Advancing the diagnostic value of the pro-agility shuttle and the acute and chronic effects of training with wearable resistance on pro-agility shuttle performance.

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Abstract

The ability to change directions effectively is critical in many sporting scenarios. Thus there is importance for practitioners to assess and develop change of direction (COD) ability in athletes, with tests such as the 5-0-5 and pro-agility shuttle tests. While, empirical efforts had been made to improve the analytical quality of COD assessments by delineating between the linear sprint and COD components, there had been no evidence of researchers differentiating between the different components for the pro-agility shuttle. Adopting such an approach could provide better diagnostics and exercise prescription.

Wearable resistance (WR) in the form of limb micro-loading has led to enhanced performance of sport-specific movements, without compromises to velocity or movement specificity during training. Yet, there was no evidence in the research to date of the acute and chronic effects of WR training on COD performance, specifically in the pro-agility shuttle. The focus of this thesis was to advance the diagnostic capabilities of the pro-agility shuttle and understand the training implications of shank and forearm WR training on pro-agility shuttle performance. The introductory chapter provided an overview of COD assessment, trainability of COD, and WR utility in a sport-specific context. This determined the framework of the thesis and necessity for exploration into diagnostic capabilities and WR utility as a novel training method.

Two systematic reviews relating to the pro-agility shuttle were conducted. Firstly, Chapter 2 found timing light and stopwatch technologies to be most commonly used to assess the pro-agility shuttle, with total-time being the most reported value and therefore of limited value to the practitioners. Additionally, normative values were established with elite athletes being the fastest (4.61 ± 0.29 s) while sub-elite and novice athletes had similar spreads in performance (4.33 to 4.86 s). In Chapter 3, non-specific and specific training methods were reviewed the main findings being that sprint training (0.11 effect size (ES)), plyometric training (0.09 ES), resistance training (0.09 ES), and a combination of these training methods (0.08 ES) were found to be most effective at enhancing pro-agility shuttle performance. Furthermore, it was apparent that changes in pro-agility shuttle performance in response to WR training had yet to be investigated. These reviews highlighted important gaps and limitations and therefore provided a more focused direction for the experimental chapters of the thesis.

Abstract

To gain understanding of how the pro-agility shuttle could be used to differentiate between linear and COD components, the test was segmented into acceleration, deceleration, COD and reacceleration phases. Two experimental repeated measures studies were used to determine the reliability of this advanced diagnostic pro-agility protocol using timing light and radar technology. In Chapter 4, low typical error (coefficient of variation (CV) = 0.95 to 4.42%) and excellent relative consistency (intraclass correlation coefficient (ICC) 0.90 to 0.99) between sessions 2-3 for phases of the pro-agility shuttle was observed. In Chapter 5, the reliability of radar velocity profiling was investigated and was found to have acceptable absolute consistency (CV = 3.16 to 7.07%), yet relative consistency ranged from "very poor" to "good" (ICC = 0.14 to 0.76) between sessions 2-3.

In Chapters 6 and 7 the acute and chronic implications of shank and forearm WR on pro-agility shuttle performance were investigated. Chapter 6 used a randomized cross-over design to compare the acute effects of 1.5% body mass (BM) shank (WRs) and forearm (WRf) WR loading on the pro-agility shuttle in twenty-eight team sport athletes. Compared to unloaded, WRs loading had significantly faster COD1 time (-12.8%, d=-0.49, p<0.05) and total-time (-10.6%, d=-0.90, p<0.05), while WRf had significantly slower linear speed time during the acceleration (ACC) 2 phase (6.98%, d=0.47, p<0.05). In Chapter 7 the effects of six-week progressively overloaded WRs and WRf COD training compared to unloaded COD training in forty-two team sport athletes were compared. Chronic WR training over a 6-week period did not result in any significant change to pro-agility shuttle total-time. Significant slower reaccelerative performance (24.11%, d = 0.84, p = 0.01), and faster sprint times (d = -0.55 to -0.60) were found following WRs compared to unloaded training. Significantly faster ACC1 time (-8.60%, d = 1.39, p = 0.04), yet slower in ACC2 time (41.54%, d = 0.94, p = 0.00), and shorter horizontal jump distance (d = -1.12 to 0.09, p <0.01) were observed after WRf compared to unloaded training.

Chapter 8 provided an overall summary of the findings, detailed practical applications, and proposed future research directions. It is suggested for practitioners to use the advanced diagnostic protocol to better assess athlete performance in the pro-agility shuttle. Furthermore, WR COD training can be used to overload sport-specific actions and is beneficial to the development of COD associated athletic qualities.

Table of Contents

List of Figures

List of Tables

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, nor material which to a substantial extent has been accepted for the qualification of any degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

James Forster
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Authored Works

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

Published Manuscripts:

Forster, J. W. D., Uthoff, A. M., Rumpf, M. C., & Cronin, J. B. (2022). Pro-agility unpacked: Variability, comparability and diagnostic value. *International Journal of Sports Science & Coaching, 0*(0), 1-16. https://doi.org/10.1177/17479541211069338

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

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Ethical Approval

Ethical approval for this research was obtained from the AUT Ethics Committee (reference 20/67) on the 27th of March 2020 (see Appendix 2).

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Chapter One: Introduction

1.1.1 Importance of Change of Direction

Change of direction (COD) ability, a rapid change in movement direction (Sheppard & Young, 2006), is a fundamental determinant of successful athletic performance in both field (Sheppard & Young, 2006) and court-sport athletes (Eriksson, Johansson, & Back, 2015). Adept ability to change direction efficiently provides an indication of athletes' underlying capabilities to quickly decelerate and reaccelerate in a different direction (Chaabene, 2017; Spiteri, Cochrane, Hart, Haff, & Nimphius, 2013). Athlete COD ability proves pivotal to impacting the outcome during key instances in sport. For example, accelerating, decelerating, and reaccelerating in a new direction when transitioning between offensive and defensive moments in sport or manoeuvring around opposing players (Bradshaw, Young, Russell, & Burge, 2011; Spiteri et al., 2013). Consequently, the ability to assess and develop COD ability is important across a diverse range of sports (Banda, Beitzel, Kammerer, Salazar, & Lockie, 2019; Freitas et al., 2018; Lockie, Callaghan, & Jeffriess, 2013; Lockie et al., 2018).

1.1.2 Assessing Change of Direction

Given the importance of COD ability in sport, it is no surprise that a myriad of research has been conducted into the area of COD assessment. One highly impactful piece of research by Nimphius, Callaghan, Spiteri, and Lockie (2016) identified that linear sprinting components within a COD test, influence the measurement of total-time as a COD performance metric (Nimphius, Geib, Spiteri, & Carlisle, 2013). This confounding information can be addressed by assessing linear sprinting and COD as individual performance components (Nimphius et al., 2013; Salaj & Markovic, 2011; Vescovi & McGuigan, 2008). For example, the 5-0-5 COD test has been updated to include the COD deficit, the average difference between 5-0-5 and 10 m sprint times, providing a practical isolation of COD time and better indication of athlete COD ability (Nimphius et al., 2016). While the differentiation between speed and COD performance are addressed for the 5-0-5 test, few efforts have been made to improve the diagnostic value of the pro-agility shuttle.

The pro-agility shuttle, a widely utilised assessment of 180° COD ability over a total of 18.28 m (20 yards) (McKay et al., 2020), is used to identify and distinguish between athlete 180° COD performance, involving predetermined actions in which an athlete starts in a crouched three-point position on the start/finish line, turns and sprints 4.57 m one way, touches the first COD line, turning 180°, sprinting 9.14 m to and touching the second COD line, turn another 180°, and sprint 4.57 m back to the start/finish line (Banda et al., 2019; Bishop, Herridge, & Turner, 2017; McGee & Burkett, 2003; Nuzzo, 2015; Vescovi, Brown, & Murray, 2006; Vescovi & McGuigan, 2008). Yet, total-time quantification of pro-agility shuttle COD performance likely provides insufficient information relating to the differentiation between linear speed, accelerative, and COD capabilities of the athlete. As such, the utility and diagnostic potential of the pro-agility shuttle remains inadequately examined. The use of advanced protocols may enable more in-depth diagnostics of pro-agility shuttle performance by decompartmentalising the linear and COD components of the test. The ability to distinguish between the accelerative, decelerative, reaccelerative and COD phases may improve our understanding of an athlete's capabilities, allowing for better programming specific to athletic needs (Nimphius et al., 2016; Nimphius et al., 2013).

1.1.3 Trainability of Change of Direction

Since a large emphasis has been placed on athlete pro-agility shuttle performance for both talent identification and developmental purposes (Banda et al., 2019; Bishop et al., 2017; McGee & Burkett, 2003; Nuzzo, 2015), a great deal of consideration has been aimed at identifying training methods to improve pro-agility shuttle COD performance. Distinctly, researchers have found an association between the improvement of COD performance and application of traditional resistance training interventions (Falch, Rædergård, & Tillaar, 2020). The majority of studies have investigated non-specific forms of training (Falch, Rædergård, & Tillaar, 2019) that is, typically gym-based training, using high-loads and low-velocities. However, these types of movements and training methods do not emulate biomechanical movements similar to those performed during COD-specific sporting tasks. Specific methods of resisted sprinting, such as using sleds, have been shown to develop acceleration performance in sprinting (Kawamori, Newton, Hori, & Nosaka, 2014; Pantoja, Carvalho, Ribas, & Peyré-Tartaruga, 2018). While more biomechanically similar to linear sprinting, pushing or pulling a sled does not simulate the actions performed during a COD. A resistance training modality that can provide direct overload and permit athletes to perform COD actions, may present an effective and efficient means for transference of training related adaptation to 180° COD performance in tests such as the pro-agility shuttle.

1.1.4 Wearable Resistance Utility for Sport-specific Actions

Development of speed and COD performance training should be specific relative to the task at hand to enable optimal transference of training adaptation to performance (Campos-Vazquez et al., 2015; Falch et al., 2019; Macadam, Cronin, & Simperingham, 2016). Furthermore, while previously it has been cumbersome and technically disruptive to try and add load to an athlete while performing sport-specific movements, recent interest and advancements in resistance training technology have enabled WR to be worn on different segments of the body to provide specific overload when performing sport specific movements (Figure 1).

WR is a novel training tool, using light-loading placed on the torso or limbs to elicit overload in high-velocity sport-specific tasks with minimal disruptions to technique (Dolcetti, Cronin, Macadam, & Feser, 2018). WR limb-loading has been found to produce changes to linear sprint performance (Macadam, Cronin, Uthoff, & Feser, 2018). Researchers have shown shank loading to provide acute overload to 5 and 10 m sprint times with 2%BM attached to the shank (ES: 0.44 and 0.33, p <0.02) (Feser, Bezodis, et al., 2021) and elicit chronic adaptations with 200-600g over a training cycle i.e. reduced ($p < 0.05$) 10 and 20m linear sprint times (-1.64%, ES: -0.46 and -1.23%, ES: -0.33, respectively) and increased vertical jump height and horizontal jump distance (4.27%, ES: 0.38 and 6.25%, ES: 0.77, respectively) (Bustos, Metral, Cronin, Uthoff, & Dolcetti, 2020).

Alternatively, Scudamore et al. (2016) found weighted vest loaded training with 11.2%BM over a 3-week period to significantly reduce 36 m linear sprint (-1.48%, ES = 1.80) and 137 m shuttle run times (-1.0%, ES = 1.71), and moderately improve single leg vertical (1.9%, ES = 0.51) and repetitive jump height (1.2%, ES = 0.62) in athletic men. Furthermore, Rey, Padron-Cabo, and Fernandez-Penedo (2017) found 6-weeks of 18.9%BM weighted vest training improved 10 m and 30 m linear sprint (9.42%, ES = 1.77 and 6.04%, ES = 3.30, respectively), and 25 m repeated sprint ability (7.74%, ES = 2.15). Vest loading near the center of mass mainly affects the vertical force, and step length, whereas, limb-loading provides increases the inertial moment of the relative joints during cyclic action, thereby having a greater effect on horizontal force and step frequency (Couture et al., 2018; Macadam, Cronin, et al., 2016).

Despite the apparent utility of WR, few studies (Faigenbaum, McFarland, et al., 2006; Joseph et al., 2019; Turki et al., 2019) have investigated the acute or chronic effects of wearable resistance on COD performance. Researchers have shown vest loading of 10% body mass during a dynamic warm-up to have a positive acute effect on COD performance post-warm-up (*d* = 0.83 – 2.09, *p* = <0.01) (Maloney, Turner, & Miller, 2014; Turki et al., 2019). However, there is a paucity of research surrounding the use of WR limb loading (e.g. Figure 1) during high-velocity movement, and the ensuing acute overload and chronic training effects of WR on COD performance (Joseph et al., 2019; Maloney et al., 2014; Rantalainen, Ruotsalainen, & Virmavirta, 2012; Rey et al., 2017; Scudamore et al., 2016; Swain, Ringleb, Naik, & Butowicz, 2011; Turki et al., 2019).

Figure 1: Shank loaded Wearable Resistance.

1.2 Thesis Rationale

The pro-agility shuttle is a common COD test; however, the current utility of total-time is inadequate at detailing phase-specific information. The diagnostic advancement of the pro-agility shuttle may provide a more comprehensive understanding of phase-specific COD performance. Phase-specific approaches have been used in the 5-0-5 (Ryan, Uthoff, McKenzie, & Cronin, 2022), but no attempt has been made to take such an approach with the pro-agility shuttle test. It is important therefore, to establish the reliability of the linear speed and COD phases comprising the pro-agility shuttle. Furthermore, WR limb-loading can be used to enhance sport-specific movement capability, yet no empirical information is available pertaining to the acute and chronic effects of this form of training on COD performance. Therefore, it is imperative to understand the ensuing acute effects of different WR loading strategies using this protocol. This information will provide insights into WR forearm and shank limb loading strategies and how these strategies acutely affect different phases (i.e. acceleration, COD, and reacceleration) and sub-tests (e.g. 5-0-5 and modified 5-0-5), providing insight into a potential new training method for improving COD performance. This thesis provides original scientific research into why using advanced pro-agility shuttle diagnostics may be useful for assessing athlete phase-specific COD performance and how to prescribe WR limb-loading for athletes by providing a broad experimental application to this body of knowledge. This project has the potential to take the next step in advancing COD assessments from a measure of total time, thereby providing greater diagnostic value to practitioners. This includes differentiating the phases of acceleration, deceleration, turn and reacceleration. Furthermore, the investigation into the acute and longitudinal effects of WR loading strategies may lead to the development of new sport specific training methods for improving the different components of COD and overall COD performance in athletes.

1.3 Research Aims and Hypothesis

The overarching questions that this thesis will attempt to answer is: “What are the acute and chronic effects of forearm and shank loading WR on pro-agility shuttle performance?” To answer this question, information was collated regarding the current diagnostic value of the pro-agility shuttle and the effectiveness of current training modalities on pro-agility shuttle performance. It was then investigated as to whether a modified pro-agility shuttle test could reliably measure the different linear and COD phases within COD performance. Then addressed the acute and chronic effects of forearm and shank WR on those phases.

This question was answered through a series of acute and longitudinal studies that endeavoured to answer the following:

1) What is the variability, comparability, and diagnostic value of the pro-agility shuttle?
2) Can the diagnostic value of the pro-agility shuttle be enhanced to provide greater diagnostic information than total time? This will include:
    a. Are pro-agility shuttle total-time and phases comprising the test reliable when measured using an advanced diagnostic protocol with timing lights?
    b. Is radar analysis a reliable method of measuring velocity characteristics during different phases of the pro-agility shuttle?
3) What are the effects of different non-specific and specific training methods on pro-agility shuttle performance?
4) What effect does forearm and shank WR have on pro-agility shuttle performance and associated performance characteristics? This will include:
    a. What are the acute effects of forearm and shank WR on pro-agility shuttle performance?
    b. What are the chronic effects of WR training on pro-agility shuttle performance?

1.4 Thesis Originality

This thesis is novel and original to the pro-agility shuttle test and area of advancing diagnostic protocols of COD assessment. Furthermore, establishing novel acute and longitudinal effects of WR training for pro-agility shuttle performance will enhance practitioners exercise prescription for improving COD performance. Despite the utilisation of the pro-agility shuttle to assess COD performance in athletes, there is no review or critique of the body of research investigating the pro-agility shuttle. Previous researchers investigating COD performance assessment have indicated total-time measures provide ambiguous information, confounded by linear and COD qualities. However, advancement of diagnostic protocols to discern between linear and COD qualities during the pro-agility shuttle have yet to be investigated. Therefore, the topic of advancing the diagnostic protocol for pro-agility shuttle COD assessment is original with no current research investigating the utility and reliability of this protocol. The advancement of the pro-agility shuttle, if reliable, may provide insightful and practicable information regarding athlete performance in the different linear and COD phases constituting the pro-agility shuttle. The use of limb-loading via WR, has shown great promise to provide overload to high-velocity actions by manipulating the inertial moment of the arms and legs. Previous researchers investigating WR have predominantly focused on the effects regarding linear sprint performance, and lacked investigation relating to the effectiveness of sport-specific movement tasks, such as COD. Therefore, this thesis is also original as it is one of the first to investigate and determine the effectiveness of forearm and shank WR loading and training on COD performance and how these loading strategies acutely and chronically effect the linear and COD phases.

1.5 Thesis Organisation

This thesis is organized to answer the over-arching question, "What are the acute and chronic effects of forearm and shank loading wearable resistance on pro-agility shuttle performance?".

The chapters of this thesis, barring the first and last, were formatted and written for publication as scientific journal articles. The eight chapters of this thesis began with a prelude to expound how each chapter connects and thereafter builds upon the preceding chapters to ensure the thesis is a cohesive oeuvre. This thesis consists of four thematic sections to answer the overarching question of, "what are the acute and chronic effects of WR on pro-agility shuttle performance?". The structure of the thesis is depicted in Figure 2. Chapters 2-7 have been published or submitted for publication in scientific journals. Therefore, Chapters 2-7 were written in the format of the journal they had been submitted to, within the area of strength and conditioning as it relates to sport and exercise science. As a result, some information is repeated in the articles between the chapters. References were collated over the entire thesis and are provided in an overall list at the end of the final chapter.

