methods. This would provide scientists and coaches alike with detailed insights into the exact nature of adaptations which may lead to improved athletic performance.
6. Finally, BR is thought to be reliant on concentric muscle actions, yet was found to improve sprinting, jumping, and stretch shorten cycle movements which also have a large eccentric component to them. Therefore, future research should examine the influence of BR modalities on isometric, concentric, and eccentric force production around the lower limb joints.

8.5 Conclusion

This thesis provided original academic research into unresisted and resisted BR training and its applications for improving athletic performances. Strength and speed coaches can use the data presented in this thesis to understand why BR should be considered for athletic training, how to prescribe and progressively overload different BR modalities, and to guide athlete training programmes aimed at improving speed and power development. Summarily, while future research is required to further elucidate the effectiveness of BR as a method to promote athleticism, including BR as part of a comprehensive athlete development programme may supply a novel stimulus which fosters components of athletic performance, encourages training variability, and thwarts burnout associated with the monotonies of traditional sprint training.

References

1. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, and Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeleton muscle following resistance training. *J Appl Physiol* 93: 1318-1326, 2002.
2. Abbiss CR and Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med* 38: 239-252, 2008.
3. Adesola AM and Azeez OM. Comparison of cardio-pulmonary responses to forward and backward walking and runnin. *Af J Biomed Res* 12: 95-100, 2009.
4. Aguilar AJ, DiStefano LJ, Brown CN, Herman DC, Guskiewicz KM, and Padua DA. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *J Strength Cond Res* 26: 1130-1141, 2012.
5. Alcaraz PE, Carlos-Vivas J, Oponjuru BO, and Martínez-Rodriguez A. The effectiveness of resisted sled training for sprint performance: a systematic review and meta-analysis. *Sports Med* 48: 2143-2167, 2018.
6. Alcaraz PE, Palao JM, Elvira JLL, and Linthrone NP. Effects of three types of resisted sprint training devices on the kinematics os sprinting at maximum velocity. *J Strength Cond Res* 22: 890-897, 2008.
7. Anderson T. Biomechanics and Running Economy. *Sports Med* 22: 76-89, 1996.
8. Arampatzis A, Bruggemann GP, and Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech* 32: 1349-1353, 1999.
9. Arata A. Kinematic and kinetic evaluations of high speed backward running, in: *The department of the air force*. University of Oregon, 1999, p 119.
10. Arazi H, Keihaniyan A, Boroujeni AE, Oftade A, Takhsha S, Asadi A, and Ramirez-Campillo R. Effects of hear rate vs. speed-based high intensity interval training on aerobic and anaerobic capacity of female soccer players. *Sports* 5, 2017.
11. Arnold JA, Brown B, Micheli RP, and Coker TP. Anatomical and physiological characteristics to predict football ability - report of study methods and correlations. *Am J Sport Med* 8: 119-122, 1980.
12. Ayala F, Calderón-López A, Delgado-Gosálbez JC, Parra-Sánchez S, Pomares-Moguera C, Hernández-Sánchez S, López-Valenciano A, and De Ste Croix M. Acute effects of three neuromuscular warm-up strategies on several physical performance measures in football players. *PLoS ONE* 12: e0169660, 2017.
13. Ayala F, Pomares-Moguera C, Robles-Palazón FJ, Del Pilar Garcia-Vaquero M, Ruiz-Pérez I, Hernández-Sánchez S, and De Ste Croix M. Training effects of the FIFA 11+ and Harmoknee on several neuromuscular parameters of physical performance measures. *Int J Sport Med* 38: 278-289, 2017.
14. Bates BT, Morrison E, and Hamill J. A comparison between forward and backward running. Presented at The 1984 Olympic Scientific Congress Proceedings:Biomechanics, Eugene, Oregon, 1984.
15. Behm DG, Young W, Whitten JHD, Reid JC, Quigley PJ, Low J, Li Y, Lima CD, Hodgson DD, Chaouachi A, Prieske O, and Granacher U. Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: a systematic review and meta-analysis. *Front Physiol* 8: 423, 2017.
16. Beunen GP and Malina RM. Growth and bilogical maturation: Relevance to athletic performance, in: *The Child and Adolescent Athlete*. O Bar-Or, ed. Oxford, United Kingdom: Blackwell Pblishing, 2005, pp 3-17.

17. Bezodis NE, Trewartha G, and Salo AI. Understanding the effect of touchdown distance and ankle joint kinematics on sprint acceleration performance through computer simulation. *Sports Biomech* 14: 232-245, 2015.
18. Blickhan R. The spring-mass model for running and hopping. *J Biomech* 22: 1217-1227, 1989.
19. Bompa TO. *Total Training for Young Champions.* Champaign, IL: Human Kinetics, 2000.
20. Borges JH, Conceição MS, Vechin FC, Pascoal EHF, Silva RP, and Borin JP. The effects of resisted sprint vs. plyometric training on sprint performance and repeated sprint ability during the final weeks of the youth soccer season. *Sci Sports* 31: e101-e105, 2016.
21. Borges JH, Conceição MS, Vechin FS, Pascoal EHF, Silva RP, and Borin JP. The effects of resisted sprint vs. plyometric training on sprint performance and repeat sprint ability during the final weeks of the youth soccer season. *Sci Sport* 31: e101-e105, 2016.
22. Bramble DM and Lierberman DE. Endurance running and the evolution of *Homo*. *Nature* 432: 345-352, 2004.
23. Brughelli M and Cronin J. Influence of running velocity on vertical, leg and joint stiffness: modelling and recommendations for future research. *Sports Med* 38: 647-657, 2008.
24. Brughelli M, Cronin J, and Chaouachi A. Efffects of running velocity on running kinetics and kinematics. *J Strength Cond Res* 25: 933-939, 2011.
25. Buchheit M and Mendez-Villanueva A. Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: effect of age and maturation. *J Sports Sci* 31: 1332-1343, 2013.
26. Buchheit M, Mendez-Villanueva A, Quod M, Quesnel T, and Ahmaidi S. Improving acceleration and repeated sprint ability in well-trainined adolescent handball players: speed versus sprint interval training. *Int J Sport Physio Perf* 5: 152-164, 2010.
27. Butler RJ, Corwell III HP, and Davis IM. Lower extremity stiffness: implications for performance and injury. *Clin Biomech* 18: 511-517, 2003.
28. Cappellini G, Ivanenko YP, Poppele RE, and Lacquaniti F. Motor patterns in human walking and running. *J Neurophysio* 95: 3426-3437, 2006.
29. Cavagna GA, Legramandi MA, and La Torre A. Running backwards: soft landing-hard takeoff, a less efficient rebound. *Proceedings of Biologicial Sciences* 278: 339-346, 2011.
30. Cavagna GA, Legramandi MA, and La Torre A. An analysis of the rebound of the body in backward human running. *J Exper Biol* 215: 75-84, 2012.
31. Cavagna GA, Legramandi MA, and Peyre-Tartaruga LA. The landing-takeoff asymmetry of human running is enhanced in old age. *J Explor Biol* 211: 1571-1578, 2008.
32. Cavanaugh JT and Powers M. ACL rehabilitation progression: where are we now? *Current Reviews in Musculoskeletal Medicine* 10: 289-296, 2017.
33. Chaabene H, Prieske O, Negra Y, and Granacher U. Change of direciton speed: toward a strength training approach with accentuated eccentric muscle actions. *Sports Med* 48: 1773-1779, 2018.
34. Chaouachi A, Chtara M, Hamammi R, Chtara T, Turki O, and Castagna C. Multidirectional sprints and small-sided games training effect on agility and

change of direction abilities in youth soccer. *J Strength Cond Res* 28: 3121-3127, 2014.