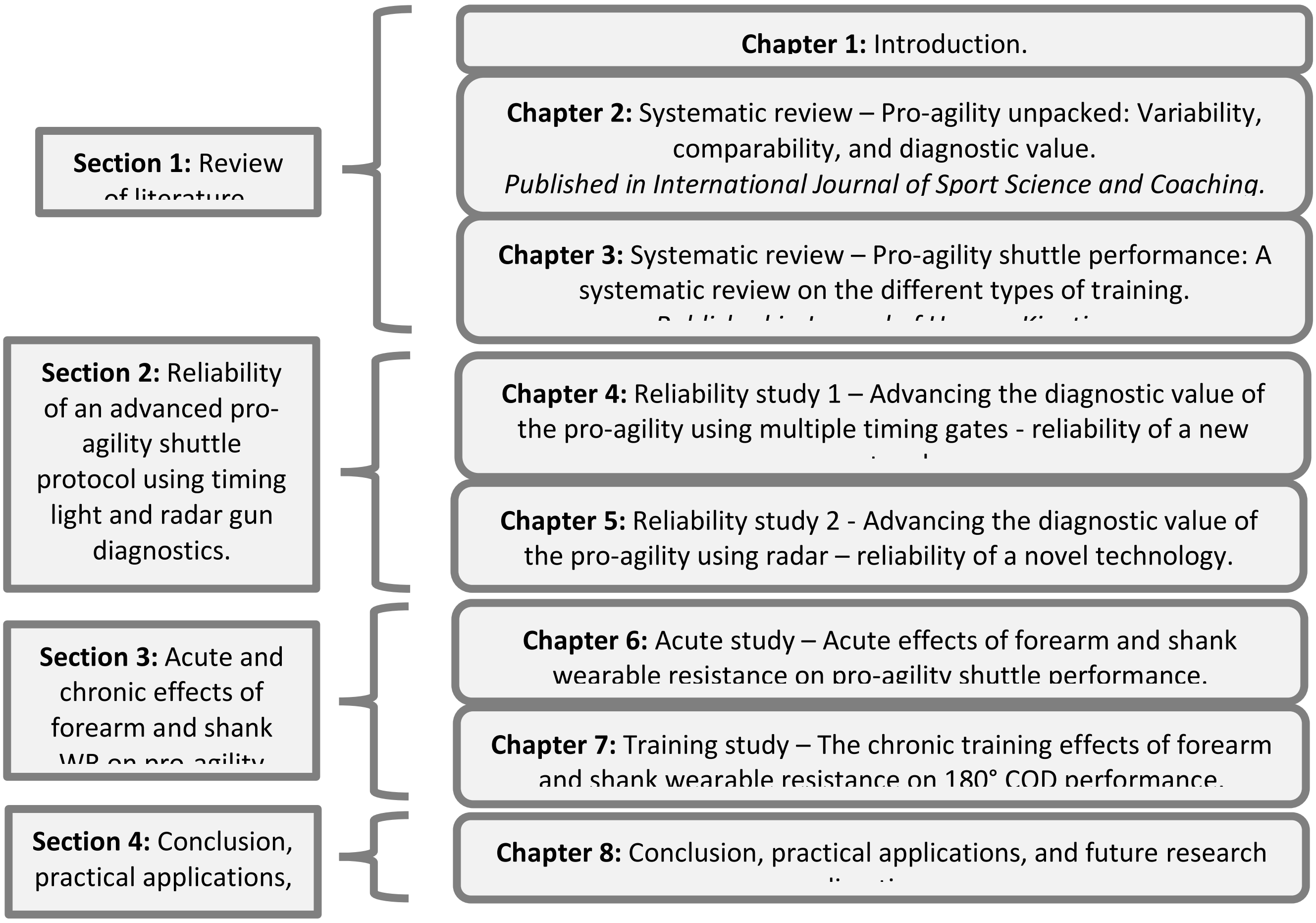

Figure 2: Thesis structure

The first section is comprised of the introduction and systematic review of the literature relating to the pro-agility shuttle. The introductory chapter provides the background and rationale, originality, and structure of the thesis. Chapter 2 is a systematic review of the literature critiquing the body of research on the pro-agility shuttle specifically addressing reliability and validity as it relates to methods of assessing the pro-agility shuttle. Additionally normative performance values for athletes of different sports and skill levels are established in this chapter. The review also explored current limitations and future research directions to enhance the assessment of COD performance using the pro-agility shuttle. Chapter 3 is another systematic review critiquing the body of research relating to specific and non-specific training methods used to affect pro-agility shuttle performance and established the effectiveness of these methods. The review also detailed the limitations and future research directions for training to develop pro-agility performance.

Section 2 is comprised of Chapter 4 and Chapter 5, which are the reliability chapters of this thesis. These studies serve to determine the reliability of an advanced pro-agility shuttle protocol and its diagnostic value. The purpose of Chapter 4 was to establish the test-retest reliability of an advanced diagnostic protocol and measurement of different sub-components (i.e. acceleration, deceleration, reacceleration, and COD) within the pro-agility shuttle using timing light technology. In Chapter 5 the test-retest reliability of radar velocity-profiling for the pro-agility shuttle and different sub-components within the test, is investigated.

Section 3 is comprised of two intervention chapters to determine the effect of WR training on pro-agility shuttle performance. In Chapter 6, a randomized cross-over design to was used to investigate the acute effects of WR, in which the pro-agility shuttle was performed with three conditions (unloaded, 1.5%BM WRs, and 1.5%BM WRf). This chapter compared the acute effects of WRs and WRf loading on pro-agility shuttle total-time, phases, and sub-test performance, and presented practitioners with practical applications to guide training strategy. The chronic training effects of forearm and shank WR on pro-agility performance were investigated in Chapter 7. A repeated measures experimental design was utilized to compare the effects of 6-week COD unloaded or progressively overloaded WRs or WRf training on pro-agility total-time, phases and sub-tests, and associated speed, lower body power, and peak force capabilities. The limitations and practical applications informing the decisions of practitioners regarding utilising forearm or shank WR for the development of pro-agility performance, were also detailed.

Chapter 8 summarises the thesis main findings provides practical applications for strength and conditioning practitioners, and outlines future research directions.

Chapter Two. Pro-agility Unpacked: Variability, Comparability, and Diagnostic Value.

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2.0 Preface

Despite widespread use of the pro-agility shuttle, there had been little understanding of the variability of measures and athlete performance across different sporting codes. The aim of this chapter is to provide a comprehensive understanding of the pro-agility shuttle's reliability and performance values by reviewing relevant literature. This review served as a foundation for subsequent reliability chapters, which explored the advancement of pro-agility shuttle assessment protocol reliability. Additionally, this chapter identified the diagnostic limitations of the pro-agility shuttle and provided guidance for future research.

Chapter Two. Pro-agility Unpacked: Variability, Comparability, and Diagnostic Value.

2.1 Introduction

Change of direction (COD) ability is one of the core determinants of successful athletic performance in both field and court-sport athletes (Eriksson et al., 2015; Sheppard & Young, 2006). The ability to change direction efficiently provides an indication of an athlete's underlying physiological capabilities, such as multi-directional reactive strength and anaerobic power (Reilly, Williams, Nevill, & Franks, 2000; Young, James, & Montgomery, 2002). Therefore, the assessment of COD ability has become important in many sporting codes (Banda et al., 2019; Freitas et al., 2018; Lockie, Callaghan, et al., 2013; Lockie et al., 2018). One of the most common tests to measure COD ability is the pro-agility shuttle test. Providing insight into acceleration, deceleration and COD, the pro-agility test is comprised of two 180° changes of direction over a total of 18.28 m (20 yards) (Brechue, Mayhew, & Piper, 2010; Jones & Nimphius, 2018; Nimphius, 2014; Nimphius, Callaghan, Bezodis, & Lockie, 2018).

The pro-agility shuttle has been used to determine team sport athletes' COD performance in sports such as basketball (Banda et al., 2019), cricket (Bishop et al., 2017), ice hockey (Cordingley, Sirant, MacDonald, & Leiter, 2019), lacrosse (Hoffman et al., 2009; Vescovi, Brown, & Murray, 2007), and rugby (La Monica et al., 2016). In some studies, the pro-agility shuttle test has also been used to distinguish positional differences in athletic qualities between sporting codes, for example, soccer and lacrosse (Vescovi et al., 2006; Vescovi & McGuigan, 2008). The pro-agility shuttle has also been used to benchmark individual athlete ability against other athletes for talent identification and recruitment within the American football combine (Banda et al., 2019; Bishop et al., 2017; McGee & Burkett, 2003; Nuzzo, 2015). This is due to the sharing of similar game-related movements, such as performing short accelerated sprints with rapid deceleration and high degrees of COD when transitioning from attacking to defending (Bourgeois, McGuigan, Gill, & Gamble, 2017; Jones, Bampouras, & Marrin, 2009; Vescovi et al., 2007). However, despite its widespread use there is little understanding as to the validity and reliability of the pro-agility shuttle test and therefore is a focus of this review.

One of the goals of collecting sport performance data is to gather normative information that provides insight in to the representation and spread of typical performance, relative to the sport, performance level or individual (O'Donoghue, 2005). By providing normative data, it enables practitioners to make appropriate comparisons between player performance to those of other groups (i.e. player positions and skill level). Therefore, establishment of pro-agility shuttle normative values is critical for the identification, monitoring and development of athlete performance and provides a focus of this review.

Despite the use of pro-agility shuttle as a performance assessment, little thought or critique has been given to the utility of the test. Given the preceding information, the aims of this review were:1) to quantify the variability associated with the pro-agility shuttle test; 2) establish normative data; and, 3) identify current limitations and future research directions. By taking such an approach, users of the pro-agility will have a better appreciation of the utility and limitations of this test.

2.2 Methods

2.2.1 Study Design

A systematic review was conducted in accordance with the Preferred Reporting Item for Systematic Reviews and Meta-analysis (PRISMA) guidelines (Moher et al., 2015) and was defined by the Population, Intervention, Comparison, and Study Design (PICOS) model. This review aimed to determine the utility of the pro-agility shuttle, through quantifying variability and reliability, establish normative performance values of different sports, skill levels and player positions, and identify limitations and areas of future research for the pro-agility shuttle.

2.2.2 Search Strategies

A systematic search of four electronic data bases (SPORTDiscus, PubMed, ScienceDirect, and OVID journals) was undertaken between January and May 2020 to identify original research articles published from the earliest available records up to and including May 2020. The keywords ‘pro-agility’, OR ‘20 yard shuttle’, OR ‘5-10-5 shuttle’ were used in Boolean logic for query. The reference sections of the selected studies were also examined for identification of other applicable studies.

2.2.3 Study and Screening Selection

Studies that included the pro-agility shuttle (Figure 3) were initially included in the first screening phase (*n* = 282). Additionally, studies must have been written in English. To determine the number of eligible studies a three-stage screening process was implemented; 1) Removal of duplicate studies (*n* = 127); 2) Screening of article title and abstract. Studies that were deemed to be 'out of scope' were excluded (*n* = 65); and, 3) Exclusion of studies that did not meet the inclusion criteria after screening the full text (*n* = 31). An additional eight eligible articles were included after reference checks, resulting in 67 studies included for analysis in this review. The selected studies comprised of 38 acute studies, 16 intervention studies, and 13 archival data (stored data) studies.

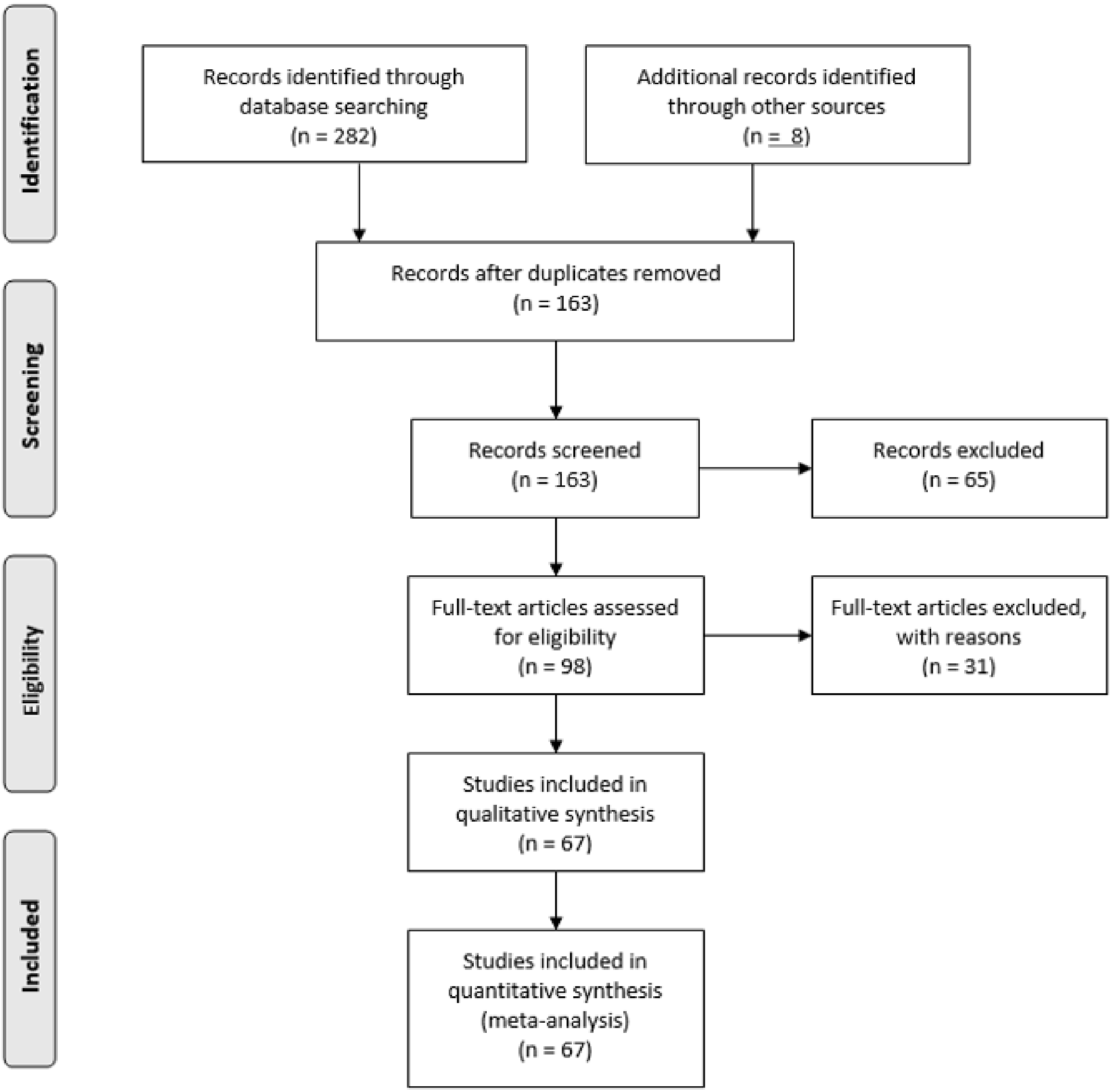

Figure 3: Flow diagram of study selection process.

2.2.4 Data Extraction

One author extracted the data using a custom designed standardised excel database (version 16.0, Microsoft, Redmond, WA, USA). A second author validated a cross-section of these ratings for quality assessment control. General study information (i.e. author, year), subject characteristics (i.e. sample size, gender, age, body mass, height, sport, performance level), type of study (i.e. acute, training, archival), methods of assessment (i.e. testing equipment, surface), and primary outcome measures (i.e. means and standard deviations of velocity or time) were extracted. Descriptive information relating to the sport and performance level were used to categorise each of the subjects. Subjects who were not identified with a sport were grouped as “general athletes”. In the case that data for different sports was reported in an article, performance results were categorised in the appropriate sport for analysis. There is a wide array of definitions for elite, sub-elite, and novice athletes (Lorenz, Reiman, Lehecka, & Naylor, 2013). Therefore, to clearly differentiate between groups, skill level was defined by the competitive level of athletes in their respective sport in this review. Elite athletes were classified to be competing at National Collegiate Athletic Association (NCAA) divisions 1 or 2, national, international, or professional competitive levels. Sub-elite athletes being those of NCAA division 3 athletes (Hoffman et al., 2009; Lorenz et al., 2013), regional level club athletes, or undrafted athletes. With novice athletes being classed high school or recreational athletes.

2.2.5 Study Quality Assessment

To assess the standard of the included studies, a quality scale designed to evaluate research conducted in athletic-based environments, was implemented (McMaster, Gill, Cronin, & McGuigan, 2013). This scale was modified and utilised based upon the scale created by Brughelli, Cronin, Levin, and Chaouachi (2008), using a combination of items from the Cochrane, Delphi, and PEDRO, as shown in Table 1. The quality of each study was evaluated on 10 items (2 points per item): inclusion criteria stated, subject assignment, intervention description, control groups, dependent variables definition, assessment methods, study duration, statistics, results section, and conclusions. The total quality score for each study ranged between 0 to 20, where a score of 0 = clearly no; 1 = maybe; and 2 = clearly yes.

Table 1: Study quality score

Study quality score (Brughelli et al., 2008)		
Number	**Item**	**Score**
1	Inclusion criteria stated	0-2
2	Subjects assigned appropriately	0-2
3	Intervention described	0-2
4	Control group	0-2
5	Dependant variable defined	0-2
6	Assessments practical	0-2
7	Duration	0-2
8	Statistics appropriate	0-2
9	Results detailed	0-2
10	Conclusions insightful	0-2

2.2.6 Data Analysis

IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA) was used to analyse the data from the studies collected. Data was reported using mean and standard deviation (±SD). Subjects were grouped by sport, skill level (novice, sub-elite, and elite), and position where appropriate. The level of relative reliability ICC was described as: ≤0.50 poor, 0.50 – 0.75 moderate, 0.75 – 0.90 good, and ≥0.90 excellent reliability (Koo & Li, 2016). Absolute reliability CV was deemed acceptable at a level ≤10% (Hopkins, 2000; Uthoff, Oliver, Cronin, Winwood, & Harrison, 2018).

2.3 Results

2.3.1 Quality Score

For acute studies items 3 and 4 on the modified scale could not be assessed, additionally archival studies, where data collection came from historical archives, items 3, 4, and 7 on the modified scale could not be assessed and was excluded for these studies, therefore, these studies are assessed on a scale of 0 to 16 and 0 to 14, respectively. Quality score for all studies averaged 15.9 (± 2.09). Acute studies averaged 14.2 (± 1.72) out of 16, for intervention studies 17.5 (± 1.51) out of 20, and for archival data studies a 13.4 (± 0.77) out of 14 (Table 1). Acute study quality was affected by the inclusion or exclusion of item 1 and 9 in Table 1 (i.e., inclusion criteria stated, and use of results detailed). Of the 38 acute studies four did not state inclusion criteria, and 14 of the 38 studies 'maybe' stated inclusion criteria. Seventeen of the 38 acute studies 'maybe' stated detailed results (i.e. results lacked detail or were not presented clearly). Intervention study quality was affected by the inclusion or exclusion of item 4 and 8 (Table 1) (i.e., use of a control group, and appropriate use of statistics). Nine of the 16 intervention studies included the use of a control group, as it was practical to use this study design in the tested population (e.g. randomised-control trial). Five of the 16 intervention studies did not use appropriate statistical analysis, where inferential statistics, within-group or between-group reliability, or effect size (ES) analysis may not have been conducted. Quality score for archival studies averaged 13.4 ± 0.77 out of 14 (Table 1). Archival study quality was affected by inclusion or exclusion of item 1, 2, and 6 in Table 1 (i.e., inclusion criteria was not clearly stated, the assignment of subjects was not defined, and results were not detailed). Ten of the 13 archival studies clearly described inclusion criteria for the subjects. Eleven of the 13 archival studies assigned subjects appropriately, based on playing position and skill level. Three of the 13 archival studies reported results in insufficient detail (i.e. reporting between group differences).

2.3.2 Overview of Studies

A summary of the included studies for this review can be found in Table 2. Data was gathered from 11 different sports in 68 population samples over 67 studies as summarised in Table 3 and herewith; most sports were found in the sub-elite and novice skill level, however, there appears to be an ample spread of data through the three skill levels. The 67 studies comprised a sample size of 32,891 subjects of different skill levels (elite: 6,631, sub-elite: 382, novice: 25,878), with an average sample size of 472.79 ± 1,193 (range 12 – 4,603) for elite, 27.3 ± 19.7 (range 12 - 84) for sub-elite, and 924.21 ± 2,505 (range 11 – 9,203) for novice subjects. The most common sport was American football (11 elite, 5 sub-elite, and 9 novice) and the least common sports were basketball, cricket, ice hockey, resistance-trained athletes, and tennis.

Table 2: Description of the studies in the review

Author	Sport	Age	Skill Level	N=	M ± SD (s)	Quality Score
Corey and Randall (2020)	American football	20+ years	Elite	628	4.39 ± 0.18	14
Yamashita, Asakura, Ito, Yamada, and Yamada (2017)	American football	26.2 ± 3.9	Elite	245	4.51 ± 0.19	18
Davis, Barnette, Kiger, Mirasola, and Young (2004)	American football	Not reported	Elite	46	4.17 ± 0.27	12
Gains, Swedenhjelm, Mayhew, Bird, and Houser (2010)	American football	18.8 ± 0.4	Elite	24	4.63 ± 0.06	17
Mann, Ivey, Mayhew, Schumacher, and Brechue (2016)	American football	20.5 ± 1.2	Elite	64	4.47 ± 0.29	17
Nesser, Huxel, Tincher, and Okada (2008)	American football	Not reported	Elite	29	4.50 ± 0.30	15
Nimphius et al. (2013)	American football	18-22 years	Elite	66	4.53 ± 0.33	17
Nuzzo (2015)	American football	Not reported	Elite	4603	4.39 ± 0.19	13
Robbins (2011)	American football	Not reported	Elite	1136	4.43 ± 0.30	14
Robbins, Goodale, Kuzmits, and Adams (2013)	American football	Not reported	Elite	1712	4.66 ± 0.02	14
Stodden and Galitski (2010)	American football	Not reported	Elite	84	4.17 ± 0.09	17
Hoffman, Ratamess, and Kang (2011)	American football	Not reported	Sub-elite	289	4.33 ± 0.19	18
Leutzinger et al. (2018)	American football	Not reported	Sub-elite	7160	4.67 ± 0.18	13
Lockie, Schultz, Callaghan, and Jeffriess (2012)	American football	16.53 ± 0.77	Sub-elite	36	4.85 ± 0.53	15
Newsom and Probst (2016)	American football	Not reported	Sub-elite	25	4.58 ± 0.16	12
Yuasa, Kurihara, and Isaka (2018)	American football	19.9 ± 0.9	Sub-elite	17	4.42 ± 0.13	18
Caswell et al. (2016)	American football	12.4 ± 1.32	novice	819	5.60 ± 0.23	17
Collins, Coburn, Galpin, and Lockie (2018)	American football	15.93 ± 0.96	novice	15	5.03 ± 0.21	18
Dupler, Amonette, Coleman, Hoffman, and Wenzel (2010)	American football	9-12 grade	novice	2327	4.63 ± 0.06	14
Ghigiarelli (2011)	American football	Not reported	novice	161	4.45 ± 0.19	14
Gillen, Shoemaker, McKay, and Cramer (2019a)	American football	Not reported	novice	9203	4.49 ± 0.18	14
Gillen, Shoemaker, McKay, and Cramer (2019b)	American football	Not reported	novice	7214	4.60 ± 0.30	13
Lockie, Lazar, et al. (2016)	American football	20.11 ± 1.60	novice	62	4.59 ± 0.20	17

Table 2: Description of the studies in the review (continued).

Author	Sport	Age	Skill level	N=	M ± SD (s)	Quality Score
McKay et al. (2018)	American football	Not reported	novice	7478	4.92 ± 0.48	14
McKay et al. (2020)	American football	Not reported	novice	7478	4.92 ± 0.48	13
Banda et al. (2019)	Basketball	Not reported	Elite	12	4.72 ± 0.29	16
Bishop et al. (2017)	Cricket	26.2 ± 5.3	Sub-elite	14	4.75 ± 0.18	18
Cesar, Edwards, Hasenkamp, and Burnfield (2017)	General Athletes	20.0 ± 0.42	Elite	160	4.64 ± 0.33	16
Jones, Matthews, Murray, Raalte, and Jensen (2010)	General Athletes	Not reported	Sub-elite	46	5.39 ± 0.24	17
Wagner, Oden, Glave, and Hyman (2014)	General Athletes	Not reported	Sub-elite	15	5.47 ± 0.13	16
Faigenbaum, Kang, et al. (2006)	General Athletes	15.5 ± 0.9	novice	30	5.14 ± 0.03	17
Faigenbaum et al. (2007)	General Athletes	13.5 ± 0.14	novice	17	5.60 ± 0.00	18
Gillen, Miramonti, McKay, Leutzinger, and Cramer (2018)	General Athletes	10.9 ± 2.1	novice	69	6.05 ± 0.35	17
Jones and Lorenzo (2013)	General Athletes	11.8 ± 0.07	novice	157	5.92 ± 0.11	18
Markovic, Jukic, Milanovic, and Metikos (2007)	General Athletes	20.1 ± 1.10	novice	93	4.97 ± 0.08	19
Sekulic, Spasic, Mirkov, Cavar, and Sattler (2013)	General Athletes	21.1 ± 0.71	novice	63	5.52 ± 0.45	17
Stewart, Turner, and Miller (2014)	General Athletes	16.7 ± 0.6	novice	44	4.93 ± 0.44	15
Toyomura et al. (2018)	General Athletes	22.8 ± 2.20	novice	18	10.97 ± 0.01	17
Cordingley et al. (2019)	Ice Hockey	14 ± 1	novice	92	4.86 ± 0.18	14
Vescovi and McGuigan (2008)‡	Lacrosse	19.7 ± 1.1	Elite	79	4.99 ± 0.24	16
Greene, Perryman, Cleary, and Cook (2019)	Lacrosse	20.25	Sub-elite	20	5.20 ± 0.78	16
Hoffman et al. (2009)	Lacrosse	19.2 ± 1	Sub-elite	22	4.93 ± 0.05	16
Sell et al. (2018)	Lacrosse	19.6 ± 1.6	Sub-elite	41	4.39 ± 0.03	18
Vescovi et al. (2007)	Lacrosse	19.8 ± 1.1	Sub-elite	84	4.99 ± 0.23	14
Carlson, Fowler, and Lawrence (2019)	Recreational Athletes	20.5 ± 0.5	novice	11	5.53 ± 0.14	17
Chan, Ho, and Yung (2018)	Recreational Athletes	29.8 ± 9.9	novice	16	5.25 ± 0.04	19

Nikolenko, Brown, Coburn, Spiering, and Tran (2011)	Recreational Athletes	23.40 ± 1.88	novice	20	5.04 ± 0.30	15
Zweifel, Vigotsky, Contreras, and Njororai Simiyu (2017)	Resistance-trained athletes	22.15 ± 2.2	novice	26	4.92 ± 0.07	14
Freitas et al. (2018)	Rugby	backs: 22.0 ± 2.3, forwards: 23.1 ± 3.2	Elite	24	Not reported	16
Freitas et al. (2019)	Rugby	23.6 ± 1.41	Elite	36	Not reported	17
Beyer et al. (2016)	Rugby	21.2 ± 1.4	Sub-elite	12	5.06 ± 0.28	13
Speirs, Bennett, Finn, and Turner (2016)	Rugby	18.1 ± 0.5	Sub-elite	18	4.66 ± 0.13	20
La Monica et al. (2016)	Rugby	20.2 ± 1.6	novice	25	5.15 ± 0.01	18

Table 2: Description of the studies in the review (continued).

Author	Sport	Age	Skill Level	N=	M ± SD (s)	Quality Score
Lockie and Jalilvand (2017)	Soccer	20.10 ± 1.20	Elite	20	5.07 ± 0.17	18
Lockie et al. (2017)	Soccer	20.2 ± 1.2	Elite	21	5.08 ± 0.13	18
Lockie et al. (2018)	Soccer	20.19 ± 1.20	Elite	26	5.09 ± 1.60	16
McFarland, Dawes, Elder, and Lockie (2016)	Soccer	18-23	Elite	36	5.00 ± 0.51	15
Risso et al. (2017)	Soccer	starters: 20.4 ± 1.3, non-starters: 20.1 ± 1.2	Elite	22	5.07 ± 0.04	17
Vescovi and McGuigan (2008)ǂ	Soccer	19.9 ± 0.9,	Elite	51	4.88 ± 0.20	16
Kavaliauskas, Kilvington, and Babraj (2017)	Soccer	22.00 ± 8.00	Sub-elite	14	5.99 ± 0.04	19
Magal, Smith, Dyer, and Hoffman (2009)	Soccer	Not reported	Sub-elite	12	4.88 ± 0.11	15
Ferley, Scholten, and Vukovich (2020a)	Soccer	INC: 15.75 ± 0.92; LEV: 15.1 ± 0.42; CG: 16.0 ± 0.57	novice	46	5.20 ± 0.09	18
Millar, Colenso-Semple, Lockie, Marttinen, and Galpin (2020)	Soccer	Hip thrust: 15.7 ± 0.8, Squat Group: 15.3 ± 0.7	novice	15	5.26 ± 0.01	16
Moran et al. (2018)	Soccer	Pre-PHV – Experimental Group: 10.4 ± 0.8, Control Group: 10.0 ± 1.0; Post-PHV – Experimental Group: 13.6 ± 0.7, Control Group: 14.5 ± 1.0	novice	42	5.44 ± 0.29	17
Vescovi and McGuigan (2008)ǂ	Soccer	15.1 ± 1.6	novice	83	4.91 ± 0.22	16
Halil, Nurtekin, Dede, Amze, and Mine (2013)	Swimming	11.5 ± 0.07	novice	20	6.08 ± 0.29	12
Kemal, Cecilia, Metin, Tunga, and Halil (2013)	Swimming	11.62 ± 0.07	novice	21	6.06 ± 0.04	10
Eriksson et al. (2015)	Tennis	14 ± 1.6	novice	34	5.10 ± 0.04	18

ǂ Denotes use of an article in more than one sport

Table 3: Number of population samples by sport and skill level

	Basketball	Cricket	General Athletes	Ice Hockey	Lacrosse	NFL	Recreational Athletes	Resistance-trained Athletes	Rugby	Soccer	Swimming	Tennis	Total
Elite	1		1		1	11			2	6			22
Sub-elite		1	2		4	5			2	2			16
Novice			8	1		9	3	1	1	4	2	1	30
Total	1	1	11	1	5	25	3	1	5	12	2	1	68

Key: NFL = American Football.

2.3.3 Reliability and Technology.

Reliability of the pro-agility shuttle was found to be reported in five different sports and in general athletic populations (Table 4). The change in mean denotes the systematic bias or random error of measurement (Hopkins, 2000), and only three studies have reported the change in mean over multiple testing occasions (Bishop et al., 2017; Gillen et al., 2018; Mann et al., 2016). The change in mean varied by 0.60% to 1.71%. The greatest change in the mean was found in general athletes (Gillen et al., 2018), the smallest change was noted in elite American football athletes (Mann et al., 2016).

Table 4: Reliability and technology

Author	N =	Sport	Skill level	Timing Technology	Number of trials x sessions (between trial length)	Reliability type	Change in mean (%)	ICC	CV (%)
Gains et al. (2010)	24	American football	Elite	Stopwatch	2 x 2 (1 week)	Between-session		Turf: 0.92, grass: 0.98	
Mann et al. (2016)	64	American football	Elite	Stopwatch	2 x 2 (1 week)	Within-group (%), Between-session (ICC), within-session (CV)	0.60%	0.914	1.9
Lockie et al. (2012)	36	American football	Sub-elite	Timing light (dual beam)	2 x 1	Within-session (ICC)		0.93	
Bishop et al. (2017)	14	Cricket	Sub-elite	Timing light (single beam)	3 x 2 (18 weeks)	Within-group (%), Between-session (ICC), within-session (CV)	1.05%	0.852	1.35
Gillen et al. (2018)	69	General Athletes	novice	Timing light (single beam)	2 x 2 (5 days)	Within-group (%), Between-session (ICC), within-session (CV)	1.71%	6-9y: 0.86, 10-11y: 0.87, 12-15y: 0.80	6-9y: 4.24, 10-11y: 3.65, 12-15y: 4.95
Sekulic et al. (2013)	63	General Athletes	novice	Timing light (single beam)	3 x 1	within-session (CV)			0.06
Stewart et al. (2014)	44	General Athletes	novice	Timing light (single beam)	2 x 1	Relative within-day, reliability (ICC), between test (CV)		0.90	2.19
Carlson et al. (2019)	11	Recreational Athletes	novice	Timing light (single beam)	2 x 2 (1 week)	Between session (ICC)		0.802	
Speirs et al. (2016)	18	Rugby	Sub-elite	Timing light (single beam)	3 x 2 (5 weeks)	Cohens *d*		0.89	
Eriksson et al. (2015)	34	Tennis	novice	Timing light (single beam) and Stopwatch	3 x 2 (3 days)	Between session and within session reliability (ICC)		Between-session: Timing light: 0.91 (0.83 – 0.96), Stopwatch: 0.95 (0.90 – 0.97) Within-session: Timing light - S1: 0.95, S2: 0.96; Stopwatch - S1: 0.95, S2: 0.96	

Key: 6-9y = 6- to 9-year-old, 10-11y = 10 to 11 years old, 12-15y = 12 to 15 years old, S1 = session 1, S2 = session 2.

The ICC gives insight into rank order consistency between repeated testing occasions (Koo & Li, 2016). Nine studies reported ICCs (Bishop et al., 2017; Carlson et al., 2019; Eriksson et al., 2015; Gains et al., 2010; Gillen et al., 2018; Lockie et al., 2012; Mann et al., 2016; Speirs et al., 2016; Stewart et al., 2014), with seven studies reporting between-session reliability (Bishop et al., 2017; Carlson et al., 2019; Eriksson et al., 2015; Gains et al., 2010; Gillen et al., 2018; Mann et al., 2016; Stewart et al., 2014). The ICC ranged from 0.80 to 0.98, the lowest reliability was found in a novice general athlete population (Gillen et al., 2018), the highest ICC reported in an elite American football populations (Gains et al., 2010).

The CV provides insight into the absolute consistency of measures and is calculated as a ratio of the standard deviation to the mean (Hopkins, 2000) and presented as a percentage. Only five studies reported the CV for within-day reliability (Bishop et al., 2017; Gillen et al., 2018; Mann et al., 2016; Sekulic et al., 2013; Stewart et al., 2014). The CV ranged from 0.06% to 4.95%. The lowest and highest CVs were found in novice general athletes (Gillen et al., 2018; Sekulic et al., 2013), indicating low individual consistency and high variability of within-session measurement within the novice population. The only CV for elite and sub-elite athletes were in American football (Mann et al., 2016) and cricket (Bishop et al., 2017) (CV = 1.9%, 1.35% respectively).

In terms of the reliability associated with the various technologies, it seems that infrared timing light technology (ICC = 0.80 - 0.96; CV = 0.06% - 4.95%) is less stable than stopwatch measures (ICC = 0.91 - 0.98; CV = 1.9%). It should be noted that most studies used single beam timing light technology. Seven of these studies (Bishop et al., 2017; Carlson et al., 2019; Eriksson et al., 2015; Gillen et al., 2018; Sekulic et al., 2013; Speirs et al., 2016; Stewart et al., 2014) reported the reliability of single beam timing lights, only a single study (Lockie et al., 2012) reported the reliability of dual beam timing lights, and three studies (Eriksson et al., 2015; Gains et al., 2010; Mann et al., 2016) reported reliability of stopwatches.

2.3.4 Overview of Skill Level

Mean pro-agility shuttle time across all studies was 4.93 ± 0.86 s, ranging from 4.17 to 6.08 s (Figure 4A). Averaged times for skill levels were 4.61 ± 0.29 s in elite, 4.91 ± 0.44 s in sub-elite, and 5.16 ± 1.14 s in novice athletes. When examining the performance times of each skill level, an overlap in pro-agility shuttle performance range was observed between the sub-elite and novice skill levels (Figure 4B). However, when using an averaged trendline, it was observed that there was a 0.30 s difference in mean pro-agility shuttle time between elite and sub-elite (4.61 ± 0.29 and 4.91 ± 0.44 s, respectively) and a 0.41 s difference between sub-elite and novices (4.91 ± 0.44 and 5.16 ± 1.14 s, respectively).