35. Chelly MS and Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sci Sport Exerc* 33: 326-333, 2001.
36. Choi JT and Bastian AJ. Adaptation reveals independent control networks for human walking. *Nat Neurosci* 10: 1055-1062, 2007.
37. Christou M, Smilios I, Sotiropoulos K, Volaklis K, Pilianidis T, and Tokmakidis SP. Effects of resistance training on the physical capacities of adolescent soccer players. *J Strength Cond Res* 20: 783-791, 2006.
38. Coh M and Bracic M. Kinematic, dynamic and EMG factors of a sprint start. *Track Coach*: 6172-6176, 2010.
39. Cohen J. *Stastical Power Analysis for the Behavioral Sciences.* Hillsdale, NJ: Lawrence Erlbaum Associates, 1988.
40. Comfort P, Steward A, Bloom L, and Clarkson B. Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *J Strength Cond Res* 28: 173-177, 2014.
41. Conti CA. The mechanical determinats of energetic cost in backward running, in: *Kinesiology: Execise Science/ Wellness Mangement*. Humboldt State University, 2009.
42. Cronin J, Hansen K, Kawamori N, and McNair P. Effects of weighted vests and sled towing on sprint kinematics. *Sports Biomech* 7: 160-172, 2008.
43. Cronin J, McNair PJ, and Marshall RN. Velocity specificity, combination training and sport specific tasks. *J Sci Med Sport* 4: 168-178, 2001.
44. Cronin JB and Templeton RL. Timing light height affects sprint times. *J Strength Cond Res* 22: 318-320, 2008.
45. Cross MR, Brughelli M, Samozino P, Brown SR, and Morin JB. Optimal loading for maximizing power during sled-resisted sprinting. *Int J Sport Physio Perf* 12: 1069-1077, 2017.
46. Cross MR, Lahti J, Brown SR, Chedati M, Jimenez-Reyes P, Samozino P, Eriksrud O, and Morin JB. Training at maximal power in resisted sprinting: Optimal load determination methodology and pilot results in team sport athletes. *PLoS One* 13: e0195477, 2018.
47. Curtiss C, Orloff H, and Usagawa T. Analysis of round reaction forces produced in basketball maneuvers over a season. Presented at XXIV International Symposium on Biomechanics in Sports, Salzburg, Austria, 16 July, 2006.
48. Dalleau G, Bell A, Viale F, Lacour JR, and Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med* 25: 170-176, 2004.
49. Daneshjoo A, Mokhtar A, H, Rahnama N, and Yusof A. Effectiveness of injury prevention programs on developing quadriceps and hamstrings strength of young male professional soccer players. *J Hum Kinet* 39: 115-125, 2013.
50. Daneshjoo A, Mokhtar A, H, Rashnama N, and Yusof A. The effects of comprehensive warm-up programs on proprioception, static and dynamic balance on male soccer players. *PLoS ONE* 7: e51568, 2012.
51. de Salles BF, Simão R, Miranda F, da Silva Novaes J, Lemos A, and Willardson JM. Rest interval between sets in strength training. *Sports Med* 39: 765-777, 2009.
52. Debaere S, Jonkers L, and Delecluse C. The contribution of step characteristics to sprint running performance in high-level male and female athletes. *J Strength Cond Res* 27: 116-124, 2013.

53. Denadai BS, de Aguiar RA, de Lima LC, Greco CC, and Caputo F. Explosive training and heavy weight training are effective for improving running economy in endurance athletes: a systematic review and meta-analysis. *Sports Med* 47: 545-555, 2017.
54. Derrick TR, Hamill J, and Caldwell GE. Energy absorption of ipacts during running at various stride lengths. *Med Sci Sport Exerc* 30: 128-135, 1998.
55. DeVita P and Stribling J. Lower extremity joint kinetics and energetics during backward running. *Med Sci Sport Exerc* 23: 602-610, 1991.
56. Dietz V. Human neuronal control of automatic functional movements. Interaction between central programs and afferent input. *Physiol Rev* 72: 33-69, 1992.
57. Duysens J, Tax AA, Murrer L, and Dietz V. Backward and forward walking use different patterns of phase-dependent modulation of cutaneous reflexes in humans. *J Neurophysio* 76: 301-310, 1996.
58. Ellis RG, Sumner BJ, and Kram R. Muscle contributions to propulsion an dbraking during walking and running: insights from external force perturbations. *Gait Posture* 40: 594-599, 2014.
59. Faigenbaum AD, Kraemer WJ, Blimkie CJR, Jeffreys I, Micheli LJ, Nitka M, and Rowland TR. Youth resistance training: Updated position statment paper from the National Strength and Conditioning Association. *J Strength Cond Res* 23: S60-S79, 2009.
60. Faigenbaum AD, Lloyd RS, MacDonald J, and Myer GD. *Citius, Altius, Fortius*: beneficial effects of resistance training for young atheltes: Narrative review. *Br J Sport Med* 50: 3-7, 2016.
61. Faigenbaum AD, McFarland JE, Keiper FB, Bevlin W, Ratamess NA, and Hoffman JR. Effects of short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *J Sport Sci Med* 6: 19-25, 2007.
62. Floria P, Sanchez-Sixto A, Ferber R, and Harrison AJ. Effects of running experience and its variability in runners. *J Sports Sci* 36: 272-278, 2017.
63. Flynn TW, Connery SM, Smutok MA, Zeballos RJ, and Weisman IM. Comparison of cardiopulmonary responses to forward and backward walking and running. *Med Sci Sport Exerc* 26: 89-94, 1994.
64. Flynn TW and Soutas-Little RW. Mechanical power and muscle action during forward and backward running. *J Orthop Sport Phy Ther* 17: 108-112, 1993.
65. Flynn TW and Soutas-Little RW. Patellofemoral joint compressive forces in forward and backward running. *J Orthop Sport Phy Ther* 21: 277-282, 1995.
66. Folland JP, Allen SJ, Black MI, Handsaker JC, and Forrester SE. Running technique is an important component of running economy and performance. *Med Sci Sport Exerc* 49: 1412-1423, 2017.
67. Ford P, De Ste Croix M, Lloyd R, Meyers R, Moosavi M, Oliver J, Till K, and Williams C. The long-term athlete development model: Physiological evidence and application. *J Sports Sci* 29: 389-401, 2011.
68. Francis C. The Structure of Training for Speed. 2013.
69. Gabbet T. Influence of physiological characteristics on selection in a semiprofessional first grade rugby league team: a case study. *J Sports Sci* 20: 399-405, 2002.
70. Gabbett TJ. Physiological characteristics of junior and senior rugby league players. *Br J Sport Med* 36: 334-339, 2002.

71. Gabbett TJ, Kelly JN, and Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. *J Strength Cond Res* 22: 174-181, 2008.
72. Gajer B, Thépaut-Mathieu C, and Lehénaff D. Evolution of stride and amplitude during course fo the 100m event in athletics. *New Studies Athletics* 14: 43-50, 1999.
73. Gambetta V. *Athletic Development: The Art and Science of Functional Sports Conditioning.* Champaign, IL: Human Kinetics, 2007.
74. Gelman A, Carlin J, Stern H, Dunson D, Vehtari A, and Rubin D. *Bayesian Data Analysis.* Chapman and hall, 2013.
75. Gerodimos V, Zafeiridis A, Perkos S, Dipla K, Manou V, and Kellis S. The contribution of stretch-shortening cycle and arm-swing performance in children, adolescents, and adult basketball players. *Ped Exerc Sci* 20: 379-389, 2008.
76. Gil S, Ruiz F, Irazusta A, Gil J, and Irazusta J. Selection of young soccer players in terms of antrhopometric and physiological factors. *J Sport Med Phys Fit* 47: 25-32, 2007.
77. Gilchrist J, Mandelbaum BR, Melancon H, Ryan GW, Silvers HJ, Griffin LY, Watanabe DS, D RW, and Dvorak J. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sport Med* 36: 1476-1483, 2008.
78. Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, and Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Res Sport Med* 14: 205-214, 2006.
79. Golubitsky M, Stewart I, Buono PL, and Collins JJ. Symmetry in locomotor central pattern generators and animal gaits. *Nature* 401: 693-695, 1999.
80. Gonaus C and Müller E. Using physiological data to predict future career progression in 14-to 17-year-old Austrian soccer academy players. *J Sports Sci* 30: 1673-1682, 2012.
81. Gonzalo-Skok O, Tous-Fajardo J, Valero-Campo C, Berzosa C, Bataller AV, Arjol-Serrano JL, Moras G, and Mendez-Villanueva A. Eccentric-overload training in team-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *Int J Sport Physio Perf* 12: 951-958, 2017.
82. Gottlieb R, Eliakim A, Shalom A, Dellolacono A, and Meckel Y. Improving anaerobic fitness in young basketball players: plyometric vs. specific sprint training. *J Athlet Enhanc* 3, 2014.
83. Grasso R, Bianci L, and Lacquaniti F. Motor patterns for human gait: backward versus forward locomotion. *J Neurophysio* 80: 1868-1885, 1998.
84. Gravina L, Gil SM, Ruiz F, Zubero J, Gil J, and Irazusta J. Anthropometric and physiological differences between first team and reserve soccer players aged 10-14 years at the beginning and end of the season. *J Strength Cond Res* 22: 1308-1314, 2008.
85. Guo L, Su F, Yang C, Wang S, Chang J, Wu W, and Lin H. Effects of speed and incline on lower extremity kinemtics during treadmill jogging in healthy subjects. *Biomed Eng Appl Basis Commun* 18: 73-79, 2006.
86. Hamner SR, Seth A, and Delp SL. Muscle contributions to propulsion and support during running. *J Biomech* 43: 2709-2716, 2010.