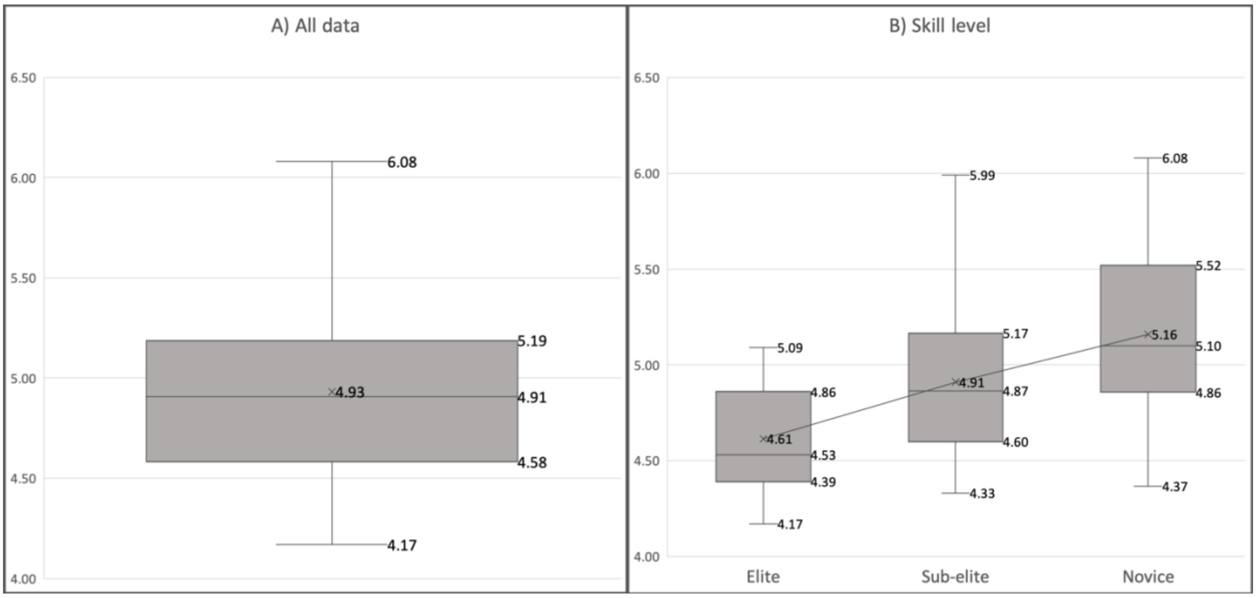

Figure 4: Averaged and skill-level performance quartiles.

In Figure 4A quartiles for averaged data across all studies are presented. The lower quartile can be observed between 4.17 - 4.58 s and represents the fastest 25% of pro-agility shuttle times, with the middle 50% of times between 4.58 - 5.19 s, and the slowest 25% between 5.19 - 6.08 s presented in the upper quartile). The quartile rankings for each skill level (elite, sub-elite, and novice) are presented in Figure 4B. The fastest 25% of performance times for each skill level are between 4.17 – 4.39 s in elite athletes, 4.33 – 4.60 s in sub-elite athletes, and 4.37 – 4.86 s in novice athletes.

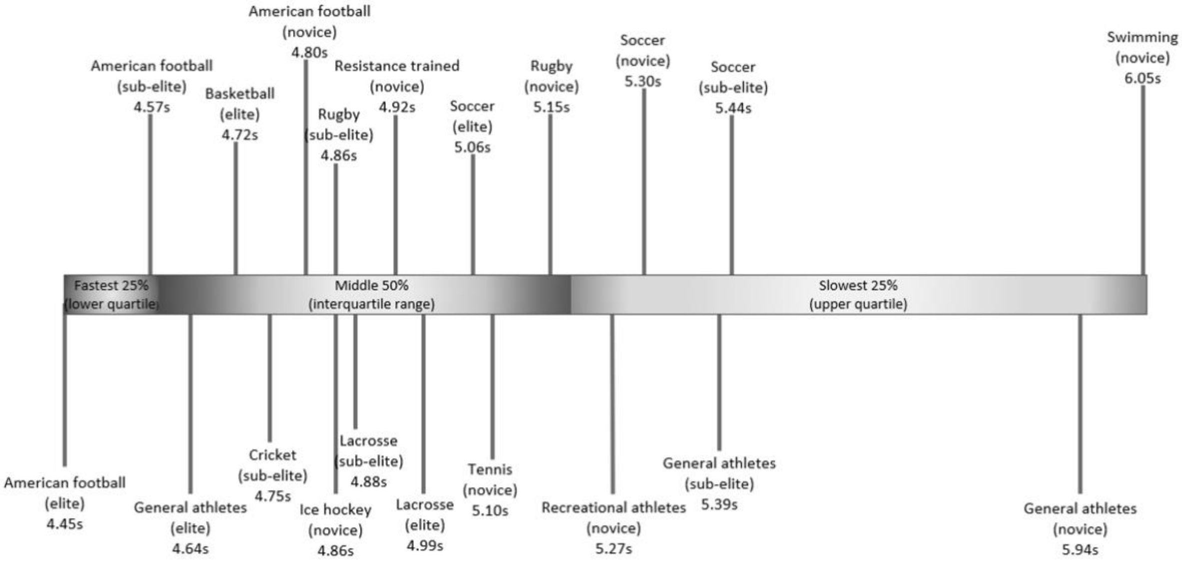

Figure 5: Normative performance timeline

2.3.5 Overview of Sports.

An overview of the performance times per sport is shown in Figure 5. Based on percentile ranks of all included literature, the fastest 25% (lower quartile) of pro-agility shuttle times include elite and sub-elite American football athletes. The middle 50% of all times was represented by elite general athletes (4.64 ± 0.33 s), basketball (4.72 ± 0.29 s), cricket (4.75 ± 0.18 s), novice American football (4.80 ± 0.42 s), ice hockey (4.86 ± 0.18 s), sub-elite and novice rugby athletes (4.86 ± 0.28 and 5.15 ± 0.01 s), elite and sub-elite lacrosse athletes (4.99 ± 0.24 and 4.88 ± 0.34 s), resistance-trained athletes (4.92 ± 0.07 s), elite soccer (5.06 ± 0.04 s), and tennis athletes (5.10 ± 0.04 s). With the slower 25% (upper quartile) of athletes being recreational athletes, (5.27 ± 0.25 s), novice soccer (5.30 ± 0.12 s), novice general athletes (5.94 ± 1.81 s), and swimming athletes (6.05 ± 0.12 s).

As for positional performance findings (Table 5), American football was the only sport to provide pro-agility shuttle times in novice, sub-elite, and elite skill groups. Interestingly, at both novice and sub-elite levels pro-agility shuttle time was not reported in the fullback position. In lacrosse, only sub-elite positional performance was reported. Similarly, the same was observed in novice rugby and elite soccer players.

Table 5: Pro-agility positional differences

Sport	Position	Skill level Novice (s)	Sub-elite (s)	Elite (s)
American football	Defensive back	4.52 ± 0.31	4.60 ± 0.11	4.25 ± 0.11
	Quarter back	4.62 ± 0.34	4.65 ± 0.10	4.34 ± 0.04
	Running back	4.59 ± 0.30	4.50 ± 0.10	4.30 ± 0.10
	Fullback			4.45 ± 0.14
	Wide receiver	4.53 ± 0.30	4.58 ± 0.08	4.27 ± 0.12
	Tight end	4.64 ± 0.35	4.68 ± 0.06	4.42 ± 0.12
	Offensive linemen	5.11 ± 0.40	5.40 ± 0.49	4.84 ± 0.32
	Defensive linemen	4.79 ± 0.49	5.06 ± 0.60	4.71 ± 0.35
	Linemen (offensive and defensive)	4.97 ± 0.50	5.35 ± 0.46	4.84 ± 0.38
	Line-backer	4.64 ± 0.34	4.62 ± 0.04	4.36 ± 0.13
Lacrosse	Starter		4.92 ± 0.22	
	Non-starters		4.94 ± 0.13	
	Attackers		4.81 ± 0.34	
	Defenders		4.77 ± 0.33	
	Midfielders		4.74 ± 0.32	
	Goal keepers		4.91 ± 0.14	
Rugby	Forwards	5.14 ± 0.30		
	Backs	5.16 ± 0.30		
Soccer	Starter			5.04 ± 0.17
	Non-starters			5.09 ± 0.17
	Attackers			4.88 ± 0.00
	Defenders			5.14 ± 0.29
	Midfielders			5.11 ± 0.08
	Goal keepers			4.94 ± 0.00

2.4 Discussion

This systematic review aimed to identify the reliability and established normative values for performance time in the pro-agility shuttle from the available literature. To the authors knowledge, this was the first study to establish variability and normative data of pro-agility shuttle performance across different sports, skill levels, and positions. Pro-agility shuttle times from relevant literature have been collated and synthesised to provide an overview of test variability, categorical performance values, and guide identification of ability relative to sport, skill level, or player position in the pro-agility shuttle (where applicable) (O'Donoghue, 2005). However, there was limited data pertaining the use of the pro-agility shuttle test across the different skill levels in each sport.

Hopkins (2000), believes measures of change in mean, relative (ICC), and absolute (CV) consistency need to be reported to fully understand the reliability of measures (Hopkins, 2000, 2015). Only three studies (Bishop et al., 2017; Gillen et al., 2018; Mann et al., 2016) reported all three measures of reliability, only one study (Stewart et al., 2014) reported the CV and ICC, and six studies (Carlson et al., 2019; Eriksson et al., 2015; Gains et al., 2010; Lockie et al., 2012; Sekulic et al., 2013; Speirs et al., 2016) reported a single reliability measure.

To quantify the repeatability of measures for a given performance task, reliability of measures should be determined over multiple testing occasions i.e. test-retest reliability. Additionally, to understand the effectiveness of a training programme, coaches must be confident that the tests they use are consistent across multiple testing occasions. Generally, three testing occasions are needed to observe whether changes in measures are becoming more consistent. Only seven studies (Bishop et al., 2017; Carlson et al., 2019; Eriksson et al., 2015; Gains et al., 2010; Gillen et al., 2018; Mann et al., 2016; Speirs et al., 2016) reported test-retest reliability and these were only conducted over two testing occasions. All other studies calculated within session reliability. Furthermore, the pro-agility shuttle as it stands provides limited diagnostic value due to total-time being a single measure of performance (Nimphius et al., 2018). Whereas advancing diagnostic capabilities of the pro-agility shuttle to differentiate between acceleration, deceleration, and COD measures would provide further insight into the capabilities of underlying physiological components is of value to applied practitioners and may be used to guide COD programming.

From this review, it appears that stopwatches and timing lights are the most commonly used technologies to measure performance time of the pro-agility shuttle (Table 4). While these technologies are portable and easily available resources to applied practitioners, the technologies reported in these articles are not without limitations. It would be logical to assume that measures from infrared timing light technology would be more stable than stopwatch measures. This assumption is not supported with the presented data, as there is greater variability reported for infrared timing light technology, compared to stopwatch measures. However, data pertaining to infrared timing light technologies was represented more in novice and sub-elite athletes. This may increase variability due to less developed neuromuscular capacity to perform more complex movement patterns resulting in more variation in performance (Cormie, McGuigan, & Newton, 2011; Duchateau & Baudry, 2010). Additionally, stopwatch measures reliability was limited to two sporting populations (American football and tennis). Therefore, while present data does not support the above assumption, we suggest additional research be conducted to establish a meaningful conclusion.

Interestingly, a single study quantified performance using dual beam timing light technology (Lockie et al., 2012). While timing lights provide practitioners with more precise measurement of time, Cuthbert, Dos' Santos, Thomas, and Jones (2017) reported moderate to relative reliability in single-beam timing lights (ICC = 0.63 – 0.86), acknowledging this could be improved with the use of dual beam timing lights (Haugen & Buchheit, 2016). Previous sprinting studies with dual beam timing lights have been shown to elicit greater accuracy of measurement compared to single beam lights (Earp & Newton, 2012; Yeadon, Kato, & Kerwin, 1999) as dual beam systems are thought more accurate and reliable due to both lights having to be broken to record a time i.e. mitigating false triggers such as a hand breaking the infrared beams. However, this was counter to findings in this review, as dual beam was observed to be less reliable (ICC = 0.76) in sub-elite American football athletes (Lockie et al., 2012), compared to studies using single beam lights (ICC = 0.80 – 0.90) in sub-elite cricket and rugby, and novice general athletes (Bishop et al., 2017; Carlson et al., 2019; Cordingley et al., 2019; Gillen et al., 2018; Sekulic et al., 2013; Speirs et al., 2016; Stewart et al., 2014).

While some single beam timing lights have built-in software to prevent false triggers from occurring, such as the SPARQ XLR8 timing system (SPARQ Products, Oconomowoc, WI, USA) used by Carlson et al. (2019), other studies using single beam timing lights did not utilise this technology (Bishop et al., 2017; Eriksson et al., 2015; Gillen et al., 2018; Sekulic et al., 2013; Speirs et al., 2016; Stewart et al., 2014). Therefore, while both single and dual beam timing lights can be used reliably, there is no clear conclusion as to which type of system is more consistent with regards to pro-agility shuttle performance.

Some scientists have arbitrarily chosen an analytical goal of the CV being 10% or below and ICC greater than 0.70 for measures to have acceptable reliability (Atkinson & Nevill, 1998). In terms of this review all studies measuring reliability reported acceptable levels of reliability for the pro-agility shuttle., However, more variability was observed in novice athletes and general athlete populations, compared to elite and sub-elite American football (Table 4).

The results show the pro-agility shuttle is used in practice and research across a number of sports (Eriksson et al., 2015; Halil et al., 2013; Kemal et al., 2013; Lockie et al., 2012; McKay et al., 2020; Sekulic et al., 2013; Stewart et al., 2014; Yuasa et al., 2018). American football comprised nearly 40% of all reviewed studies and 95% of all subjects. This could be due to the fact that most American football testing batteries include the pro-agility shuttle, and test performance has implications for NFL draft status (Corey & Randall, 2020; Leutzinger et al., 2018; McGee & Burkett, 2003; McKay et al., 2020; Nuzzo, 2015). However, since other sports, such as soccer, cricket, and tennis include many changes of direction (Bishop et al., 2017; Bloomfield, Polman, & O'Donoghue, 2007; Leone, Comtois, Tremblay, & Leger, 2006; Lockie, Callaghan, et al., 2013), the utility of the pro-agility shuttle could benefit sports which require multiple high degree directional changes.

From the review, it is clear that skill level plays an important factor in pro-agility shuttle performance (see Figure 4B). As would be expected, elite athletes have been found to complete the pro-agility shuttle faster than sub-elite and novice athletes, across all sports, excluding lacrosse (Table 2). Elite athletes are likely faster as a result of more developed neuromuscular systems, enabling greater force capacity to perform more complex movement skills with high synergistic muscle activation and high rates of force development (Cormie et al., 2011; Duchateau & Baudry, 2010). Interestingly, findings from the similar spread in performance, indicate that sub-elite and novice athletes are characterised by similar athletic capabilities when it comes to 180^{o} COD performance (Kavaliauskas et al., 2017). It is important to note however, the variation in number of studies found for the data presented in each sport, in terms of skill level and player positions. For example, lacrosse performance data gathered was mostly in sub-elite athletes (Greene et al., 2019; Hoffman et al., 2009; Sell et al., 2018; Vescovi et al., 2007), with elite athlete performance being reported in a single study (Vescovi &

McGuigan, 2008). Therefore, we recommend caution to be taken when interpreting values representative of single studies or skill levels.

The type of sport athletes participate in also appears to influence pro-agility shuttle performance. This is because each sport has specific requirements for performance. American football athletes had the fastest pro-agility shuttle time in comparison to any other sports reported in this review. These faster performance times may be due to the historic use of the pro-agility shuttle in the NFL combine to identify specific components of athletic fitness (Corey & Randall, 2020; LaPlaca & McCullick, 2020; McGee & Burkett, 2003). American football athletes perform better than other sports because it either might represent sport specific movement patters for this sport, or because these athletes spend more time practicing this movement. For example, because match performance may be more reliant on short accelerative and decelerative ability in American football athletes, sprints are shorter than that performed by rugby athletes (Brechue et al., 2010; Deutsch, Maw, Jenkins, & Reaburn, 1998; Docherty, Wenger, & Neary, 1988).

Additionally, applied practitioners need to select and administer performance assessments appropriately based on the context of the sport and physiological capabilities to be measured (McGuigan, Cormack, & Gill, 2013). It would be thought that the pro-agility shuttle's current diagnostic capabilities are inefficient and limit the applicability of this test across a variety of sports, due to requiring large horizontal forces for multiple fast lateral movement over a small distance over ground (LaPlaca & McCullick, 2020; Nimphius, 2014; Nimphius et al., 2018). However, research has reported use of the pro-agility shuttle in novice youth swimmers to assess athlete ability to efficiently apply vertical and horizontal forces to initiate movement, and change direction relating to start and quick turn performance (Halil et al., 2013; Kemal et al., 2013; Kilani, Al-Tuieb, & Kilani, 2013). Therefore, maximising ground reaction force and minimising ground reaction time should be a focus of programming for strength and conditioning coaches who are looking to develop athlete COD capabilities (Bishop et al., 2013).

It is also of great importance for applied practitioners and coaches to understand the differences in performance values between the playing position of their athletes, and why these differences exist. Robbins (2011) substantiated this posit by concluding that athletic capabilities are partially moderated by playing position. The normative results of this review also indicate that mean performance times for each player position differ for American football, lacrosse, rugby, and soccer (Table 5).

A recent study by LaPlaca and McCullick (2020), found the pro-agility shuttle to be correlated to player performance. They concluded certain performance test results are significant for different player positions in American football. The study reported the pro-agility shuttle was correlated with better grades for offense. In offensive positions, pro-agility shuttle performance for players in the fullback position showed a correlation to the ability to avoid more tackles (*r* = -0.753). However, pro-agility shuttle performance had small correlation to number of games played in centre and quarterback positions (*r* = -0.29, -0.34, respectively). This smaller correlation may be explained, for example, by being in the middle of the offensive line creating the nonessential need for centres to perform 180° degree CODs, due to the amount of support which can be offered by nearby teammates (LaPlaca & McCullick, 2020). In defensive positions, they reported small correlations to pro-agility shuttle performance in defensive tackle position with more pressure, hits, and sacks per pass rush snap count (*r* = -0.22, -0.23, -0.25, respectively). Faster pro-agility shuttle performance was correlated, although small, with more interceptions per pass coverage snap count (*r* = -0.29). Additionally, in the strong safety position slower pro-agility shuttle performance was correlated with tackling performance (*r* = 0.37). However, these findings are unsurprising, due to the performance demands of playing in defensive positions does not inherently require high 180° COD ability (i.e. ability to decelerate and change direction suddenly) (LaPlaca & McCullick, 2020; Nuzzo, 2015; Robbins, 2011).

Pro-agility shuttle times for rugby players (novice backs and forwards) has been reported in one study only (La Monica et al., 2016). There was no observable difference in pro-agility times between the two positional groups (5.14 ± 0.3 and 5.16 ± 0.3 s (respectively)). In the case for lacrosse athletes, where minimal differences were observed between attack, midfield, and defender positions, with goal keepers reported to be the slowest of the sub-elite athletes. While attackers, midfielders, and defence players cover the field, the goal keepers cover the goal, thereby moving the least of all players. Goals in lacrosse are smaller than those used in hockey. Therefore, first step quickness may be more influential than 180° COD (i.e. they can stay in the frontal plane more instead of transitioning between sprinting, decelerating, and turning). This would be the opposite for soccer athletes; individual position times for goal keep (4.94 ± 0.00 s), defenders (5.14 ± 0.29 s), midfielders (5.1 ± 0.08 s), and attackers (4.88 ± 0.00 s) were reported in elite athletes (Lockie et al., 2018). Interestingly, faster pro-agility shuttle times were reported in goal keep and attacker positions. The physical and technical constraints imposed upon goal keepers may explain this, as they are required to perform high-intensity lateral movements and sprints over 5m with a high rate of force development and application, while being co-ordinated (Di Salvo, Benito, Calderon, Di Salvo, & Pigozzi, 2008; Spratford, Mellifont, & Burkett, 2009). As for swimming athletes, they presented the slowest times (6.05 ± 0.12 s). It would be expected for swimmers to present the slowest times over all sports, as assessments should reflect the demands of the sport, and swimmers may have the slowest times because of the limited applicability of over ground assessment to water sports. Nonetheless, further research needs to be conducted into positional differences in other sporting codes at the different skill levels before a comprehensive analysis of positional differences can be determined.

This review was the first to establish normative performance values for the pro-agility shuttle, across different sporting codes. While being the catalyst, this also presented itself as a limitation for this review. Given the limited data presented in literature, comprehensive identification of normative pro-agility shuttle times could not be established, except for American football, throughout the range of sports and their respective skill levels. Therefore, an overview of pro-agility shuttle performance was identified, with normative values for each skill level and player position being reported where appropriate. Additionally, values represented by few or single studies should be interpreted with caution. It should also be noted that athletes from different genders, specific training methods, and training ages were not characterised in this review. Future research should explore the inclusion of other technologies, such as additional timing lights, smartphone camera, inertial sensor or radar technology to provide advancement to the diagnostic protocol of the pro-agility shuttle test. Nonetheless, future analysis of pro-agility shuttle performance and diagnostic protocol advancement presents itself to be necessary in order to establish comprehensive normative data within a wide range of sports and provide insightful value to applied practitioners.

The results of this review demonstrate the utility of the pro-agility shuttle, concluding the test to be reliable when using stopwatch and timing light measurement technology. It would seem from the data reviewed that a comprehensive understanding of the reliability of the pro-agility shuttle is yet to be established. Test-retest methodologies that use a comprehensive suite of reliability statistics are essential to fully understand the reliability of the pro-agility shuttle test. Furthermore, establishing variability between single and dual beam timing lights, and the reliability associated with other technologies such as smartphone camera, radar, contact mat, etc. is needed. This review provided normative values that practitioners can use to understand performance in sport, skill level, and player positions. It was also the first to collectively provide normative pro-agility shuttle performance data across a range of sports and present areas requiring investigation. It was apparent the sporting context influenced pro-agility shuttle performance. However, whether the movement patterns associated with these sports is assessed specifically within the pro-agility shuttle is unclear i.e. the ecological validity of the pro-agility across these sports for quantifying COD capability. Additionally, the current diagnostic value of the pro-agility shuttle is limited as it provides practitioners with a total-time. Higher level diagnostics could be achieved by breaking the test into sub-components; however, the reliability, validity, and utility of these sub-component performance measures would need to be established. Additionally, whether other technologies such as inertial sensors, smartphone videography, and radar can add value to the diagnostics needs to be explored.

2.5 Practical Applications

Practitioners wishing to understand their athletes' 180° COD ability should look to use the pro-agility shuttle. The pro-agility shuttle can help provide insight into acceleration, deceleration, and 180° COD capabilities. As such, practitioners should look to use normative values as guidelines to compare relative performance to gauge and monitor athlete performance. In addition, the normative values established, across the various sports examined, may be used to set attainable goals appropriate to the sport, position, and skill level in context. While stopwatch timing was found to be a more reliable measure than timing light technologies for the pro-agility shuttle, caution should be taken when interpreting these results, and best practice guidelines should be followed. Ensuring that standardised procedures are used will help improve the reliability of assessment. For example, some single beam timing lights may have different software to prevent false triggers from occurring. Therefore, practitioners should utilise the same timing technology to allow for consistency of measurement.

Chapter Three: Training to Improve Pro-agility Shuttle Performance: A Systematic Review.

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3.0 Preface

Though various specific and non-specific training methods have been employed to target the enhancement of COD ability in the pro-agility shuttle, it has been determined that at this point in time, no synthesis and critique of the literature had been conducted. Specific training methods may be more effective than non-specific methods for improving pro-agility performance and form the basis of this thesis, however, research on the topic lacks was lacking. Understanding the effectiveness of specific and non-specific training on pro-agility shuttle performance enabled the identification of gaps in research and the formation of important questions to be addressed in subsequent chapters.

Chapter Three: Training to Improve Pro-agility Shuttle Performance: A Systematic Review.

3.1 Introduction

The ability to change direction is critical for field and court sport athletes, as an improved capacity for this athletic task may provide a means to either evade an opponent or navigate a tactical scenario with greater efficiency (Baker & Newton, 2008; Spiteri et al., 2013). Consequently, there is an ever-growing body of research detailing the effectiveness of training methods for developing COD performance. Given this importance, the ability to assess and monitor this athletic quality would seem critical to develop an individual's sporting performance.

The measurement of COD performance provides indication of an athletes' ability to utilise reactive strength and anaerobic power in a multi-directional fashion (Reilly et al., 2000; Young et al., 2002). This is important as the capacity of athletic qualities involved with COD performance attribute to the success of a COD manoeuvre, which can be integral during key situations during a game (Chaouachi et al., 2012; Sheppard & Young, 2006). One test that is used to measure COD performance is the pro-agility shuttle; which is comprised of two 180° CODs over a total of 18.28 m and used in sports such as rugby (Speirs et al., 2016), American football (Leutzinger et al., 2018), and soccer (Kavaliauskas et al., 2017). The pro-agility shuttle contains high force-orientated CODs (180°), thereby, requiring athletes to accelerate, decelerate and arrest the body's momentum, come to a complete stop, change direction, and reaccelerate in the opposite direction. Therefore, to perform a successful COD in the pro-agility shuttle, it is imperative that athletes possess sufficient maximum, dynamic, and reactive strength which is contraction dependant (Spiteri, Newton, Binetti, et al., 2015).

A clear link has been identified between the implementation of specific and non-specific training methods for COD ability (Falch et al., 2019). Specificity of training is a fundamental principle in optimising transference of training to physiological performance (Campos-Vazquez et al., 2015; Reilly, Morris, & Whyte, 2009). Non-specific training methods tend to be gym-based, uniplanar (typically vertical), using high-loads and low-velocities. These high-force and low-velocity movements, whether implemented unilaterally or bilaterally, relate to the force-orientated nature of 180° performance (Bourgeois et al., 2017; Speirs et al., 2016). These types of movements and training methods do not resemble the biomechanics of movements performed during specific sporting tasks, thus the label non-specific. While non-specific training may allow for the development of physiological qualities relating to pro-agility COD performance, it is speculated that specific COD training may provide better improvements in performance due to enhancements in technical and contraction-dependent capabilities relating to the actual task being performed (DeWeese & Nimphius, 2018).

Whether specific training methods are better for improving COD performance provides the focus of this review. The findings of the review will provide practitioners important insight into exercise and training method selection for the development of pro-agility performance. Given the preceding information, the aim is to: 1) examine the training effects different non-specific and specific training methods have on pro-agility performance; and, 2) detail the limitations and future research directions in this content area.

3.2 Methods

3.2.1 Study Design

A systematic search of four electronic data bases (SPORTDiscus, PubMed, ScienceDirect, and OVID journals) was undertaken to identify original research articles published from the earliest available records up to November 2021. Keywords ‘pro-agility’, OR ‘20-yard shuttle’, OR ‘5-10-5 shuttle’ were used in conjunction with “training” OR “chronic” OR “longitudinal” using Boolean logic for query.

3.2.2 Screening Strategy and Study Inclusion

The articles needed to contain the following three criteria to be included in the review: 1) measurement of pro-agility shuttle performance before and after a training intervention; 2) a description of a training intervention, detailing the type of training, length of the intervention (minimum training length of four weeks), workload (volume per training session), and frequency of sessions per week; and, 3) the study needed to state the number of subjects and descriptive statistics pertaining to their characteristics. This literature search was not limited by sex or age and had no restrictions regarding subject performance level or training status. Additionally, studies must have been written in English, otherwise they were excluded.

3.2.3 Data Extraction

Data was extracted by one author (JF) using a custom designed standardised excel database (version 16.0, Microsoft, Redmond, WA, USA). A secondary author (AU) ratified a cross-section of these ratings for quality control. Quality score cross-ratings were unanimously agreed on between authors (JF, AU) for each article. General study data (i.e., author, year), subject characteristics (i.e., number of subjects, age, body mass, height, sport, performance level), training intervention classification (e.g., resistance training, plyometric training, etc.), primary outcome measures (i.e., pre-test and post-test mean and standard deviation, percent change, statistical significance, and ES) were extracted. Descriptive information relating to training intervention classification information was used to categorise the data extracted from each of the studies. Where more than one intervention type was presented in an article, performance data and intervention effects were categorised in the appropriate intervention type for analysis.

3.2.4 Methodological Quality and Risk of Bias Assessment

To evaluate the methodological quality of the studies, a quality scale designed to evaluate research conducted in athletic-based environments was utilised (McMaster et al., 2013). This scale was modified using a combination of items from the Cochrane, Delphi, and PEDRO, as created by Brughelli et al. (2008) (Table 6). Each study's quality was independently rated against each of the 10 criteria on the list by two authors (JF, AU). The included items for quality scoring are detailed in Table 10. The quality of each study could range between 0 to 20, each criterion score as 0 = clearly no; 1 = yes, not detailed; and 2 = yes, clearly detailed (see Table 6). Scoring was assigned depending on how well each criterion was met, assuming a maximum possible score of 20 (high quality, low risk of bias).

Table 6: Study quality score

Number	Item	Score
1	Inclusion criteria stated	0-2
2	Subjects assigned appropriately	0-2
3	Intervention described	0-2
4	Control group	0-2
5	Dependant variable defined	0-2
6	Assessments practical	0-2
7	Duration	0-2
8	Statistics appropriate	0-2
9	Results detailed	0-2
10	Conclusions insightful	0-2

Note: From Brughelli et al. (2008).

3.2.5 Statistical Analysis

Summary statistics were used to represent the percent change (%) and ES of each study. After rating the quality of the articles, training programmes, un-equal workload, and differences relating to performance or sex were categorised, to quantify the subjects training improvement based on differences in workload and physical background. Percent difference and ES were calculated to compare the effects of different training interventions on pro-agility performance. ES were quantified according to Cohen's d ($\frac{M2-M1}{S}$) (M2 = post-test mean, M1 = pre-test mean, *S* = pooled standard deviation). ES values of <0.2 were considered as "trivial", 0.2–0.5 "small", 0.5–0.8, "medium", and values of > 0.8 were considered as "large" ES., 1.2–2.0 as "very large", and values exceeding 2.0 "huge" (Cohen, 1988; Sawilowsky, 2009). Percent change and effect values were then normalised by dividing pre-post change (%) or ES by the total number of sessions (length in weeks*frequency of sessions) completed, to normalise the adaptations per training dose for pro-agility performance. Decrease in pro-agility time was quantified as a positive percent change and ES, representing improved pro-agility performance.

3.3 Results and Discussion

3.3.1 Literature Search Results

Studies that included the pro-agility assessment were initially included in the first screening phase (*n* = 156). An additional five eligible articles were included after reference checks (*n* = 161). To determine the number of eligible studies a three-stage screening process was implemented; 1) removal of duplicate studies (*n* = 47); 2) screening of article title and abstract - studies that were deemed to be 'out of scope' (did not contain pro-agility data) were excluded (*n* = 26); and, 3) exclusion of studies that did not meet the inclusion criteria after screening the full text (*n* = 68). A total of 20 studies were included for analysis in this review (see Figure 6).

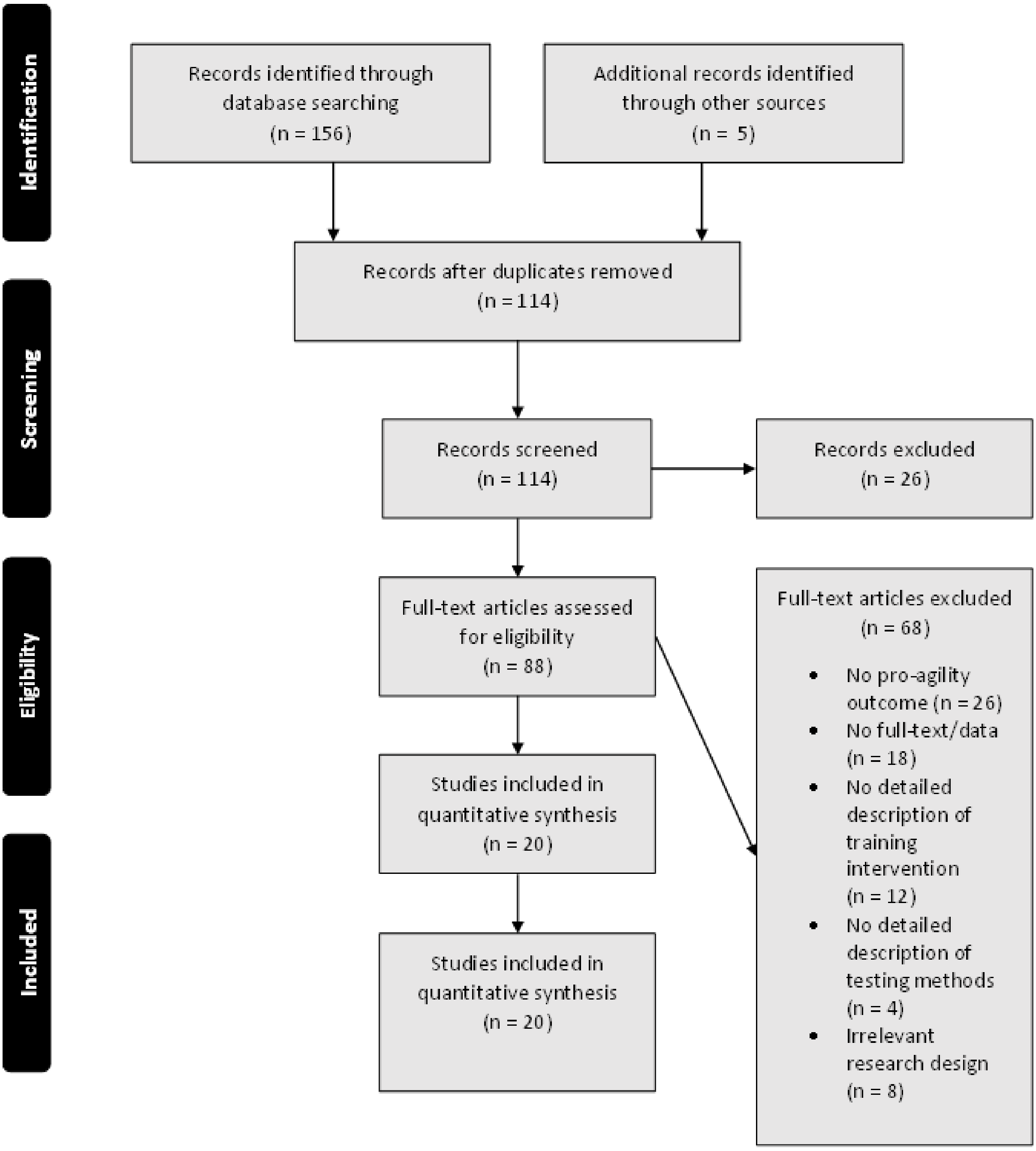

Figure 6: Search strategy

3.3.2 Overview

There were 29 intervention groups, comprised of 638 subjects within the 20 studies. The length of interventions ranged from 4 to 18 weeks with 1 to 4 training sessions per week. Regarding sporting season, two interventions were conducted pre-season, five in-season, two post-season, and 11 authors did not state the time of season. Overall percent improvement in COD performance for all studies ranged from 0.19% (Chan et al., 2018) to 12.41% (Schwarz et al., 2019), while a decrease in performance was observed in three studies, ranging from -0.86% to -2.71% (Johnson, Burns, & Azevedo, 2012; Schilling, Murphy, Bonney, & Thich, 2013; Vescovi & VanHeest, 2010). Intervention ES ranged from trivial (ES = 0.00) (Faigenbaum et al., 2007) to very large (ES = 1.3) (Kavaliauskas et al., 2017). The reader needs to be cognisant that the number of studies and sample sizes that comprise this review are relatively small, and any interpretation of the reader should be made with this limitation in mind.

3.3.3 Quality Score

Included studies averaged a score of 17.73 (± 1.55) out of a maximum of 20. Some studies did not state inclusion criteria (n = 5) or did not include use of a control group (n = 7). While some studies ‘maybe’ (i.e., lacked detail or were not presented clearly) stated inclusion criteria (n = 9), assigned subjects appropriately (n = 4), defined dependant variables (n = 1), had adequate duration (n = 1), detailed appropriate statistics (n = 4), presented detailed results (n = 6), and insightful conclusions (n = 1). No researchers reported conflicts of interest and/or funding sources or were withdrawn due to quality which may have impacted the information included in the review. An overview of the quality scores associated with each reviewed study can be found in Table 7.

Table 7: Quality score of included studies

Reference	Quality Score
Abt et al. (2016)	19
Bishop et al. (2017)	17
(Chan et al., 2018)	19
Faigenbaum et al. (2007)	16
Ferley, Scholten, and Vukovich (2020b)	17
Johnson et al. (2012)	17
Jones et al. (2010)	15
Kavaliauskas et al. (2017)	19
Markovic et al. (2007)	19
Millar et al. (2020)	16
Moran et al. (2018)	19
Schilling et al. (2013)	16
Schwarz et al. (2019)	19
Šišková, Kaplánová, Longová, Kohút, and Vanderka (2021)	17
Speirs et al. (2016)	20
Thompson et al. (2017)	19
Toyomura et al. (2018)	17
Vescovi and VanHeest (2010)	20
Wagner et al. (2014)	15
Weiss et al. (2010)	18

3.3.4 Resistance Training

Eleven resistance training interventions from six different studies were analysed (see Table 8 and 9), of which four interventions were found to produce statistically significant ($p < 0.05$) changes in pro-agility performance (Abt et al., 2016; Speirs et al., 2016). Resistance training intervention length ranged from 5 to 7 weeks (Abt et al., 2016; Speirs et al., 2016), an average change of 0.027% to 0.173%, and 0.008 to 0.087 ES per session (Millar et al., 2020; Speirs et al., 2016), was observed across the studies. As can be seen from the results, most of the interventions resulted in 0.02 to -0.11% and 0.008 to 0.017 ES, per session changes in COD performance. The greatest per session improvements (i.e., decreased pro-agility time), however, were noted in the study of Speirs et al (15) where unilateral (0.173% and 0.087 ES) and bilateral (0.15% and 0.048 ES) strength (squat) training interventions over 10 sessions with sub-elite rugby athletes were completed.