87. Hansen AH, Childress DS, Miff SC, Gard SA, and Mesplay KP. The human ankle during walking: implications for design of biomimetic ankle protheses. *J Biomech* 37: 1467-1474, 2004.
88. Harman E and Garhammer J. Administration, scoring and interpretation of selected tests, in: *Essentials of Strength Training and Conditioning*. TR Breachle, RW Earle, eds. Champaign, IL: Human Kinetics, 2008, pp 250-292.
89. Harries SK, Lubans DR, and Callister R. Systmatic review and meta-analysis of linear and undulating periodized resistance training programs on muscular strength. *J Strength Cond Res* 29: 1113-1125, 2015.
90. Haugen T, Ommundsen Y, and Seller S. The relationship between physical activity and physical self-esteem in adolescents: The role of physical fitness indices. *Ped Exerc Sci* 25: 138-153, 2013.
91. Haugen T, Tonnessen E, Leirstein S, Hem E, and Seiler S. Not quite so fast: effect of training at 90% sprint speed on maximal and repeated-sprint ability in soccer players. *J Sports Sci* 32: 1979-1986, 2014.
92. Heglund NC and Taylor CR. Speed, stride frequency and energy cost per stride: how do they change with body size and gait? *J Exper Biol* 138: 301-318, 1988.
93. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, and Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc* 43: 296-302, 2011.
94. Heiderscheit BC, Sherry MA, Silder A, Chumanov ES, and Thelen DG. Hamstring strain injuries: recommendations for diagnosis, rehabilitation, and injury prevention. *J Orthop Sports Phys Ther* 40: 67-81, 2010.
95. Herman K, Barton C, Malliaras P, and Morrissey D. The effectiveness of neuromuscular warm-up strategies, that require no additional equipment, for preventing lower limb injuries during sports participation: A systematic review. *BMC Medicine* 10: 1-12, 2012.
96. Herzog W, Leonard TR, Joumaa V, and Mehta A. Mysteries of muscle contraction. *J Appl Biomech* 24: 1-13, 2008.
97. Hewett TE, Paterno MV, and Myer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthoppaedics and Related Research* 408: 76-94, 2002.
98. Högberg P. Length of stride, stride frequency, "flight" period and maximum distance between the feet during rinning with different speeds. *Arbbeitphysiologie* 14: 431-436, 1952.
99. Hoogkamer W, Kram R, and Arellano CJ. How biomechanical improvements in running economy could break the 2-hour marathon barrier. *Sports Med* 47: 1739-1750, 2017.
100. Hoogkamer W, Meyns P, and Duysens J. Steps forward in understanding backward gait: From basic circuits to rehabilitation. *Exerc Sport Sci Rev* 42: 23-29, 2014.
101. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 30: 1-15, 2000.
102. Hopkins WG. A scale of magnitudes for effect statistics. http://sportsci.org/resource/stats/effectmag.html, 2002.
103. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience* 14: 49-58, 2010.
104. www.sportsci.org. Accessed July/2017.

105. Hoy MG, Zajac FE, and Gordon ME. A musculoskeletal model of the human lower extremity: the effect of muscle, tendon, and moment arm on the moment-angle relationship of musculotendon actuators at teh hip, knee and ankle. *J Biomech* 23: 157-169, 1990.
106. Hunter G. Muscle physiology, in: *Essentials of Strength Training and Conditioning*. T Beachle, R Earle, eds. Champaign, IL: Human Kinetics, 2000, pp 3-12.
107. Hunter JP, Marshall RN, and McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech* 21: 31-43, 2005.
108. Ivanenko YP, Cappellini G, Poppele RE, and Lacquaniti F. Spatiotemporal organization of alpha-motoneuron activity in the human spinal cord during different gaits and gait transitions. *Eur J Neurosci* 27: 3351-3368, 2008.
109. Jeffreys I. Motor Learning - applications for agility, part 1. *Strength Cond J* 28: 72-76, 2006.
110. Jones P, Bampouras T, and Marrin K. An investigation into the physical determinants of change of direction speed. *J Sport Med Phys Fit* 49: 97-104, 2009.
111. Joshi S, Vij JS, and Singh SK. Medical science retrowalking: a new concept in physiotherapy and rehabilitation. *Int J Sci Res* 4: 152-156, 2015.
112. Kawamori N, Newton R, and Nosaka K. Effects of weighted sled towing on ground reaction force during the acceleration phase of sprint running. *J Sports Sci* 32: 1139-1145, 2014.
113. Kawamori N, Nosaka K, and Newton RU. Relationships between ground reaction impulse and sprint acceleration performance in team sport atheltes. *J Strength Cond Res* 27: 568-573, 2013.
114. Kiani A, Hellquist E, Ahlqvist K, Gedeborg R, Michaélsson K, and Byberg L. Prevention of soccer-related knee injuries in teenaged girls. *Arch Intern Med* 170: 43-49, 2010.
115. Komi PV, Gollhofer A, Schmidtbleicher D, and Frick U. Interaction between man and shoe in running: considerations for a more comprehensive measurement approach. *Int J Sports Med* 8: 196-202, 1987.
116. Koo TK and Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chirop Med* 15: 155-163, 2016.
117. Kraemer WJ. A series of studies: The physiological basis for strength training in Amercian football: Fact over philosophy. *J Strength Cond Res* 11: 131-142, 1997.
118. Kram R and Taylor R. Energetics of running: A new perspective. *Nature* 346: 265-267, 1990.
119. LaBella CR, Huxford MR, Grissom J, Kim K, Peng J, and Christoffel KK. Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high school. *Arch Ped Adol Med* 165: 1033-1040, 2011.
120. Laffaye G, Wagner PP, and Tombleson TI. Countermovement jump height: gender and sport-specific differences in force-time variables. *J Strength Cond Res* 28: 1086-1105, 2014.
121. Lesinski M, Prieske O, and Granacher U. Effects and dose-response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *Br J Sport Med* 0: 1-17, 2016.

122. Lindstedt SL, LaStayo PC, and Reich TE. When active muscles lengthen: properties and consequences of eccentric actions. *News of Physiological Sciences* 16: 256-261, 2001.

123. Little T and Williams AG. Sutability of soccer training drills for endurance training. *J Strength Cond Res* 20: 316-319, 2006.

124. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, Michell LJ, Myer GD, and Oliver JL. National strength and conditioning association position statement on long-term athletic development. *J Strength Cond Res* 30: 1491-1509, 2016.

125. Lloyd RS and Oliver JL. The youth physical development model: A new approach to long-term athletic development. *Strength Cond J* 34: 61-72, 2012.

126. Lloyd RS, Oliver JL, Hughes MG, and Williams AC. The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths. *J Strength Cond Res* 26: 2812-2819, 2012.

127. Lloyd RS, Oliver JL, Hughes MG, and Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *J Sports Sci* 27: 1565-1573, 2009.

128. Lloyd RS, Radnor JM, De Ste Croix MB, Cronin JB, and Oliver JL. Changes in sprint and jump performance following traditional, plyometric and combined resistance training in male youth pre- and post-peak height velocity. *J Strength Cond Res* 30: 1239-1247, 2016.

129. Lockie RG, Murphy A, and Spinks CD. Effects of resisted sled towing on sprint kinematics in field-sport athletes. *J Strength Cond Res* 17: 760-767, 2003.

130. Lockie RG, Murphy AJ, Schultz AB, Knight TJ, and Janse de Jonge XAK. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res* 26: 1539-1550, 2012.

131. Longo UG, Loppini M, Berton A, Marinozzi A, Maffulli N, and Denaro V. The FIFA 11_ program is effective in preventing injuries in elite male basketball playes: a cluster randomized controlled trial. *Am J Sports Med* 40: 96-1005, 2012.

132. Lubans DR, Organ PJ, Cliff DP, Barnett LM, and Okely AD. Fundamental movement skill in children and adolescents: review of associated health benefits. *Sports Med* 40: 1019-1035, 2010.

133. Mackie JW and Dean TE. Running backward training effects on upper leg musculature and ligamentous instability of injured knees. *Med Sci Sport Exerc* 16: 151, 1984.

134. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin NA, and Duchateau J. Rate of force development: Physiological and methodological considerations. *Eur J Appl Physiol* 116: 1091-1116, 2016.

135. Magalhães T, Ribeiro F, Pinheiro A, and Oliveira J. Warming-up before sporting activity improves knee position sense. *Phys Ther Sport* 11: 86-90, 2010.

136. Maio Alves JM, Rebelo AN, Abrantes C, and Sampaio J. Short-term effects of complex and contrast training in soccer players' vertical jump, sprint, and agility abilities. *J Strength Cond Res* 24: 936-941, 2010.

137. Malina RM, Bouchard C, and Bar-Or O. *Growth, Maturation and Physical Activity.* Champaign, Illinois: Human Kinetics, 2004.

138. Mann R and Herman J. Kinematic analysis of Olympic sprint performance, Men's 200 meters. *Int J Sports Biomech* 1: 151-162, 1985.

139. Mann RA and Hagy J. Biomechanics of walking, running, and sprinting. *Am J Sport Med* 8: 345-350, 1980.

140. Mathisen G. Effect of high-speed and plyometric training for 13-year-old male soccer players on acceleration and agility performance. *J Sports Sci* 5: 3-14, 2014.

141. Mattacola CG and Dwyer MK. Rehabilitation of the ankle after acute sprain or chronic instability. *J Athl Train* 37: 413-429, 2002.

142. Mattson MP. Evolutionary aspects of human exercise - born to run purposefully. *Ageing Research Reviews* 11: 347-352, 2012.

143. McDavid RF. Predicting potential in football players. *Res Quart Am Allian Health Phys Ed Rec* 48: 98-104, 1977.

144. McGee KJ and Burkett LN. The National Football League Combine: A reliable predictor of draft status? *J Strength Cond Res* 17: 6-11, 2003.

145. McMillan K, Helgerud J, Macdonald R, and Hoff J. Physiological adaptations to soccer specific endurance training in professional youth soccer players. *Br J Sport Med* 39: 273-277, 2005.

146. McNeill AR. *The human machine.* New York: Columbia University Press, 1992.

147. Meckel Y, Gefen Y, Nemet D, and Elliakim A. Influence of short vs. long repetition sprint training on selected fitness components in young soccer players. *J Strength Cond Res* 26: 1845-1851, 2012.

148. Mehdizadeh S, Arshi AR, and Davids K. Quantifying coordination and coordination variability in backward versus forward running: Implications for control of motion. *Gait Posture* 42: 172-177, 2015.

149. Mergersen KL, Drovandi CC, Robert CP, Pyne DB, and Gore CJ. Bayesian estimation of small effects in exercise and sports science. *PLoS One*, 2016.

150. Mero A, Kauhanen H, Peltola E, Vuorimaa T, and Komi PV. Physiological performance capacity in different prepubescent athletic groups. *J Sport Med Phys Fit* 30: 57-66, 1990.

151. Mero A, Komi PV, and Gregor RJ. Biomechanics of sprint running: A review. *Sports Med* 13: 376-392, 1992.

152. Meyers R, Oliver JL, Hughes MG, Lloyd RS, and Cronin JB. New insights into the development of maximal sprint speed in male youth. *Strength Cond J* 39: 2-10, 2017.

153. Meyers RW, Moeskops S, Oliver JL, Hughes MG, Cronin JB, and Lloyd RS. Lower limb stiffness and maximal sprint speed in 11-16-year-old boys. *J Strength Cond Res* Published Ahead-of-Print, 2017.

154. Meyers RW, Oliver JL, Hughes MG, Cronin JB, and Lloyd RS. Maximal sprint speed in boys of increasing maturity. *Ped Exerc Sci* 27: 85-94, 2015.

155. Meyers RW, Oliver JL, Hughes MG, Lloyd RS, and Cronin JB. The influence of maturation on sprint performance in boys over a 21-month period. *Med Sci Sport Exerc* 48: 2555-2562, 2016.

156. Meyers RW, Oliver JL, Hughes MG, Lloyd RS, and Cronin JB. Influence of age, maturity, and body size on the spatiotemporal determinants of maximal sprint speed in boys. *J Strength Cond Res* 31: 1009-1016, 2017.

157. Meyers RW, Sylvia M, Oliver JL, Hughes MG, Cronin JB, and Lloyd RS. Lower limb stiffness and maximal sprint speed in 11-16-year-old boys. *J Strength Cond Res* Published Ahead of Print, 2018.

158. Meylan C and Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. *J Strength Cond Res* 23: 2605-2613, 2009.
159. Meylan CM, Cronin JB, Oliver J, and Hughes M. Talent identification in soccer: the role of maturity status on physical, physiological and technical characteristics. *Int J Sport Sci Coach* 5: 571-592, 2010.
160. Michalsik LB, Aagaard P, and Madsen K. Locomotion characteristics and match-induced impairments in physical performance in male elite team handball players. *Int J Sport Sci* 34: 590-5999, 2013.
161. Millet GP, Jaouen B, Borrani F, and Candau R. Effects of concurrent endurance and strength training on running economy and VO(2) kinetics. *Med Sci Sport Exerc* 34: 1351-1359, 2002.
162. Minetti AE and Alexander RM. A theory of metabolic costs for bipedal gaits. *Journal of Theoretical Biology* 186: 467-476, 1997.
163. Mirwald RL, Baxter-Jones ADG, Bailey DA, and Beunene GP. An assessment of maturity from anthropometric measures. *Med Sci Sport Exerc* 34: 689-694, 2002.
164. Mohr M, Krustrup P, and Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci* 21: 519-528, 2003.
165. Moir GL. *Strength and Conditioning: A Biomechanical Approach.* Burlington, MA: Jones & Bartlett Learning, 2015.
166. Monte A, Nardello F, and Zamparo P. Sled towing: the optimal overload for peak power production. *Int J Sports Physiol Perf* 12: 1052-1058, 2016.
167. Moran J, Parry DA, LIeuan L, Collison J, and Rumpf MC. Maturation-related adaptations in running speed in response to sprint training in youth soccer players. *J Sci Med Sport* in-press, 2017.
168. Moran J, Sandercock G, Rumpf MC, and Parry DA. Variation in responses to sprint training in male youth athletes: A meta-analysis. *Int J Sport Med* 38: 1-11, 2017.
169. Moran J, Sandercock GRH, Ramirez-Campillo R, Todd O, Collison J, and Parry DA. Maturation-related effect of low-dose plyometric training on performance in youth hockey players. *Ped Exerc Sci* 29: 194-202, 2017.
170. Moran JJ, Sandercock GR, Ramirez-Campillo R, Meylan CM, Collison JA, and Parry DA. Age-related variation in male youth athletes' countermovement jump after plyometric training: A meta-analysis of controlled trials. *J Strength Cond Res* 31: 552-565, 2017.
171. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, and Lacour JR. Mechanical determinants of 100-m sprint running performance. *Eur J Appl Physiol* 112: 3921-3930, 2012.
172. Morin JB, Slawinski J, Dorel S, Saez de villareal E, Couturier A, Samozino P, Brughelli M, and Rabita G. Acceleration capability in elite sprinters and ground impulse: Push more brake less? *J Biomech* 48: 49-54, 2015.
173. Morton C. Running backward may help athletes move forward. *The Physician and Sports Medicine* 14: 149-152, 1986.
174. Muehlbauer T, Pabst J, Granacher U, and Büsch D. Validity of the jump-and-reach test in subelite adolescent handball players. *J Strength Cond Res* 31: 1282-1289, 2017.

175. Myer GD, Faigenbaum AD, Ford KR, Best T, Bergeron MF, and Hewett TE. When to initiate integrative neuromuscular training to reduce sports-related injuries and enhance health in youth? *Cur Sport Med Rep* 10: 155-166, 2011.
176. Nagahara R, Takai Y, Harmura M, Mizutani M, Matsuo A, Kanehisa H, and Fukunaga T. Age-related differences in spatiotemporal variables and ground reaction forces during sprinting in boys. *Ped Exerc Sci* 30: 335-344, 2018.
177. Napier C, Cochrane CK, Taunton JE, and Hunt MA. Gait modifications to change lower extremity gait biomechanics in runners: A systematic review. *Br J Sports Med* 49: 1382-1388, 2015.
178. Neto MG, Conceição CS, de Lima Brasileiro AJA, de Sousa CS, Carvalho VO, and de Jesus LA. Effects of the FIFA 11 training program on injury prevention and performance in football players: A systematic review and meta-analysis. *Clinical Rehabilitation* 31: 651-659, 2017.
179. Nourbakhsh MR and Kukulka CG. Relationship between muscle length and moment arm on EMG activity of human triceps surae muscle. *J Electromy Kinesio* 14: 263-273, 2004.
180. Novacheck TM. The biomechanics of running. *Gait Posture* 7: 77-95, 1998.
181. Nuzzo JL, McBride JM, Cormie P, and McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res* 22: 699-707, 2008.
182. Oliver J, Williams AC, and Armstrong N. Reliability of a field and laboratory test of repeated sprint ability. *Ped Exerc Sci* 18: 339-350, 2006.
183. Oliver JL, Lloyd RS, and Rumpf MC. Developing speed throughout childhood and adolescence: The role of growth, maturation and training. *Strength Cond J* 35: 42-48, 2013.
184. Oliver JL and Rumpf MC. Speed development in youths, in: *Strength and Conditioning for Young Athletes: Science and Application*. RS Lloyd, JL Oliver, eds. New York, NY, USA: Routledge, 2013.
185. Olsen OE, Myklebust G, Engebretsen L, Holme I, and Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ* 330: 449-452, 2005.
186. Ordway JD, Laubach LL, Vanderburgh PM, and Jackson KJ. The effects of backwards running training on forward running economy in trained males. *J Strength Cond Res* 30: 763-767, 2016.
187. Ovalle WK. The human muscle-tendon junction: A morphological study during normal growth and maturity. *Anat Embryo* 176: 281-294, 1987.
188. Papaikovou G, Giannakos A, Michailidis C, Patikas D, Bassa E, Kalopisis V, Anthrakidis N, and Kotzamanidis C. The effect of chronological age and gender on the development of sprint performance during childhood and puberty. *J Strength Cond Res* 23: 2568-2573, 2009.
189. Pearson DT, Naughton GA, and Torode M. Predictability of physiological testing and the role of maturation in talent identificaton for adolescent team sports. *J Sci Med Sport* 9: 277-287, 2006.
190. Perrier ET, Pavol MJ, and Hoffman MA. The acute effects of a warm-up including static or dynamic stretching on countermovement jump height, reaction time, and flexibility. *J Strength Cond Res* 25: 1925-1931, 2011.
191. Petrakos G, Morin JB, and Egan B. Resisted sled sprint training to improve sprint performance: a systematic review. *Sports Med* 46: 381-400, 2016.