Interestingly, the largest per session training effects (Speirs et al., 2016) were noted in the study involving unilateral squat training (Speirs et al., 2016), whereas bilateral exercises were performed in all other resistance training interventions (Abt et al., 2016; Johnson et al., 2012; Millar et al., 2020; Schilling et al., 2013; Weiss et al., 2010). The reasons for the larger effects could be attributed to: 1) the unilateral training emphasis and therefore greater specificity to COD performance; 2) the training history of the cohort, those who underwent unilateral squat training were sub-elite athletes, while most other subjects in other studies were novice athletes; 3) a shorter more intense training mesocycle (5 weeks), therefore less likelihood of training monotony and plateaus in adaptation; and, 4) related to the previous points is that the single and bilateral squat training utilised by Speirs et al. implemented high intensity loading schemes (4 sets x 3–6 reps, 75–92% 1RM), which was very different to the loading used with the novice athletes (2-3 sets x 10 reps, 50-70% 1RM) (Millar et al., 2020; Weiss et al., 2010).

It needs to be noted that the second largest training effect was found in the Speirs study also, the bilateral squat intervention changes, whilst not practically (% change and ES) the same, were found to be statistically similar to the unilateral intervention. Whether unilateral or bilateral training is implemented, may be less important than the magnitude or intensity of the loading the subjects are exposed to. Nonetheless, intuitively it seems to make sense to train unilaterally given the nature of the pro-agility test.

Table 8: Overview of resistance training interventions

Reference	Number (*n*) of subjects and mean age	Sport training status	Control group	Experimental group	Improvement [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details Week/Sessions (total number of sessions) Loading parameters
Abt et al. (2016)	EG, *n* = 46 Age = 29.4 ± 5.5 CG, *n* = 39 Age = 29.0 ± 6.0	Tactical Professional	Pre: R, 5.02 ± 0.26 L, 5.02 ± 0.27 Post: R, 5.00 ± 0.33 L, 4.98 ± 0.31	Pre: R, 5.10 ± 0.38 L, 5.09 ± 0.4 Post: R, 4.95 ± 0.34 L, 4.93 ± 0.32	R: 2.94% [0.06%] ES: 0.41 [0.009], *p* <0.001 L: 3.14% [0.07], ES: 0.44 [0.009], *p* <0.001	12/4 (48) Week 1–4: Upper and lower resistance training, 8–12 1RM. Week 5–8: Olympic lifts, 4–6 1RM. Week 9–12: High intensity strength and power training, 3–5 1RM.
Johnson et al. (2012)	*N* = 39 TRAD = 16 CIRC = 23 Age = TRAD, 16 ± 2; CIRC, 16 ± 1	American football Novice	Pre: Post:	Pre: CIRC, 4.61 ± 0.23 TRAD, 4.92 ± 0.45 Post: CIRC, 4.65 TRAD, 4.99	CIRC: -0.86% [-0.04%], ES -0.25 [-0.014], *p* >0.05 TRAD: -1.42% [-0.08%], ES: -0.22 [-0.012], *p* >0.05	6/3 (18) Day 1: hang clean, power jerk, bench press, dumbbell split squat, inverted rows. Day 2: dumbbell snatch, upright row, front squat, military press, lunges, pullups. Day 3: Hang clean, push press, back squat, incline bench, weighted step-ups.
Schilling et al. (2013)	STG: *N* = 5, Age = 20.0 ± 0.71; ETG: *N* = 5, Age = 22.0 ± 3.54	College students Novice	Pre: Post:	Pre: STG, 5.49 ± 0.34; ETG, 5.43 ± 0.34 Post: STG, 5.55 ± 0.33; ETG, 5.36 ± 0.33	STG: -1.09% [-0.091%], ES: -0.18 [-0.015], *p* >0.05 ETG: 1.29% [0.107%], ES: 0.21 [0.017], *p* >0.05	6/2 (12) STG: sit up, curl up, and trunk extension. 2–3 sets x10–15 reps ETG: curl up, side plank, and bird dog 3 sets x3-9 reps, 8–10s hold

Key: EG: experimental group; CG: control group; R: right side; L: left side; TRAD: traditional training; CIRC: circuit training; STG: strength training group; ETG: endurance training group; UNI: unilateral group; BI: bilateral group; 1RM: 1 repetition maximum; HT: hip thrust group; SG: squat group.

Table 9: Overview of resistance training interventions (continued)

Reference	**Number (*n*) of subjects and mean age**	**Sport training status**	**Control group**	**Experimental group**	**Improvement [normalised % change] Effect Size (ES) [normalised ES] Pvalue (*p*)**	**Training intervention details Week/Sessions (total number of sessions) Loading parameters**
Speirs et al. (2016)	*N* = 18 Age = 18.1 ± 0.5	Rugby Sub-elite		Pre: UNI, 4.61 ± 0.11; BI, 4.71 ± 0.15 Post: UNI, 4.53 ± 0.07; BI, 4.64 ± 0.14	UNI: 1.74% [0.173%], ES: 0.87 [0.87], *p* <0.05 BL: 1.49% [0.15%], ES: 0.48 [0.048], *p* <0.05	5/2 (10) Bilateral or unilateral squat, 4 sets x3–6 reps, 75–92% 1RM Tempo 2-0-1 (concentric-eccentric) Rest 3 min between sets
Weiss et al. (2010)	*N* = 38 Age = 18-32	Recreational athletes Novice	Pre: 5.49 ± 0.39 Post: 5.42 ± 0.29	Pre: 5.73 ± 0.33 Post: 5.65 ± 0.31	EG: 1.40% [0.066%], ES: 0.34 [0.016], *p* >0.05 CG: 1.28%, ES: 0.20, *p* >0.05	7/3 (21) CG: single and multi-joint machine and free-weight modalities EG: Multi-joint, multi-planar free weight and machine modalities
Millar et al. (2020)	*N* = 14 HT = 6, SG = 8 Age = HT, 15.7 ± 0.8; SG, 15.3 ± 0.7	Soccer Novice	Pre: Post:	Pre: HT, 5.267; SG, 5.285 Post: HT, 5.25 ± 0.19; SG, 5.27 ± 0.20	HT: 0.32% [0.027%], ES: 0.13 [0.011] SG: 0.28% [0.237%], ES: 0.09 [0.008]	6/2 (12) Day 1: hip thrust or squat, bench press, unilateral row, 30s plank hold 2–6 sets x 3–8 reps Day 2: hip thrust or squat, overhead press, lat pulldown, 30s plank hold 2–6 sets x 3–8 reps

Key: EG: experimental group; CG: control group; R: right side; L: left side; TRAD: traditional training; CIRC: circuit training; STG: strength training group; ETG: endurance training group; UNI: unilateral group; BI: bilateral group; 1RM: 1 repetition maximum; HT: hip thrust group; SG: squat group.

3.3.5 Plyometric Training

Two plyometric training interventions from two studies were analysed (see Table 10), of which both interventions reported statistically significant ($p < 0.05$) changes in pro-agility performance (Faigenbaum et al., 2007; Markovic et al., 2007). Plyometric training intervention length ranged from 6 to 10 weeks with 2–3 training sessions per week, an average change of 0.046% to 0.297%, and 0.01 to 0.092 ES per session changes in COD performance were observed across the interventions (Faigenbaum et al., 2007; Markovic et al., 2007). The greatest improvements per session (0.297% and 0.092 ES) were noted in the study of Faigenbaum et al. (2007) where a plyometric training intervention over 12 sessions with novice American football and baseball athletes was completed.

The largest per session training effects (Faigenbaum et al., 2007) utilised a combination of bilateral and unilateral exercises in the horizontal, vertical, and lateral directions. Conversely, Markovic et al. (2007) performed only bilateral hurdle jumps in the horizontal direction and drop jumps in the vertical direction. It should be noted that both plyometric training interventions involved the use of fast stretch-shorten cycle (SSC) exercises, however, greater volume (72–120 vs 50–100 repetitions) and number of exercises (12 vs 1), and in turn foot contacts, were performed in Faigenbaum et al. (2007), compared to those implemented by Markovic et al. (2007). Therefore, the discrepancies in intervention ES per session may be attributed to the relevancy and progression of exercises and number of foot contacts performed. This highlights the importance of specificity and movement variability in exercise selection, and total workload per session in affecting the performance outcome (Reilly et al., 2009). These finding are comparable to Brughelli et al. (2008), who concluded that both unilateral and bilateral plyometric training should be performed and force application exerted in the horizontal, vertical, and lateral directions when aiming to develop COD ability.

Table 10: Overview of plyometric training interventions

Reference	**Number (*n*) of subjects and mean age**	**Sport Training status**	**Control group**	**Experimental group**	**Improvement [normalised % change] Effect Size (ES) [normalised ES] Pvalue (*p*)**	**Training intervention details Week/Sessions (total number of sessions) Loading Parameters**
Faigenbaum et al. (2007)	*N* = 13 Age = 13.4 ± 0.90	Baseball and American football Novice	Pre: Post:	Pre: 5.60 ± 0.18 Post: 5.40 ± 0.18	3.57% [0.29%], ES: 1.11 [0.093}, *p* <0.05	6/2 (12) Forward jump, backward jump, hurdle hops, lateral hops, 90° jump turn, unilateral hops, 180° jump turn, tuck jumps. 2 sets x6–10 reps
Markovic et al. (2007)	*N* = 93 Age = 20.1 ± 1.1	Highschool students Novice	Pre: 5.02 ± 0.20 Post: 5.04 ± 0.18	Pre: PG, 5.05 ± 0.24 Post: PG, 4.98 ± 0.20	PG: 1.39% [0.046%], ES: 0.32 [0.011], *p* <0.001	10/3 (30) PG: hurdle and drop jumps

Key: PG: Plyometric Group

3.3.6 Sprint Training

Seven sprint training intervention effects from five different studies were analysed (see Table 11 and 12), of which three interventions were found to have statistically significant ($p < 0.05$) changes in pro-agility performance (Kavaliauskas et al., 2017; Markovic et al., 2007; Toyomura et al., 2018). Sprint training intervention length ranged from 4 to 8 weeks (Chan et al., 2018; Ferley et al., 2020b; Moran et al., 2018). An average change of 0.016% (Chan et al., 2018) to 0.476% (Moran et al., 2018) and 0.00 to 0.108 ES per session in COD performance was observed across these studies. The greatest per session improvements, in percentage, were noted in the study of Moran et al. (2018), where short repetitive sprint training (16 sets of 20 metre sprints) in pre-PHV (0.476% and 0.086 ES) novice soccer athletes over 8 sessions was completed. However, the greatest per session effects were found to be in the study by Kavaliauskas et al. (2017), where training involved incline sprint training (10 sets of 10 second sprints at a 7% gradient) (0.265% and 0.108 ES) over 12 sessions in novice soccer athletes.

Interestingly, the largest per session training effects were noted in studies that included incline sprinting (Ferley et al., 2020b; Kavaliauskas et al., 2017), while level ground sprints were completed in all other sprint training interventions (Chan et al., 2018; Ferley et al., 2020b; Markovic et al., 2007; Moran et al., 2018; Toyomura et al., 2018). The reason for the larger effects may be attributed to: 1) the effect of greater hip flexion involved with incline sprinting, as well as a greater force demands, similar to that of resisted sprinting (Okudaira et al., 2021); 2) the younger age of the athletes, where sprint training may be more effective in those pre-PHV (Bourgeois et al., 2017); and, 3) the sprint duration (i.e. 6–10 seconds) and/or distance (i.e. 20 metres), may allow for higher intensity performance and greater relevance to that performed in the pro-agility.

Overall, the improvements were significant when performing incline sprinting at a 5%-30% gradients with a 6–30 second duration (Ferley et al., 2020b; Kavaliauskas et al., 2017). Although, in regards to sprinting over flat ground the majority of researchers reported small to medium significant and non-significant effects on pro-agility performance, except for one study where a significant effect (0.144% and 0.036 ES, $p < 0.001$) was observed when performing 3–4, 10-50 m sprints, 3 times per week for 10 weeks (Markovic et al., 2007). These findings indicate that accelerated sprinting on an incline provides adaptations which transfer the most to pro-agility performance. This makes sense intuitively, considering that incline sprinting has biomechanical similarities with accelerating into and out of the COD in the pro-agility shuttle.

Table 11: Overview of sprint training interventions

Reference	Number (*n*) of subjects and mean age	Sport training Status	Control group	Experimental group	Improvement [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
(Chan et al., 2018)	*N* = 16 Age = 29.8 ± 9.9 CG: *n* = 8 Age = 35.1 ± 11.5 EG: *n* = 8 Age = 23.7 ± 4.3	Soccer, basketball, and badminton Novice	Pre: 5.27 ± 0.17 Post: 5.29 ± 0.19	Pre: 5.22 ± 0.23 Post: 5.21 ± 0.11	CG: -0.3% [-0.025%], ES: -0.11 [-0.009], *p* >0.05 EG: 0.19% [0.016%], ES: 0.006 [0.0005], *p* >0.05	4/3 (12) 4 sets x30 second sprints. Number of sprints increased by 1 per week.
Ferley et al. (2020b)	INC: *N* = 17; male = 8; female = 9 Age = male, 16.4 ± 1.1; female, 15.1 ± 1.1 LEV: *n* = 14; male = 8; female = 6 Age = male, 15.4 ± 0.9; female, 14.8 ± 1.1 CG: *n* = 15; male = 8; female = 7 Age = male, 16.4 ± 1.5; female, 15.6 ± 0.5	Basketball, softball, baseball, and track Novice	Pre: 5.10 ± 0.40 Post: 5.09 ± 0.40	Pre: INC, 5.24 ± 0.30 LEV, 5.27 ± 0.30 Post: INC, 5.08 ± 0.30 LEV, 5.19 ± 0.30	INC: 3.05% [0.127%], ES: 0.53 [0.022], *p* = 0.53 LEV: 1.52% [0.063%], ES: 0.267 [0.011], *p* = 0.267 CG: 0.63% [0.026%], ES:0.025 [0.001], *p* >0.05	8/2–3 (16–24) INC: 15–26 sets x6-30 second sprints, 5–30% gradient. LEV: 10–14 sets x4–30 second sprints, 1.5% gradient.
Kavaliauskas et al. (2017)	*N* = 14 Age = 22 ± 8	Soccer Novice	Pre: 6.012 ± 0.14 Post: 6.03 ± 0.14	Pre:5.96 ± 0.16 Post: 5.77 ± 0.23	CG: -0.1% [-0.008%], ES: -0.12 [-0.01], *p* >0.05 EG: 3.19% [0.265%], ES: 1.3 [0.108], *p* <0.05	6/2 (12) Up hill sprint training. 10 sets x10 second sprints, 7% gradient.

Key: EG: Experimental group; CG: Control group; INC: Incline sprint group; LEV: Level ground sprint group; Pre-PHV: Pre-peak height velocity; Post-PHV: Post-peak height velocity; SG: Sprint group.

Table 12: Overview of sprint training interventions (continued)

Reference	Number (*n*) of subjects and mean age	Sport training status	Control group	Experimental group	Improvement [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
Moran et al. (2018)	Pre-PHV - EG: *N* = 12, Age = 10.4 ± 0.8, CG: *N* = 13, Age = 10.0 ± 1.0; Post-PHV - EG: *N* = 7, Age = 13.6 ± 0.7, CG: *N* = 10, Age = 14.5 ± 1.0	Soccer Novice	Pre: Pre-PHV, 5.93 ± 0.22; Post-PHV, 5.29 ± 0.25 Post: Pre-PHV, 5.85 ± 0.34; Post-PHV, 5.04 ± 0.24	Pre: Pre-PHV, 5.77 ± 0.30; Post-PHV, 5.26 ± 0.31 Post: Pre-PHV, 5.55 ± 0.32; Post-PHV, 5.14 ± 0.26	Pre-PHV: 3.81% [0.476%], ES:0.69 [0.086] Post-PHV: 2.28% [0.285%], ES:0.43 [0.005]	8/1 (8) 16 sets x20 metre sprints, 90s rest between
Toyomura et al. (2018)	*N* = 18 Age = 22.8 ± 2.2	Recreational athletes Novice	Pre: Post:	Pre: Post: 10.97 ± 0.01	3.00% [0.2%], ES:0.67 [0.044], *p* = 0.007	5/3 (15) 20 minute treadmill run, -10% gradient, 14.9 ± 0.6 km.h^{-1}
Markovic et al. (2007)	*N* = 93 Age = 20.1 ± 1.1	Highschool students Novice	Pre: 5.02 ± 0.20 Post: 5.04 ± 0.18	Pre: SG, 5.10 ± 0.21 Post: SG, 4.88 ± 0.20	SG: 4.31% [0.144%], ES: 1.1 [0.036], *p* <0.001	10/3 (30) 3–4 sets x10–50 metre sprints

Key: EG: Experimental group; CG: Control group; INC: Incline sprint group; LEV: Level ground sprint group; Pre-PHV: Pre-peak height velocity; Post-PHV: Post-peak height velocity; SG: Sprint group.

3.3.7 COD Training

Three COD training interventions from two different studies were included for analysis (see Table 13), of which all interventions were found to produce statistically significant ($p < 0.05$) improvements in pro-agility performance (Šišková et al., 2021; Wagner et al., 2014). COD training intervention length ranged from 6 to 8 weeks (Šišková et al., 2021; Wagner et al., 2014), where an average change of 0.162% to 0.247% and 0.018 to 0.045 ES per session was noted (Šišková et al., 2021; Wagner et al., 2014). The greatest per session effects were noted in the study by Šišková et al. (2021), where COD drill training (0.243% and 0.045 ES, $p < 0.01$) was implemented over 12 sessions in novice soccer players. Albeit, similar per session percent change was shown in Wagner et al. (2014), where agility ladder training over 16 sessions led to improvements in performance in sub-elite recreational athletes (0.247% and 0.026 ES, $p < 0.025$).

Interestingly, the largest per session training effects noted in the study by Šišková et al. (2021) involved COD drills performed as short sprints with 60°, 90°, and 180° directional changes, whereas the interventions in Wagner et al. (2014) involved exercises more focused around the use of agility ladder and agility cube equipment. The reasons for the larger effects in the Šišková et al. (2021) could be attributed to: 1) the sprint COD drills by Šišková et al. (2021), providing greater exercise specificity to the pro-agility, compared to the small multi-dimensional (horizontal, vertical, and lateral orientation) movements performed in the ladder and cube intervention; 2) a more intense training mesocycle (6 weeks vs 8 weeks) including higher volume (greater distance covered and repetitions performed) per session; and, 3) inclusion of 180° COD drills, leading to improved 180° efficiency and technical competency.