192. Petré H, Löfving P, and Psilander N. The effect of two different concurrent training programs on strength and power gains in highly-trained individuals. *J Sport Sci Med* 17: 167-173, 2018.
193. Pettersen SA and Mathisen GE. Effect of short burst activities on sprint and agility performance in 11- to 12-year-old boys. *J Strength Cond Res* 26: 1033-1038, 2012.
194. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, Bourgois J, Vrijens J, Beunen G, and Malina RM. The relationship between peak height velocity and physical performance in youth soccer players. *J Sports Sci* 24: 221-230, 2006.
195. Pollitt DJ. Sled dragging for hockey training. *Strength Cond J* 25: 7-16, 2003.
196. Quatman-Yates CC, Quatman CE, Meszaros AJ, Paterno MV, and Hewett TE. A systematic review of sensorimotor function during adolescence: a developmental stage of increased motor awkwardness? *Br J Sport Med* 46: 649-655, 2012.
197. Radnor JM, Oliver JL, Waugh CM, Myer GD, Moore IS, and Lloyd RS. The influence of growth and maturation on stretch-shortening cycle function in youth. *Sports Med* 48: 57-71, 2018.
198. Rebelo A, Brito J, Seabra A, Oliveira J, and Krustrup P. Physical match performance of youth football players in relation to physical capacity. *Eur J Sport Sci* 14: S148-S156, 2014.
199. Reilly T, Williams AM, Nevill A, and Franks A. A multidisciplinary approach to talent identification in soccer. *J Sports Sci* 18: 695-702, 2000.
200. Rommers N, Mostaert M, Goossens L, Vaeyens R, Witvrouw E, Lenoir M, and D'Hondt E. Age and maturity related differences in motor coordination among male elite youth soccer players. *J Sports Sci* Epub ahead of print: 1-8, 2018.
201. Roos PE, Barton N, and van Deursen RWM. Patellofemoral joint compression forces in backward and forward running. *J Biomech* 45: 1656-1660, 2012.
202. Ross A, Leveritt M, and Riek S. Neural influences on sprint training: training adaptations and acute responses. *Sports Med* 31: 409-425, 2001.
203. Rössler R, Donath L, Bizzini M, and Faude O. A new injury prevention programme for children's football - FIFA 11+ Kids - can improve motor performance: A cluster-randomised controlled trial. *J Sports Sci* 34: 549-556, 2016.
204. Rumpf MC, Cronin JB, Mohamad IN, Mohamad S, Oliver JL, and Hughes MG. The effect of resisted sprint training on maximum sprint kinetics and kinematics in youth. *Eur J Sport Sci* 15: 374-381, 2015.
205. Rumpf MC, Cronin JB, Mohamed IN, Oliver JO, and Hughes M. Acute effects of sled towing on sprint time in male youth of different maturity status. *Ped Exerc Sci* 26: 71-75, 2014.
206. Rumpf MC, Cronin JB, Oliver J, and Hughes M. Kinematics and kinetics of maximum running speed in youth across maturity. *Ped Exerc Sci* 27: 277-284, 2015.
207. Rumpf MC, Cronin JB, Oliver JL, and Hughes M. Assessing youth sprint ability-methodological issues, reliability and performance data. *Pediatr Exerc Sci* 23: 442-467, 2011.
208. Rumpf MC, Cronin JB, Oliver JL, and Hughes MG. Vertical and leg stiffness and stretch-shortening cycle changes across maturation during maximal sprint running. *Hum Mov Sci* 32: 668-676, 2013.

209. Rumpf MC, Cronin JB, Pinder SD, Oliver J, and Hughes M. Effect of different training methods on running sprint times in male youth. *Ped Exerc Sci* 24: 170-186, 2012.
210. Rumpf MC, Lockie RG, Cronin JB, and Jalilvand F. The effect of different sprint training methods on sprint performance over various distances: A brief review. *J Strength Cond Res*, 2016.
211. Sáez de Villarreal E, Suarez-Arrones L, Requena B, Haff GG, and Ferrete C. Effects of plyometric and sprint training on physical and technical skill performance in adolescent soccer players. *J Strength Cond Res* 29: 1894-1903, 2015.
212. Santos EJ and Janeira MA. Effects of complex training on explosive strength in adolescent male basketball players. *J Strength Cond Res* 22: 903-909, 2008.
213. Saunders PU, Telford RD, Pyne DB, Peltola EM, Cunningham RB, Gore CJ, and Hawely JA. Short-term plyometric training improves running economy in highly trained middle and long distance runners. *J Strength Cond Res* 20: 947-954, 2006.
214. Saunders PU, Telford RD, Pyne DD, and Hahn AG. Improved race performance in elite middle-distance runners after cumulative altitude exposure. *Int J Sport Physio Perf* 4: 134-138, 2009.
215. Sekine Y and Okada J. Effects of resisted sprint training on sprint performance in high school baseball players. *Am J Sports Sci* 4: 90-97, 2016.
216. Shalfawi SA, Ingebrigtsen J, Dillern T, Tønnessen E, Delp TK, and Enoksen E. The effect of 40 m repeated sprint training on physical performance in young elite male soccer players. *Serbian Journal of Sports Science* 6: 111-116, 2012.
217. Sierer PS, Battaglini B, Mihalik JP, Shields EW, and Tomasini JT. The National Football League Combine: performance differences between drafted and nondrafted players entering the 2004 and 2005 drafts. *J Strength Cond Res* 22: 6-7, 2008.
218. Sirotic AC, Knowles H, Catterick C, and Coutts AJ. Positional match demands of professional rugby league competition. *J Strength Cond Res* 25: 3076-3087, 2011.
219. Slawinski J, Bonnefoy A, Levêque JM, Ontanon G, Riquet A, Dumas R, and Chèze L. Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *J Strength Cond Res* 24: 896-905, 2010.
220. Soligard T, Myklebust G, Steffen K, Holme I, Silvers H, Bizzini M, Junge A, Dvorak J, Bahr R, and Andersen TE. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *Br Med J*: 1-9, 2008.
221. Spiteri T, Nimphius S, Hart NH, Specos C, Sheppard JM, and Newton RU. The contribution of strength characteristics to change of direction and agility perofrmance in female basketball athletes. *J Strength Cond Res* 28: 2415-2423, 2014.
222. Sterzing T, Frommhold C, and Rosenbaum D. In-shoe plantar pressure distribution and lower extremity muscle activity patterns of backward compared to forward running on a treadmill. *Gait Posture* 46: 135-141, 2016.
223. Stöggl T and Wunsch T. Biomechanics of Marathon Running, in: *Marathon Running: Physiology, Psychology, Nutrition and Training Aspects*. C Zinner, B Sperlich, eds*.* Switzerland: Springer International Publishing, 2016, pp 13-45.

224. Stone MH, Collins D, Plisk S, Haff GG, and Stone ME. Training principles: Evaluation of modes and methods of resistance training. *Strength Cond J* 22: 65-76, 2000.
225. Støren O, Helgerud J, Støa EM, and Hoff J. Maximal strength training improves running economy in distance runners. *Med Sci Sport Exerc* 40: 1087-1092, 2008.
226. Sussman DH, Alrowayeh H, and Walker ML. Patellofemoral joint compressive forces during backward and foward running at the same speed. *J Musculo Res* 4: 107-118, 2000.
227. Swati K, Ashima C, and Saurabh S. Efficacy of backward training on agility and quadriceps strength. *Elix Hum Physio* 53: 11918-11921, 2012.
228. Talpey SW and Siesmaa EJ. Sports injury prevention: the role of the strength and conditioning coach. *Strength Cond J* 39: 14-19, 2017.
229. Terblanche E, Page C, Kroff J, and Venter RE. The effect of backward locomotion training on the body composition and cardiorespiratory fitness of young women. *Int J Sport Med* 26: 214-219, 2005.
230. Terblanche E and Venter RE. The effect of backward training on the speed, agility and power of netball players. *S Afr J Res Sport Phy Ed Rec* 31: 135-145, 2009.
231. Threlkeld AJ, Horn TS, Wojtowicz G, Rooney JG, and Shapiro R. Kinematics, ground reaction force, and muscle balance produced by backward running. *J Orthop Sport Phy Ther* 11: 56-63, 1989.
232. Tønnessen E, Shalfawi SA, Haugen T, and Enoksen E. The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *J Strength Cond Res* 25: 2364-2370, 2011.
233. Towlson C, Cobley S, Parkin G, and Lovell R. When does the influence of maturation on antrhopometric and physical fitness characteristics increase and subside? *Scand J Med Sci* 28: 1946-1955, 2018.
234. Turner AN and Jeffreys I. The stretch-shortening cycle: proposed mechanisms and methods for enhancement. *Strength Cond J* 32: 87-99, 2010.
235. Uthoff A, Oliver J, Cronin J, Harrison C, and Winwood P. A new direction to athletic performance: Understanding the acute and longitudinal responses to backward running. *Sports Med* 48: 1083-1096, 2018.
236. Uthoff A, Oliver J, Cronin J, Winwood P, and Harrison C. Prescribing target running intensities for high-school athletes: an forward and backward running performance be autoregulated? *Sports* 6: 77, 2018.
237. Uthoff A, Oliver J, Cronin J, Winwood P, and Harrison C. Prescribing target running intensities for high-school athletes: can forward and backward running performance be autoregulated? *Sports* 6: 1-10, 2018.
238. Uthoff A, Oliver JL, Winwood PW, Harrison C, and Cronin JB. Sprint-specific training in youth: backward running versus forward running training on speed and power measures in adolescent male athletes. *J Strength Cond Res* Published ahead of print, 2018.
239. van den Tillar R, Lerberg E, and von Heimburg E. Comparison of three types of warm-up upon sprint ability in experienced soccer players. *J Sport Health Sci* 30: 2258 - 2265, 2016.
240. van Oeveren BT, de Ruiter CJ, Beek PJ, and van Dieën JH. Optimal stride frequencies in running at different speeds. *PLoS ONE* 12: e0184273, 2017.

241. Viru A, Loko J, Harro M, Volver A, Laaneots L, and Viru M. Critical periods in the development of performance capacity during childhood and adolescence. *Eur J Phys Ed* 4: 75-19, 1999.
242. West DJ, Cunningham DJ, Finn CV, Scott PM, Crewther BT, Cook CJ, and Kilduff LP. The metabolic, hormonal, biochemical, and neuromuscular function responses to a backward sled drag training session. *J Strength Cond Res* 28: 265-272, 2014.
243. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950-961, 2010.
244. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 81: 1991-1999, 2000.
245. Wild J, Bezodis N, Blagrove R, and Bezodis I. A biomechanical comparison of accelerative and maximum velocity sprinting: Specific strength training considerations. *Prof Strength Cond* 21: 23-37, 2011.
246. Williams CA, Oliver JL, and Faulkner J. Seasonal monitoring of sprint and jump performance in a soccer youth academy. *Int J Sport Physio Perf* 6: 264-275, 2011.
247. Williams KR. Biomechanical factors contributing to marathon race success. *Sports Med* 37: 420-423, 2007.
248. Winter DA, Pluck N, and Yang JF. Backward walking: A simple reversal of forward walking? *J Motor Beh* 21: 291-305, 1989.
249. Winwood PW and Buckley JJ. Short term effects of resistance training modalities on performance measures in male adolescents. *J Strength Cond Res* Epub ahead of print, 2017.
250. Witzke KA and Snow CM. Effects of plyometric jump training on bone mass in adolescent girls. *Med Sci Sport Exerc* 32: 1051-1057, 2000.
251. Wright S and Weyand PG. The application of ground force explains the energetic cost of running backward and forward. *J Exp Biol* 204: 1805-1815, 2001.
252. Wrigley RD, Drust B, Stratton G, Atkinson G, and Gregson W. Long-term soccer-specific training enhances the rate of physical development of academy soccer players independent of maturation status. *Int J Sport Med* 35: 1090-1094, 2014.
253. Zatsiorsky VM. *Science and Practice of Strength Training.* Champaign, IL: Human Kinetics, 1995.
254. Zois J, Bishop D, and Aughey R. High-intensity warm-ups: Effects during susequent intermittent exercise. *Int J Sport Physio Perf* 10: 498-503, 2015.

APPENDICES

Appendix 1. Additional Research Outputs Since Starting the PhD

Schofield, M, Tinwala, F, Cronin, J, Hébert-Losier, K, **Uthoff, A.** (In review). Kinematic and kinetic variability associated with the cable put and seated rotation assessments. *Journal of Sports Sciences.* Submitted Jun 20th, 2019

Uthoff, A, Nagahara, R, Cronin, JB, Macadam, P, Neville, J, Tinwala, F, Graham, SP. (In-review). Effects of forearm wearable resistance on acceleration mechanics in collegiate track sprinters. *European Journal of Sports Science*. Submitted Jun 10th, 2019

Bustos, A, Metral, G, Cronin, J, **Uthoff, A.** (In review). The effect of warming up with lower body wearable resistance on physical performance measures in soccer players over an 8-week training cycle. *Journal of Strength and Conditioning Research*. Submitted Jun 7th, 2019

Schofield, M, Tinwala, F, Cronin, J, Hébert-Losier, K, **Uthoff, A.** (In review). Reliability of manual digitization of seated shotput kinematics with reduced camera numbers. *Sports Biomechanics.* Submitted May 21st 2019

Schofield, M, Tinwala, F, Cronin, J, Hébert-Losier, K, **Uthoff, A** (2019). Multi-joint musculoarticular stiffness derived form a perturbation is highly variable. *Journal of Strength and Conditioning Research*. Epub Ahead of Print. doi: 10.1519/JSCR.0000000000003186

Macadam, P, Nuell, S, Cronin, JB, Nagahara, R, **Uthoff, AM**, Graham, SP, Tinwala, F, Neville, J. (2019) Kinematic and kinetic differences in block and split-stance standing starts during 30 m sprint-running. *European Journal of Sports Science.* Epub ahead of print. doi: 10.1080/17461391.2019.1575475

Macadam, P, Cronin, J, **Uthoff, A**. (2018) The effects of different wearable resistance placements on sprint-running performance: a review and practical applications. *Strength and Conditioning Journal.* Accepted Nov 14th, 2018

Macadam, P, Cronin, JB, **Uthoff, AM**, Johnston, M, Knicker, AJ. (2018). The role of arm mechanics during sprint-running: a review of the literature and practical applications. *Strength and Conditioning Journal. 40*(5), 14-23. doi:10.1519/SSC.0000000000000391

Appendix 2. Within- and between-group ES and 95% CI for unresisted FR and BR training.

Table A.1. Within- and between-group ES and 95% CI for unresisted FR and BR training.

	Within-group change			**Between-group change**		
Variable	**CON** ES (95% CI)	**FRT** ES (95% CI)	**BRT** ES (95% CI)	**FRT-CON** ES (95% CI)	**BRT-CON** ES (95% CI)	**BRT-FRT** ES (95% CI)
10-m sprint	0.20 (-0.36 to 0.77)	-1.25 (-1.98 to -0.54)	-1.56 (-2.20 to -0.91)	1.29 (-1.97 to -0.91)	-1.59 (-2.24 to -0.94)	-0.54 (-1.17 to 0.10)
10-20-m sprint	0.41 (-0.43 to 1.20)	-0.29 (-1.47 to 0.43)	-0.24 (-1.60 to 0.30)	-0.45 (-1.09 to 0.18)	-1.05 (-1.66 to -0.44)	0.04 (-0.58 to 0.66)
20-m sprint	0.36 (-0.22 to 0.94)	-0.79 (-1.49 to -0.10)	-1.04 (-1.64 to -0.43)	-1.20 (-1.88 to -0.52)	-1.38 (-2.02 to -0.74)	-0.29 (-0.91 to 0.34)
CMJ	0.30 (-0.27 to 0.86)	0.25 (-0.44 to 0.95)	0.83 (0.25 to 1.42)	-0.10 (-0.73 to 0.53)	0.63 (0.05 to 1.21)	0.76 (0.10 to 1.41)
Stiffness	-0.07 (-0.63 to 0.50)	0.71 (0.00 to 1.43)	0.54 (-0.02 to 1.11)	0.67 (0.02 to 1.32)	0.65 (0.08 to 1.23)	-0.03 (-0.66 to 0.59)

ES = effect size; CI = confidence interval; CMJ = countermovement jump; CON = control; FRT = forward running training; BRT = backward running training.

Appendix 3. Within- and between-group ES and 95% CI for resisted FR and BR training.

Table A.2. Within- and between-group ES and 95% CI for resisted FR and BR training.

	Within-group change			Between-group change		
Variable	**CON** ES (95% CI)	**FRS** ES (95% CI)	**BRS** ES (95% CI)	**FRS-CON** ES (95% CI)	**BRS-CON** ES (95% CI)	**BRS-FRS** ES (95% CI)
10-m sprint	-0.09 (-0.60 to 0.41)	-0.13 (-0.61 to 0.35)	-0.49 (-0.91 to -0.08)	0.09 (-0.40 to 0.58)	-0.28 (-0.74 to 0.10)	-0.36 (-0.81 to 0.09)
10-20-m sprint	-0.10 (-0.55 to 0.46)	-0.18 (-0.56 to 0.41)	-0.22 (-0.73 to 0.10)	-0.11 (-0.61 to 0.38)	-0.15 (-0.61 to 0.31)	-0.03 (-0.48 to 0.41)
20-m sprint	-0.18 (-0.59 to 0.41)	-0.16 (-0.64 to 0.33)	-0.39 (-0.80 to 0.02)	-0.02 (-0.51 to 0.47)	-0.24 (-0.70 to 0.22)	-0.20 (-0.65 to 0.24)
CMJ	0.05 (-0.40 to 0.54)	0.45 (-0.03 to 0.93)	0.79 (0.29 to 1.13)	0.38 (-0.10 to 0.86)	0.67 (0.22 to 1.11)	0.27 (-0.17 to 0.72)
Stiffness	0.02 (-0.46 to 0.51)	0.90 (0.29 to 1.27)	0.79 (0.42 to 1.41)	0.69 (0.19 to 0.78)	0.94 (0.47 to 1.41)	0.29 (-0.16 to 0.74)

ES = effect size; CI = confidence interval; CMJ = countermovement jump; CON = control; FRS = resisted forward running; BRS = resisted backward running.