It is recommended that selection of 180° COD exercises be included when looking to improve performance in the pro-agility test. Furthermore, it should be acknowledged that the intervention by Šišková et al. (2021) was designed based on recommendations of previous researchers on the improvement of strength and speed parameters in the soccer population (Beato, Bianchi, Coratella, Merlini, & Drust, 2018; Miller, Herniman, Ricard, Cheatham, & Michael, 2006). In contrast, Wagner et al. (2014) did not design and target the intervention towards any specific population. This may provide reason as to the discrepancy between the findings of the two studies and further research is warranted.

Table 13: Overview of change of direction training interventions

Reference	Number (*n*) of subjects and mean age	Sport training status	Control group	Experimental group	Improvement [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
Šišková et al. (2021)	*N* = AT, 11; CG, 9 Age = AT, 10.0 ± 0.2; CG, 10.7 ± 0.1	Soccer Novice	Pre: 6.12 ± 0.15 Post: 5.17 ± 0.38	Pre: AT, 6.17 ± 0.3 Post: AT, 5.99 ± 0.23	AT: 2.92% [0.243%], ES:0.54 [0.045], *p* <0.01	6/2 (12) AT: agility training x5 sets (4 reps ×60° COD, 4 reps ×90°, 5 reps ×180°)
Wagner et al. (2014)	*N* = 15 (cube: 8, ladder: 7) Age = N/A	Recreational athletes Sub-elite		Pre: Cube, 5.37 ± 0.49; Ladder, 5.56 ± 0.52 Post: Cube, 5.23 ± 0.48; Ladder, 5.34 ± 0.53	Cube: 2.61% [0.163%], ES:0.29 [0.018], *p* <0.025 Ladder: 3.96% [0.247%], ES:0.419 [0.026], *p* <0.025	8/2 (16) Agility ladder or agility cube drills 45 minutes 3–5 sets per exercise

Key: AT: Agility training group; CG: Control group; Cube: Agility cube group; Ladder: Agility ladder group.

3.3.8 Combined Training

3.3.8.1 Resistance and Plyometric Training

The effects of two combined resistance and plyometric training interventions from two different studies were analysed (see Table 14), of which one intervention was found to produce statistically significant ($p < 0.05$) changes in pro-agility performance (Jones et al., 2010). Combined resistance and plyometric training intervention length across the studies ranged from twelve to eighteen weeks (Bishop et al., 2017; Jones et al., 2010), resulting in an average change of 0.010% to 0.062%, and 0.002 to 0.014 ES per session (Bishop et al., 2017; Jones et al., 2010). The greatest per session improvements were noted in the study by Jones et al. (2010), where a whole-body free-weight exercises (i.e., not constrained to specific degrees of freedom) (0.062% and 0.014 ES) training intervention was implemented over 36 sessions in sub-elite soccer players. It should be noted in a combined population of sub-elite soccer, field hockey, and softball athletes (Jones et al., 2010), only soccer athletes showed a statistically significant ($p < 0.05$) improvement in pro-agility performance.

Interestingly, the largest per session training effects (Jones et al., 2010) were noted in the study involving sub-elite soccer athletes. The reasons for the larger effects could be attributed to: 1) the small sample size (n = 14) used by Bishop et al. (2017), may not have had ample statistical power to find statistical difference; 2) although the workloads were similar between all intervention groups across the studies, Bishop et al. (2017) integrated combined resistance and plyometric training within a smaller mesocycle as part of the larger intervention, however only overall performance changes were reported for the intervention; and, 3) it was noted by soccer athletes possibly had a lower training age or conducted the intervention with greater effort than the other groups, as noted by Jones et al. (2010) but not measured.

It needs to be noted that the second largest training effect was found in the Bishop et al. (2017) study, in elite cricket athletes over 36 sessions. However, readers should be aware that due to including combined resistance and plyometric training as a smaller mesocycle but only reporting performance results for the greater intervention, it is difficult to discern the resulting effects on pro-agility performance in cricket athletes.

3.3.8.2 Speed and Plyometric Training

The effects from three combined sprint and plyometric training interventions from three different studies (Šišková et al., 2021; Thompson et al., 2017; Vescovi & VanHeest, 2010) were analysed (see Table 15), of which one intervention was found to produce statistically significant ($p < 0.05$) changes in pro-agility performance (Šišková et al., 2021). Combined sprint and plyometric training intervention length across the studies ranged from 6 to 16 weeks (Šišková et al., 2021; Thompson et al., 2017; Vescovi & VanHeest, 2010), resulting in an average change of 0.066% to 0.135% and 0.011 to 0.036 ES per session. The greatest per session improvements were noted in the study of Šišková et al. (2021), where a combined sprint and plyometric training intervention over 12 sessions with novice soccer athletes was implemented (0.135% and 0.036 ES).

The largest per session training effects were observed in the study involving on field combined sprint and plyometric training (Šišková et al., 2021), meanwhile combined sprint and plyometric training involving 30 seconds of lateral hops, vertical hops, and horizontal hops, jumps, shuttle runs, and diagonal running exercises within a 15-20 minute warmup was noted to have an inverse effect, decreasing in pro-agility performance (-0.075% and -0.019 ES) (Vescovi & VanHeest, 2010).

The reasons for the disparity in training effects between studies by Šišková et al. (2021) and Thompson et al. (2017) vs Vescovi and VanHeest (2010) could be attributed to: 1) training session durations of 25–45 minutes

(Šišková et al., 2021; Thompson et al., 2017), as compared to 15–20 mins (31) provided a greater stimulus for adaptation; 2) both studies showing positive effects on pro-agility performance progressively overloaded intensity during exercises (Šišková et al., 2021; Thompson et al., 2017), whereas the warmup intervention implemented by Vescovi and VanHeest (2010) emphasised lower intensity through the use of "soft landing" and large joint range of motion to ensure proper technique; and, 3) shorter more intense training mesocycle (6 weeks vs 12 and 16 weeks), therefore less likelihood of training monotony and plateaus in adaptation.

3.3.8.3 Combined Resistance, Plyometric and Speed Training

The effects of two resistance training interventions ($p < 0.05$) a single study (Schwarz et al., 2019) were analysed (see Table 16). The intervention length was 6 weeks, with an average change of 0.715% to 1.034% and 0.071 to 0.078 ES per session (Schwarz et al., 2019). Both groups performed a combination of jumping, sprinting, and COD drills, with the only difference between groups being the utilisation of free-weight squats (FWS) (barbell back squat) or machine squat (MS) (machine hack squat) resistance exercise. The greatest per session improvements were noted in the MS training intervention (1.034% and 0.078 ES) over 12 sessions with novice recreational athletes.

While the largest per session training effects were noted in the MS group, as reported by Schwarz et al. (2019) there was no statistically significant difference in percent change and ES between either group. Furthermore, Schwarz et al. (2019) acknowledged that combined sprint and plyometric training with FWS or MS resistance exercises do not provide additive effect as improvements in pro-agility performance may be a result of direct training (i.e., COD drills) and not maximal strength.

Inclusion of all three training modalities within a single intervention allowed for development of multiple components encompassing the pro-agility test. Namely, possessing adequate lower-body concentric, eccentric, and isometric strength and power for the propulsive, decelerative, and isometric phases due to high horizontal and lateral forces required during the COD portion of the pro-agility.

Table 14: Overview of combined resistance and plyometric interventions

Combined Resistance and Plyometric Training						
Reference	Number (*n*) of subjects and mean age	Sport training status	Control group	Experimental group	Improvement % [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
Bishop et al. (2017)	*N* = 14 Age = 26.2 ± 5.3	Cricket Elite	Pre: Post:	Pre: 4.75 ± 0.18 Post: 4.70 ± 0.21	1.05% [0.029%], ES:0.26 [0.007], *p* >0.05	18/2 (36) Resistance training: Week 1–6: 3 sets x10 reps, 70–80% 1RM. Week 9–16: ¾ sets x4–6 reps, 80–90% 1RM. Week 17–23: Combined maximal strength and plyometric training. Cardio and sprint training.
Jones et al. (2010)	*N* = 46 Age = N/A	Soccer, field hockey, and softball Sub-elite	Pre: Post:	Pre: 5.39 ± 0.24 Post: 5.37 ± 0.25	EG: 0.37% [0.01%], ES:0.082 [0.0023], *p* >0.05 Soccer: 2.22% [0.062%], ES:0.49 [0.014], *p* <0.05	12/3 (36) 2 whole-body lifting sessions, 1 sprint and agility session.

Key: 1RM: 1 repetition maximum; APT: Agility and plyometric training group; EG: Experimental group; CG: Control group; FWS: Free-weight squat group; MS: Machine squat group.

Table 15: Overview of combined speed and plyometric training interventions

Combined Speed and Plyometric Training						
Reference	Number (*n*) of subjects and mean age	Sport	Control group	Experimental group	Improvement % [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
Šišková et al. (2021)	*N* = APT, 10 Age = APT, 10.0 ± 0.1	Soccer Novice	Pre: 6.12 ± 0.15 Post: 5.17 ± 0.38	Pre: APT, 6.19 ± 0.35 Post: APT, 6.09 ± 0.3	APT: 1.62% [0.135%], ES:0.44 [0.036], *p* <0.05	6/2 (12) APT: Plyometric jump 3–5 sets x10–12 reps and agility training x3–5 sets
Thompson et al. (2017)	*N* = EG, 16; CG, 9 Age = EG, 11.8 ± 0.9; CG, 12.1 ± 0.93	Team sport athletes Novice	Pre: 6.52 ± 1.04 Post: 6.25 ± 0.62	Pre: 5.63 ± 0.36 Post: 5.51 ± 0.34	EG: 2.13% [0.066%], ES:0.343 [0.011], *p* = 0.52	16/2 (32) Plyometric, sprint and agility training: Hurdle hops, depth jump, long jumps, sprints. Resistance training: Back/front squat, incline/bench press, row, push press, hang clean. 2 sets x5 reps
Vescovi and VanHeest (2010)	*N* = 58 (EG: 31, CG: 27) Age = 13–18 years	Soccer Novice	Pre: 4.79 ± 0.15 Post: 4.95 ± 0.23	Pre: 4.79 ± 0.16 Post: 4.92 ± 0.22	-2.71% [-0.075%], ES:-0.676 [-0.0187], *p* = 0.106	12/3 (36) Plyometric and agility warmup

Key: 1RM: 1 repetition maximum; APT: Agility and plyometric training group; EG: Experimental group; CG: Control group; FWS: Free-weight squat group; MS: Machine squat group.

Table 16: Overview of combined resistance, speed, and plyometric training interventions

Combined Resistance, Speed and Plyometric Training						
Reference	Number (*n*) of subjects and mean age	Sport	Control group	Experimental group	Improvement % [normalised % change] Effect Size (ES) [normalised ES] P value (*p*)	Training intervention details
Schwarz et al. (2019)	*N* = 27 Age = 22.7 ± 3.5	Recreational athletes Novice	Pre: 6.17 ± 0.60 Post: 5.91 ± 0.49	Pre: FWS, 6.76 ± 0.85; MS, 6.61 ± 1.04 Post: FWS, 6.18 ± 0.46, MS, 5.79 ± 0.66	FWS: 8.88% [0.715%], ES:0.849 [0.071], *p* <0.01 MS, 12.41% [1.034%], ES:0.941 [0.078], *p* <0.01	6/2 (12) Day 1: squat 3–6 sets x3–12 reps, jump 2–3 sets x5 reps, drop jump 3–4 sets x5 reps. Day 2: squat 3–6 sets x3–12 reps, 2–4 sets x30 metre sprints, 2–4 sets x pro-agility shuttle, 2–4 sets x zigzag run

Key: 1RM: 1 repetition maximum; APT: Agility and plyometric training group; EG: Experimental group; CG: Control group; FWS: Free-weight squat group; MS: Machine squat group.

3.4 Limitations and Future Research

Several considerations should be acknowledged as to the limitations of the findings of this review. Firstly, between studies there were a number of variations in the cohorts used (i.e., gender, sport, skill level, training age). Similarly, the disparity in exercises selected in each of the interventions, coupled with intervention length, and total workload performed throughout the interventions were all factors that made comparisons and conclusions between studies problematic (i.e., the heterogeneity of the studies). Secondly, given the limited data available in the literature and consistency of methodologies for specific and non-specific training methods a meta-analysis could not be performed, therefore a comprehensive identification of the effects of the aforementioned training methods on pro-agility performance could not be established with certainty. Therefore, the conclusions made from only a few studies should be interpreted with caution. Further research is needed to determine the absolute effects of plyometric, sprint and COD training on pro-agility performance. Longitudinal examination of pro-agility performance (and pro-agility phases) is necessary to elucidate the effects of different training methods on phases of the pro-agility. This is vital to the understanding of how specific phases of the pro-agility can be developed in response to different training stimuli.

In terms of future research, it has been shown that the pro-agility is a widely utilised test of COD ability in various sports (Forster, Uthoff, Rumpf, & Cronin, 2022a). However, all studies in this review utilised total-time as the measure for performance. Recent research by Forster, Uthoff, Rumpf, and Cronin (2021a) advanced the diagnostic value of the pro-agility test and established six distinct phases and six additional sub-tests incorporating acceleration, reacceleration, deacceleration, and COD components within the pro-agility test. Currently, while this review provides comprehensive evidence of the effect of different training methods on pro-agility performance, there are questions that need answering about how different training methods (e.g. specific and non-specific training) can improve performance in different phases of the pro-agility shuttle. From this standpoint, with the available literature, the phases and sub-tests measures can be conceivably affiliated to specific athletic capability (e.g., SSC for reacceleration or eccentric strength for deceleration), which can be developed through specific training methods.

3.5 Conclusion/Practical Applications

This review is unique in respect to previous reviews regarding training methods to improve COD performance because it focuses narrowly on the effectiveness of training methods that enhance pro-agility performance specifically. This would seem important given that the pro-agility test forms part of many testing batteries such as the NFL combine, which is used for scouting purposes. Assuming no technique issues, then taking an evidence-based approach to understanding and implementing training methods that produce the greatest pro-agility improvements, could make the difference in securing lucrative contracts.

Table 17: Ranking pro-agility improvement

Per Session Effect Size	Training Type
0.108	Sprint
0.092	Plyometric
0.087	Resistance
0.078	Resistance, plyometric, and sprint
0.045	COD
0.036	Plyometric and sprint
0.014	Resistance and plyometric

Cognizant of the limitations cited previously, some conclusions are made based on the summary of averaged increases in effect sizes as shown in Table 17. Sprinting, plyometric, resistance training, and a combination of those three were found to have greater per session effects (ES > 0.078) on pro-agility scores compared to COD, and a combination of plyometrics and sprinting or plyometrics and resistance training. Sprint training, specifically inclined sprint training, was found to have the largest per session training effect. This could be attributed to the fact that inclined or resisted sprint training methods have been found to be particularly effective for enhancing accelerative capability (Cahill et al., 2019; Okudaira et al., 2021). Given the large linear sprinting component and limited number of changes of direction associated with the pro-agility shuttle, this makes sense since athletes are required to accelerate between each COD (Brughelli et al., 2008). Plyometric training was found to be the second most effective method, which underlies the importance of SSC and leg power in COD given the accelerative and decelerative nature of this motor task. Implementing plyometric exercises that involve multi-planar motion i.e., horizontal and lateral as well as vertical jumping tasks, were found to be particularly beneficial for enhancing pro-agility shuttle performance. Resisted strength training, particularly unilateral strength training, is another training method that appears to transfer well to pro-agility performance. This makes sense in terms of specificity given the high force demands associated with 180˚ COD (Bourgeois et al., 2017) and that sprinting and changing direction are unilateral in nature. Finally, combing resistance, plyometric, and sprint training can produce beneficial neuromuscular adaptations which lead to improved pro-agility shuttle performance. This could be attributed to the simultaneous utilisation of the aforementioned training methods to allow for development of multiple neuromuscular qualities relating to performance in the pro-agility shuttle. However, training all three training types concurrently, with the same emphasis, may not provide ample stimulus compared to focusing on developing one neuromuscular quality to a greater extent compared to another. For example, coaches are likely to include jumping, sprinting, and lifting throughout an annual cycle, but programming a resistance training cycle focusing on maximum strength prior to a plyometric or sprinting-focused cycle may help improve contractile tissues capabilities which will then enable greater elastic tissue development, thereby SSC performance, in subsequent cycles.

Chapter Four. Advancing the Pro-agility Shuttle to Provide Better Change of Direction Diagnostics.

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4.0 Preface

A main finding of Chapter 2 was that the diagnostic value of the pro-agility shuttle is limited to a single measure, total time. While other COD tests have addressed this issue by separating the linear and COD components, the pro-agility shuttle has not been investigated in this regard. Consequently, this research aimed to determine the reliability of an advanced diagnostic protocol to enable distinct measurement of the linear and COD components of the pro-agility shuttle.

Chapter Four. Advancing the Pro-agility Shuttle to Provide Better Change of Direction Diagnostics.

4.1 Introduction

The knowledge of the physical components that contribute to athlete performance has gradually deepened as practitioners seek to assess and develop athletes. Notably, the capability to change direction (COD) is imperative for successful performance in many sports (Gabbett, 2005; Gil, Gil, Ruiz, Irazusta, & Irazusta, 2007; Reilly et al., 2000). The pro-agility shuttle is one such assessment that has been widely adopted in field sports such as baseball/softball (Nimphius, McGuigan, & Newton, 2010), soccer (Maio Alves, Rebelo, Abrantes, & Sampaio, 2010) and American football (Sierer, Battaglini, Mihalik, Shields, & Tomasini, 2008) as a tool to develop and distinguish between athletes' performance for team selection purposes (Sierer et al., 2008; Vescovi & McGuigan, 2008) (Chapter 2). The pro-agility shuttle is comprised of two 180° CODs, 4.57 m (5 yard) and 9.14 m (10 yard) linear sprints and has been found to be a reliable assessment of 180° COD ability (ICC = 0.90, CV = 2.19) athletes (Stewart et al., 2014).