Appendix 4. Ethics Approval Forms for Chapters 3 and 4

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

26 October 2016

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **16/374 Movement variability associated with un-resisted and resisted backward running in adolescent male athletes**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 25 October 2019.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 25 October 2019;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 25 October 2019 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor
Executive Secretary
Auckland University of Technology Ethics Committee

Cc: Aaron Uthoff, uthoffaaron@gmail.com; paul.winwood@boppoly.ac.nz

Appendix 5. Ethics Approval Forms for Chapters 5 and 6

AUTEC Secretariat

Auckland University of Technology
D-88, WU406 Level 4 WU Building City Campus
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

19 June 2017

John Cronin
Faculty of Health and Environmental Sciences

Dear John

Re Ethics Application: **17/110 The training effects of backward running on forward sprint-running performance in adolescent athletes**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 19 June 2020.

Standard Conditions of Approval

1. A progress report is due annually on the anniversary of the approval date, using form EA2, which is available online through http://www.aut.ac.nz/researchethics.
2. A final report is due at the expiration of the approval period, or, upon completion of project, using form EA3, which is available online through http://www.aut.ac.nz/researchethics.
3. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form: http://www.aut.ac.nz/researchethics.
4. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
5. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.

Please quote the application number and title on all future correspondence related to this project.

AUTEC grants ethical approval only. If you require management approval for access for your research from another institution or organisation then you are responsible for obtaining it. You are reminded that it is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.

For any enquiries, please contact ethics@aut.ac.nz

Yours sincerely,

Kate O'Connor
Executive Manager
Auckland University of Technology Ethics Committee

Cc: uthoffaaron@gmail.com; craig@athletedevelopment.org.nz; paul.winwood@boppoly.ac.nz

Appendix 6. Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 3

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: **Movement variability associated with backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the information provided about this research project in the Information Sheet dated 24th, October, 2016.
- O I have had an opportunity to ask questions and to have them answered.
- O I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- O I am between the ages of 14 and 18 years
- O I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.
- O I agree to run forward and backward for multiple trials and have the times recorded
- O I agree to take part in this research.
- O I wish to receive a copy of my results and summary of findings from the research (please tick one): YesO NoO
- O I wish to have my running times accessible to my coach/teacher (please tick one): YesO NoO

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

***Approved by the Auckland University of Technology Ethics Committee on** type the date on which the final approval was granted **AUTEC Reference number** type the AUTEC reference number*

Note: The Participant should retain a copy of this form.

2 July 2015 page 1 of 3 This version was last edited in July 2015

Appendix 6 (cont.). Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 3

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Parent/Guardian Consent Form

Project title: **Movement variability associated with backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the information provided about this research project in the Information Sheet dated 24th, October, 2016.
- O I have had an opportunity to ask questions and to have them answered.
- O I confirm that my child/children is between the ages of 14 and 18 years
- O I confirm that my child/children are not suffering heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs their physical performance.
- O I understand that I may withdraw my child/children and/or myself or any information that we have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- O If my child/children and/or I withdraw, I understand that all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- O I agree to my child/children taking part in this research.
- O I wish to receive a copy of my child/children's results and summary of findings from the research (please tick one) YesO NoO
- O I wish to have my child/children's running times accessible to their coach/teacher (please tick one): Yes O No

Child/children's name/s : ……………………………………………………………………………………

……

Parent/Guardian's signature: ……………………………………………………………………………

Parent/Guardian's name: ………………………………………………………………………………

Parent/Guardian's Contact Details (if appropriate):

……………………………………………………………………

……………………………………………………………………

……………………………………………………………………

……………………………………………………………………

Date:

***Approved by the Auckland University of Technology Ethics Committee on** type the date on which the final approval was granted* ***AUTEC Reference number** type the AUTEC reference number*

Note: The Participant should retain a copy of this form.

2 July 2015 page 2 of 3 This version was last edited in July 2015

Appendix 6 (cont.). Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 3

Assent Form

Project title: **Movement variability associated with backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

O I have read and understood the sheet telling me what will happen in this study and why it is important.

O I have been able to ask questions and to have them answered.

O I am between the ages of 14 and 18 years

O I understand that while the information is being collected, I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.

O If I stop being part of the study, I understand that all information about me, including the recordings or any part of them that include me, will be destroyed.

O I agree to take part in this research.

O I wish to receive a copy of my results and summary of findings from the research (please tick one):

YesO NoO

Participant's signature: ....

Participant's name: ....

Participant Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

2 July 2015 page 3 of 3 This version was last edited in July 2015

Appendix 7: Informed Consent and Assent Forms for Chapter 4

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: **Movement variability associated with resisted backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

O I have read and understood the information provided about this research project in the Information Sheet dated 27th, September, 2017.

O I have had an opportunity to ask questions and to have them answered.

O I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

O I am between the ages of 16 and 18 years

O I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.

O I agree to run forward and backward for multiple trials and have the times recorded

O I agree to take part in this research.

O I wish to receive a copy of my results and summary of findings from the research (please tick one):
YesO NoO

O I wish to have my running times accessible to my coach/teacher (please tick one): YesO NoO

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

………………………………………………………………………………………..

………………………………………………………………………………………..

………………………………………………………………………………………..

………………………………………………………………………………………..

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

2 July 2015 page 1 of 3 This version was last edited in July 2015

Appendix 7 (cont.): Informed Consent and Assent Forms for Chapter 4

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Parent/Guardian Consent Form

Project title: **Movement variability associated with resisted backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the information provided about this research project in the Information Sheet dated 27th, September, 2017.
- O I have had an opportunity to ask questions and to have them answered.
- O I confirm that my child/children is/are between the ages of 12 and 18 years
- O I confirm that my child/children is/are not suffering heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs their physical performance.
- O I understand that I may withdraw my child/children and/or myself or any information that we have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- O If my child/children and/or I withdraw, I understand that all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- O I agree to my child/children taking part in this research.
- O I wish to receive a copy of my child/children's results and summary of findings from the research (please tick one) YesO NoO
- O I wish to have my child/children's running times accessible to their coach/teacher (please tick one): YesO NoO

Child/children's name/s : ……………………………………………………………………………………

……

Parent/Guardian's signature: ……………………………………………………………………………………

Parent/Guardian's name: ……………………………………………………………………………………

Parent/Guardian's Contact Details (if appropriate):

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

……………………………………………………………………………

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

2 July 2015 page 2 of 3 This version was last edited in July 2015

Appendix 7 (cont.): Informed Consent and Assent Forms for Chapter 4

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Assent Form

Project title: **Movement variability associated with resisted backward running in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the sheet telling me what will happen in this study and why it is important.
- O I have been able to ask questions and to have them answered.
- O I am between the ages of 12 and 18 years
- O I understand that while the information is being collected, I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- O If I stop being part of the study, I understand that all information about me, including the recordings or any part of them that include me, will be destroyed.
- O I agree to take part in this research.
- O I wish to receive a copy of my results and summary of findings from the research (please tick one):

YesO NoO

Participant's signature: ....

Participant's name: ....

Participant Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

2 July 2015 page 3 of 3 This version was last edited in July 2015

Appendix 8: Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 5 and 6

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title: **The training effects of backward running on forward sprinting ability and other performance measures in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the information provided about this research project in the Information Sheet dated 7th, August, 2017.
- O I have had an opportunity to ask questions and to have them answered.
- O I understand that taking part in this study is voluntary and I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- O I understand that if I withdraw from the study then I will be offered the choice between having any data belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- O If I withdraw prior to completion of data collection, I understand that upon my request, all relevant information including tapes and transcripts, or parts thereof, will be destroyed.
- O I am between the ages of 16 and 18 years
- O To the best of my knowledge, I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.
- O I agree to run forward and backward for multiple trials and have the times recorded
- O I agree to take part in this research.
- O I wish to receive a copy of my results and summary of findings from the research (please tick one): YesO NoO
- O I wish to have my running times accessible to my coach/teacher (please tick one): YesO NoO

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

***Approved by the Auckland University of Technology Ethics Committee on** type the date on which the final approval was granted **AUTEC Reference number** type the AUTEC reference number*

Note: The Participant should retain a copy of this form.

2 July 2015 page 1 of 3 This version was last edited in July 2015

Appendix 8 (cont.): Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 5 and 6

Parent/Guardian Consent Form

Project title: **The training effects of backward running on forward sprinting ability and other performance measures in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

O I have read and understood the information provided about this research project in the Information Sheet dated 7th, August, 2017.

O I have had an opportunity to ask questions and to have them answered.

O I confirm that my child/children is/are between the ages of 12 and 16 years

O To the best of my knowledge, I confirm that my child/children is/are not suffering heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs their physical performance.

O I understand that my child/children's participation in this study is voluntary and I may withdraw my child/children and/or myself or any information that we have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

O I understand that if I or my child/children withdraw from the study then I/they will be offered the choice between having any data belonging to them removed or allowing it to continue to be used. However, once the findings have been produced, removal of their data may not be possible.

O If my child/children and/or I withdraw prior to completion of data collection, I understand that upon my request, all relevant information including tapes and transcripts, or parts thereof, will be destroyed.

O I agree to my child/children taking part in this research.

O I wish to receive a copy of my child/children's results and summary of findings from the research (please tick one) YesO NoO

O I wish to have my child/children's running times accessible to their coach/teacher (please tick one):

YesO NoO

Child/children's name/s : ……………………………………………………………………………………

……

Parent/Guardian's signature: ……………………………………………………………………………………

Parent/Guardian's name: ……………………………………………………………………………………

Parent/Guardian's Contact Details (if appropriate):

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

Date:

***Approved by the Auckland University of Technology Ethics Committee on** type the date on which the final approval was granted **AUTEC Reference number** type the AUTEC reference number*

Note: The Participant should retain a copy of this form.

2 July 2015 page 2 of 3 This version was last edited in July 2015

Appendix 8 (cont.): Informed Consent, Parental/Guardian Consent, and Assent Forms for Chapter 5 and 6

Assent Form

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Project title: **The training effects of backward running on forward sprinting ability and other performance measures in adolescent athletes**

Project Supervisor: ***Professor John Cronin***

Researcher: ***Aaron Uthoff***

- O I have read and understood the sheet telling me what will happen in this study and why it is important.
- O I have been able to ask questions and to have them answered.
- O I am between the ages of 12 and 16 years
- O To the best of my knowledge, I am not suffering from heart disease, high blood pressure, any respiratory condition (mild asthma excluded), any illness or injury that impairs my physical performance.
- O I understand that while the information is being collected, I can stop being part of this study whenever I want and that it is perfectly ok for me to do this.
- O If I stop being part of the study, I understand that all information about me, including the recordings or any part of them that include me, will be destroyed.
- O I agree to take part in this research.
- O I wish to receive a copy of my results and summary of findings from the research (please tick one):

YesO NoO

Participant's signature: ……………………………………………………………………………………

Participant's name: ……………………………………………………………………………………

Participant Contact Details (if appropriate):

………………………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

………………………………………………………………………………

Date:

Approved by the Auckland University of Technology Ethics Committee on type the date on which the final approval was granted AUTEC Reference number type the AUTEC reference number

Note: The Participant should retain a copy of this form.

18 December 2018 page 1 of 3 This version was edited in July 2015

Appendix 9. Chapter 2 Abstract

Backward running (BR) is a form of locomotion which occurs in short bursts during many overground field and court sports. It has also traditionally been used in clinical settings as a method to rehabilitate lower body injuries. Comparisons between BR and forward running (FR) have led to the discovery that both may be generated by the same neural circuitry. Comparisons of the acute responses to FR reveal that BR is characterised by a smaller ratio of braking to propulsive forces, increased step frequency, decreased step length, increased muscle activity, and reliance on isometric and concentric muscle actions. These biomechanical differences have been critical in informing recent scientific explorations which have discovered that BR can be used as a method for reducing injury and improving a variety of physical attributes deemed advantageous to sports performance. This includes, improved lower body strength and power, decreased injury prevalence, and improvements in change of direction performance following BR training. The current findings from research help improve our understanding of BR biomechanics and provide evidence which supports BR as a useful method to improve athlete performance. However, further acute and longitudinal research is needed to better understand the utility of BR in athletic performance programs.

Appendix 10. Chapter 3 Abstract

Target running intensities are commonly prescribed for enhancing sprint-running performance and progressing injured athletes back into competition, yet little is known about whether running speed can be achieved using autoregulation. This study aimed to investigate the consistency of running intensities in adolescent athletes using autoregulation to self-select velocity. Thirty-four healthy male athletes performed 20 m forward and backward running trials at slow (40-55% maximum effort), moderate (60-75% maximum effort) and fast intensities (+90% maximum effort) on three occasions. Absolute and relative consistency was assessed using coefficient of variation (CV) and intraclass correlation coefficients (ICC), respectively. Pairwise comparison of consecutive trials revealed systematic changes from trials 1 to 2. However, trials 2 to 3 presented no systematic bias at were characterised by low typical percentage error (CV $\leq$ 4.3%) and very good to excellent relative consistency (ICC $\geq$ 0.87) for all running speeds and directions. Despite forward running being significantly ($p \leq 0.01$) faster than backward running at slow (26%), moderate (28%) and fast intensities (26%), consistency was similar in both running directions and strongest at the fastest speeds. Following appropriate familiarisation, it appears that youth athletes can use autoregulation to accurately self-select prescribed target running intensities, forwards and backwards.

Appendix 11. Chapter 4 Abstract

Load-velocity (Lv) relationships can be used to assist load prescription during resisted sprinting (RS). However, the Lv relationships between RS forward (FRS) and RS backward (BRS) and the consistency of these performances have yet to be established. Twenty-one boys (age, 13.6 ± 0.28 y; height, 1.7 ± 0.09 m; mass, 66.1 ± 8.2 kg; maturity, 0.57 ± 0.72 y from peak height velocity) performed FRS and BRS towing weighted sleds on three occasions. Load-velocity relationships were established using an unresisted sprint and RS with loads of 20, 30 and 40 kg (25-76% BM) in both directions, and the consistency of sprint times at each load and the Lv regression slopes were examined. From the regression lines ($r^2 \geq 0.99$; $p \leq 0.01$), it was observed that 31%, 46% and 61% BM loads resulted in 23%, 33% and 43% decrease in velocity during FRS and 27%, 38% and 48% during BRS. The Lv data was consistent across multiple testing occasions during FRS (CV ≤ 7.2%; ICC = 0.66 to 0.91) and BRS (CV ≤ 7.2%; ICC = 0.67 to 0.91). Increasing FRS and BRS load by ∼15% and ~13% BM respectively, consistently results in ∼10% decreases in running velocity relative to unloaded velocities during both FRS and BRS in youth athletes. Practitioners can be confident that FRS and BRS training will result in the desired training adaptations when prescribing loads ranging from 25-76% BM.

Appendix 12. Chapter 5 Abstract

This study compared the effects of two sprint-specific training programs against the natural development of speed, jumping ability and stiffness in a group of adolescent male athletes. Forty-three male adolescents (aged 13-15 years) were randomly assigned to one of two training groups; backward running training (BRT = 26), or forward running training (FRT = 17). A physical education class (n=24) of similar age constituted a control (CON) group. Both training groups performed running sessions matched for distance and intensity biweekly for eight-weeks. Parametric and magnitude-based inferences were used to analyze within group (pre-post measures) and between group (gain scores) for 10 m, 10- to 20 m and 20 m sprint times, vertical countermovement jump (CMJ) height and vertical leg stiffness. Both running groups significantly improved ($p \leq 0.05$) in all performance tests from pre- to post-training, with effect sizes ranging from -1.25 to 0.63. When the groups were compared, the BRT and FRT groups improved significantly ($p \leq 0.01$) on all sprint performances and stiffness relative to the CON group. The BRT group demonstrated favourable effects for 10 m and 20 m sprint performances (effect size [ES] = -0.47 and -0.26, respectively) and CMJ height (ES = 0.51) compared with the FRT group. These results demonstrate that forward and backward sprint-specific training programs enhance speed and power measures more than natural development in adolescent male athletes. Furthermore, the greater training responses in sprint performance and CMJ ability indicate that BRT is a useful tool for improving concentric strength and power and may be classified as a sprint-specific training method.

Appendix 13. Chapter 6 Abstract

Resisted sprinting (RS) is a popular training method used to enhance sprinting performance in youth. However, research has only explored the effects of forward RS (FRS) training. We examined the effects of FRS and backward RS (BRS) and compared these to a traditional physical education curriculum (CON). One-hundred and fifteen males (age 13-15 years) were matched for maturity and allocated to either a FRS ($n = 34$), BRS ($n = 46$), or CON ($n = 35$) group. Training groups towed progressively overloaded sleds (20-55% bodymass) 2 $d \cdot wk^{-1}$ for 8-weeks. Pre and post-training data was collected for sprinting times over 10 and 20 m, countermovement jump (CMJ) height, and leg stiffness (K_N). Performance remained unchanged for the CON group (all $p>0.05$), while all variables significantly improved ($p<0.05$) following BRS and all but 10 m performance improved following FRS. Compared to the CON, BRS and FRS significantly ($p>0.05$) improved CMJ (ES = 0.67 and 0.38) and K_N (ES = 0.94 and 0.69), respectively. No differences were found between training groups. The probabilities of improving sprinting performance following BRS (~70%) were on average ~10% and ~8% better than the FRS and CON groups, respectively. The BRS and FRS showed similar probabilities of improving CMJ (75% and 79%) and K_N (80% and 81%), respectively, over the CON group. It appears that BRS may be a means to improve sprint performance and regardless of direction, RS seems to be a beneficial method for improving jumping height and leg stiffness in youth male athletes.

Appendix 14. Chapter 7 Abstract

Backward running (BR) is a common locomotive technique used by most overground athletes during both competition and training, yet there are limited empirically based recommendations for using BR training for athletes. This article highlights the role of BR in sports context, provides insights into why BR may benefit athletes and recommends how to integrate BR into strength and conditioning programs. Informed guidance is provided on the practical applications for athletes, which should help speed and strength coaches design and facilitate BR in a safe and progressively overloaded fashion for youth and adult athletes alike.

The End