A limitation with the pro-agility shuttle, is that total time as a measurement of performance has been shown to be influenced by linear sprint ability (Nimphius et al., 2013). Practically meaning, an athlete can compensate for poor COD performance with good sprinting ability, as identified in other 180° COD tests, such as the 5-0-5 (Nimphius et al., 2016). This problem can be addressed by assessing linear sprinting and COD as individual performance components (Nimphius et al., 2013; Salaj & Markovic, 2011; Vescovi & McGuigan, 2008). An example of this is where the 5-0-5 COD test has been updated to include the COD deficit, the average difference between 5-0-5 and 10 m sprint times, providing a practical measure for isolating COD time and better recognising athlete COD ability (Nimphius et al., 2016). The 5-0-5 test and linear sprint ability have both been found to have "high" measures of reliability, while reliability of modified 5-0-5 range from "low" to "high" (Kerdaoui, Sammoud, Negra, Attia, & Hachana, 2021; Taylor et al., 2019). While the differentiation between speed and COD performance have been addressed for other 180° COD tests (Clarke, Read, De Ste Croix, & Hughes, 2020; Nimphius et al., 2016; Ryan et al., 2022), only one study (Forster, Uthoff, Rumpf, & Cronin, 2021b) has investigated the differentiation of speed and COD performance in the pro-agility, providing insights into different athletic capabilities.

The ability to distinguish between measures of accelerative (i.e., acceleration and reacceleration) and COD may improve our understanding of an athlete's concentric and eccentric capabilities (Nimphius et al., 2016; Nimphius et al., 2013). For example, early acceleration requires concentric action of the muscle, where propulsive forces are a product of powerful concentric action of the muscle (Chaabene, Prieske, Negra, & Granacher, 2018; Markovic et al., 2007). Alternatively, deceleration is dependent on eccentric strength as the eccentric nature of deceleration requires athletes to tolerate high braking forces (Jones, Thomas, Dos'Santos, McMahon, & Graham-Smith, 2017; Spiteri et al., 2014). Additionally, possessing high levels of isometric strength will allow athletes to withstand high forces that occur during the plant phase benefitting COD technique, allowing the athlete to maintain optimal body positioning (Dos' Santos, Thomas, Jones, & Comfort, 2018; Spiteri et al., 2013; Spiteri et al., 2014). Therefore, to perform a COD successfully, it is imperative that athletes possess sufficient concentric strength, eccentric strength, and isometric strength (Chaabene et al., 2018; Spiteri, Newton, Binetti, et al., 2015). The use of advanced diagnostic protocols may enable a more in-depth analysis of pro-agility shuttle performance by decompartmentalising components of the test. For example, a single study by Forster et al. (2021b) used additional timing lights, placed 1 m before the COD line, to identify the different phases of the pro-agility shuttle. Additionally, Clarke et al. (2020) used a beam-based ground contact system (Opto Jump, Microgate, Italy) and timing lights (Witty, Microgate, Italy) to investigate different phases of the 5-0-5, and found phases of initial approach time, entry time, full approach time, time to plant, exit time, and 505 COD time to be reliable (CV = 2.3 – 6.3%, ICC = 0.73 – 0.94). The findings of Forster et al. (2021b) and Clarke et al. (2020) support investigation of individual phases within 180° COD tests. However, the entry distance used by Clarke et al. (2020) was consistent, therefore it is unknown how performance may vary between entries of different starting distances.

Movement velocity before and after COD in the pro-agility shuttle may be dependent on entry distance, eliciting different loading requirements. An example of this is that greater eccentric loading is required during deceleration into the second COD in the pro-agility, compared to that required for the first COD, due to a longer entry distance allowing for higher velocities to be reached before deceleration occurs (Brughelli et al., 2008; Spiteri et al., 2013). Similarly, higher and lower reactive acceleration ability out of a COD may also be present in the pro-agility shuttle, as determined by the eccentric-concentric force capability from 5 m and 10 m entries (Brughelli et al., 2008; Spiteri et al., 2013). Early acceleration from a stationary position, such as that performed in the stationary 5-0-5 (Barber, Thomas, Jones, McMahon, & Comfort, 2016), relies more on concentric muscle action to propel athletes over the first 5 m, where relatively slow COD entry velocity will require relatively low eccentric loading (Spiteri et al., 2013; Spiteri et al., 2014). Alternatively, during reacceleration from relatively faster COD entry velocities, due to accelerating from a flying start as those seen in the flying 5-0-5, will be more indicative of higher eccentric strength and elastic capabilities of the athlete (Jones et al., 2009; Spiteri et al., 2014).

Finally, although phases of the pro-agility shuttle were initially measured by Forster et al. (2021b), they acknowledged that reliability of measures may improve when timing gates are placed at equal distances between the COD and start/finish lines. In doing this, modified versions of the aforementioned tests may be built into the pro-agility shuttle as sub-tests (i.e., 4.57 m and 9.14 m sprints, stationary 5-0-5 and flying 5-0-5 into the first and second 180° COD). Therefore, the pro-agility may provide more diagnostic information than a singular test time, while minimising athlete fatigue caused by evaluation of multiple speed and COD assessments (Bourgeois et al., 2017; Forster et al., 2021b; Nimphius et al., 2018). While advanced protocols have enabled the differentiation between linear and COD speed for the 5-0-5 test (Nimphius et al., 2016), it is currently unknown whether an advanced diagnostic protocol can be used to reliably determine performance between different phases and sub-tests of the pro-agility shuttle.

Given that COD performance is comprised of multiple speed and COD components, it is of interest to investigate whether the individual qualities which constitute the pro-agility shuttle can be measured accurately and consistently. Therefore, the aim of this study is to investigate the reliability of different phases and sub-test measures (i.e., linear acceleration, reacceleration, and COD phases), in field sport athletes, by advancing the diagnostics provided by the pro-agility shuttle. We hypothesised that after appropriate subject familiarisation with the pro-agility shuttle, all sub-test measures would be reliable. Additionally, we hypothesised that given the complexity of COD performance, the measures of COD would be more variable relative to linear sprinting performance.

4.3 Methods

4.3.1 Experimental Approach to the Problem

To analyse the reliability of an advanced diagnostic protocol for the pro-agility shuttle, a repeated measures analysis of male field sport athletes was conducted. Subjects performed maximal effort attempts of the pro-agility shuttle, with two additional timing gates placed at 2.28 m (2.5 yards) prior to each COD line. To determine whether between-day performance differed, absolute consistency using CV and relative consistency using ICC were also used to determine the reliability of total time and sub-test performance.

4.3.2 Subjects

Ten male high school field sport athletes (age: 16.1 ± 0.32 years, height: 1.81 ± 0.11 m, body mass: 76.6 ± 18.04 kg) participated in this study. All subjects participated in field sports requiring 180° CODs, had an average training age of 4.50 ± 0.50 years, and were required to be healthy and free of injury at the time of testing. After being orally briefed on the methods and reading the information sheet, subjects provided their written informed consent, or assent, prior to participating in this study and where appropriate, subjects' guardians provided written consent. Subjects were notified that they were free to withdraw from the study at any point. This research was approved by the Auckland University of Technology Ethics Committee (20/67) and conforms to the Declaration of Helsinki.

4.3.3 Procedures

Testing was conducted on an indoor hardwood floor. Wearing the same clothing and footwear, subjects were required to attend four sessions: one familiarisation session where the subjects were accustomed with performing the pro-agility shuttle and three testing sessions. By asking the subjects to come in for three testing sessions, this allowed researchers to compare performance between sessions (i.e., session one and two and session two and three) and determine the reliability of sub-test performances with the new diagnostic setup. Testing sessions were conducted seven days apart, at the same time of the day, under the same experimental conditions. Each testing session lasted approximately one hour. During each session, subjects performed a standardised warm up consisting of progressive sprint and COD drills interspersed with dynamic lower body stretching, followed by three pro-agility trials at 70%, 90% and 100% intensity (Forster et al., 2021b).

For the pro-agility run, the subjects started on a centreline facing perpendicular to the running direction (Gillen et al., 2018). The subjects sprinted 4.55 m to the left, then 9.10 m to the right, and 4.55 m back to finish the test as they crossed the centreline, always turning on their dominant leg. Three trials on each testing session were used to gather average performance data and minimise the effect of best performances confounding the results

(Meylan et al., 2009; Simperingham, Cronin, Pearson, & Ross, 2019). Three minutes of passive rest was provided between trials to limit performance fluctuations resultant from fatigue and decrease risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008).

4.3.4 Equipment

To quantify COD performance, timing gates (Smartspeed, Fusionsport, Finland) were set at the start/finish line and 2.28 m either side of the start line (i.e., 2.28 m between the start/finish and each COD line) (see Figure 7) (Sayers, 2014, 2015). Timing gate height was set at 0.85 m for the start/finish to correspond with approximate centre of mass and gates 2.28 m from each COD were set at 0.75 m to account for subjects lower centre of mass during the COD (Morrison, Albert, & Kuruganti, 2015). This set-up enabled total time (i.e., 18.2 m) and associated sub-tests to be measured (see Table 18).

Table 18: Pro-agility diagnostic sub-test categorisation and proposed physical qualities measured.

Split	Name	Explanation/Distance	Proposed Quality
1	Acceleration 1 (ACC1)	Acceleration from gate 1 to gate 2. Distance = 2.28 m.	Initial acceleration ability
2	COD 1	Timing 2.28 m entry and exit of the first COD. Distance 4.57 m.	Moderate-intensity entry COD ability
3	Reacceleration 1 (REA1)	Acceleration from gate 2 to gate 1. Distance = 2.28 m.	Moderate-intensity reaccelerative ability
4	Acceleration 2 (ACC2)	Acceleration from gate 1 to gate 3. Distance = 2.28 m.	Final accelerative ability
5	COD 2	Timing 2.28 m entry and exit of the second COD. Distance = 4.57 m.	High-intensity entry COD ability
6	Reacceleration 2 (REA2)	Acceleration from gate 3 to gate 1. Distance = 2.28 m.	High-intensity reaccelerative ability
Sub-Test			
Acceleration 1 + COD 1	Moderate intensity 501 (501_{MI})	From gate 1 through gate 2, 180° COD back to gate 2. Distance = 6.84 m.	Moderate-intensity entry and COD ability
COD 1 + Reacceleration 1	Moderate intensity 105 (105_{MI})	From gate 2, 180° COD, through gate 2 to gate 1. Distance = 6.84 m.	Moderate-intensity COD and accelerative ability
Acceleration 2 + COD 2	High intensity 501 (501_{HI})	From gate 1, through gate 3, 180° COD back to gate 3. Distance = 6.84 m.	High-intensity entry and COD ability
COD 2 + Reacceleration 2	High intensity 105 (105_{HI})	From gate 3, 180° COD, through gate 3 to gate 1. Distance = 6.84 m.	High-intensity COD and accelerative ability
Acceleration 1 + COD 1 + Reacceleration 1	Stationary 505 (505_{static})	From gate 1 through gate 2, 180° COD, back through gate 2 to gate 1. Distance = 9.14 m.	Moderate-intensity entry, COD, and accelerative ability
Acceleration 2 + COD 2 + Reacceleration 2	Flying 505 (505_{flying})	From gate 1 through gate 3, 180° COD, back through gate 3 to gate 1. Distance = 9.14 m	High-intensity entry, COD, and accelerative ability
All	Total time	Pro-agility total time. Distance = 18.28 m.	All the above

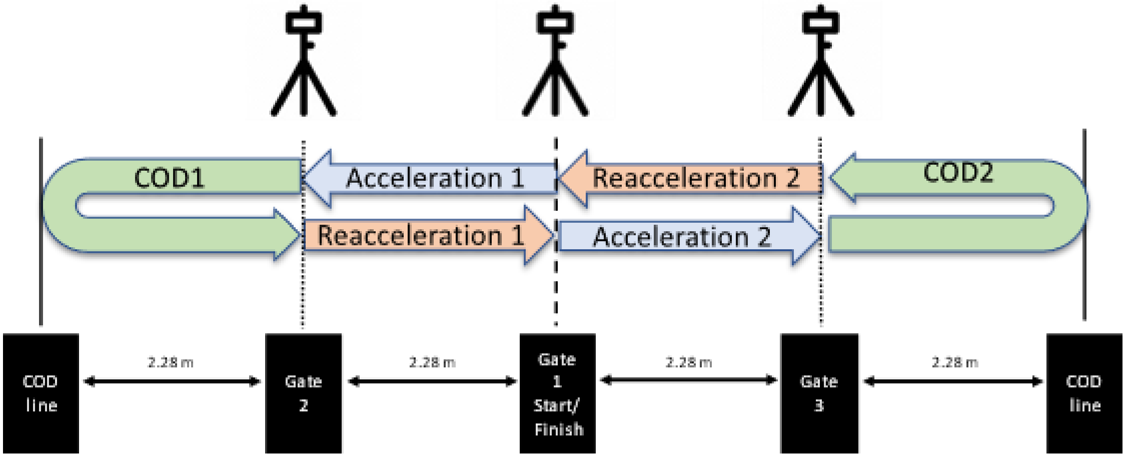

Figure 7: Advanced pro-agility shuttle protocol

4.3.5 Statistical Analysis

The two fastest trials from each session were averaged for all the variables of interest and used for subsequent analysis (Garson, 2012). Assumptions of normality were assessed using a Shapiro-Wilks test and homogeneity of variance was calculated using the Levene's statistic to test for outliers (Garson, 2012), normality and homogeneity were confirmed. Thereafter, descriptive variables were quantified using IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA). Data was reported using 95% confidence limits (CL) and means. Reliability was established using pairwise analysis. Each dependant variable was investigated between the first and second sessions and between the second and third sessions. A one-way analysis of variance (ANOVA) using repeated measures was used to determine whether between-day performance differed for total time and each of the twelve sub-tests. Additionally, a one-way ANOVA was used to compare between phase performances of relative distances (e.g., ACC1 vs ACC2 and 505_{flying} vs 505_{static}) within session 3. To determine if systematic differences were presented between testing sessions one to two and two to three, and between phases of session 3, a Bonferroni pairwise comparison was used. Absolute consistency between sessions was assessed by the root-square-mean method to calculate CV (Bland, 2006; Kang, Lee, Seong, & Hawkins, 2007), mean percentage change and relative consistency using test-retest correlations was measured via ICC using a two-way random model and averaged measures (Koo & Li, 2016). CVs of less than 10% were deemed acceptable as a percent of typical error (Uthoff et al., 2018). Categorisation of ICC was deemed as follows: 'very poor' ($\leq$ 0.20), 'poor' (0.20 - 0.49), 'moderate (0.50 – 0.74), 'good' (0.75 – 0.90) or 'excellent' ($\geq$ 0.90) (Buchheit & Mendez-Villanueva, 2013).

4.4 Results

The mean and standard deviation for each sessions' sub-test results are displayed in Table 19. The only significant difference observed existed for COD1, moderate-intensity 501 (501_{MI}), moderate-intensity 105 (105_{MI}), 505_{static} and 505_{flying} between the first two sessions (-7.37% - 4.20%, $p < 0.05$), with no significant differences being observed between the last two sessions. Between sessions 1-2 mean change in total time ranged from -6.28% to 1.19% and between sessions 2-3 the change in mean was between -0.38% to 1.36% for all conditions. The change in mean was smaller in sessions 2-3 compared to sessions 1-2 for all variables measured.

Regarding absolute consistency, CVs ranged from 0.95% to 10.22% for both days, averaged CV between session 1 and 2 was 7.15% and between sessions 2 and 3 was 1.74%. Only ACC1 and COD2 had an unacceptable CV ($\geq$ 10%) between sessions 1 and 2, with all measures reporting acceptable CVs ($\leq$ 4.42%) between sessions 2 and 3.

Relative consistency ranged from 'poor' to 'good' (ICC = 0.23 to 0.89) for all measures between sessions 1-2 and were "excellent" (ICC = 0.90 to 0.99) between sessions 2-3. Average relative consistency was 'moderate' between days 1-2 and 'excellent' between days 2-3 (ICC = 0.50 vs 0.96, respectively).

A one-way ANOVA showed significant differences on session 3 (Table 19), between phases ACC1 and ACC2 ($p < 0.001$). No significant differences were observed between reacceleration phases one and two ($p = 0.66$). There were no significant differences between COD1 and COD2 time in session 3 ($p = 0.18$). Significant differences were reported for 501_{MI} between 105_{MI} and 501_{HI} ($p < 0.001$) and between 105_{MI} and 501_{HI} ($p = 0.002$). Measures of 501_{HI} and 105_{HI} were significantly different in session 3 ($p < 0.001$), whereas no significant differences were present between 105_{MI} and 105_{HI} ($p = 0.69$). Significant differences were observed between stationary and flying 5-0-5 ($p < 0.001$) for session 3.

Table 19: Pro-agility and sub-test descriptive statistics and reliability results.

Phases	***Mean (±SD)***			***% Change in mean (95% CL)***		***CV (95% CL)***		***ICC (95% CL)***	
	Day 1	*Day2*	*Day3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*
Acceleration 1	0.75 ± 0.03	0.69 ± 0.02	0.70 ± 0.01 †R1, †A2, †R2	-8.94% (-16.419 - -0.787)	0.24% (-1.375 – 1.875)	10.03% (4.61 – 14.80)	1.45% (0.69 – 2.23)	-0.24 (-1.238 – 0.534)	0.98 (0.914 – 0.994)
COD1	1.59 ± 0.07	1.41 ± 0.08	1.44 ± 0.12	-6.52%* (-14.574 – 2.304)	1.36% (-0.599 – 3.353)	9.32% (4.23 – 13.66)	1.98% (1.00 – 3.24)	0.42 (-0.413 – 0.835)	0.96 (0.859 – 0.989)
Reacceleration 1	0.47 ± 0.03	0.51 ± 0.05	0.51 ± 0.05 †A1, †A2	7.03% (2.188 – 12.108)	-0.27% (-1.361 – 0.841)	6.33% (3.11 – 10.03)	1.00% (0.47 – 1.52)	0.72 (0.111 – 0.927)	0.99 (0.963 – 0.997)
Acceleration 2	0.42 ± 0.02	0.43 ± 0.02	0.43 ± 0.02 †A1, †R1, †R2	2.54% (0.077 – 5.065)	-0.38% (-1.661 – 0.910)	2.80% (1.32 – 4.24)	1.18% (0.59 – 1.90)	0.89 (0.597 – 0.974)	0.97 (0.874 – 0.990)
COD2	1.46 ± 0.11	1.43 ± 0.11	1.45 ± 0.12	5.01% (-5.808 – 17.068)	0.94% (-1.151 – 3.066)	10.22% (4.09 – 13.33)	1.97% (0.99 – 3.23)	0.54 (-0.235 – 0.874)	0.97 (-0.888 – 0.992)
Reacceleration 2	0.47 ± 0.05	0.50 ± 0.03	0.50 ± 0.03 †A1, †A2	4.72% (-0.483 – 10.188)	-0.38% (-1.396 – 0.651)	5.58% (2.51 – 8.10)	0.95% (0.47 – 1.50)	0.72 (0.111 – 0.927)	0.99 (0.956 – 0.997)
Sub-Test									
Moderate intensity 501	2.36 ± 0.05	2.09 ± 0.10	2.13 ± 0.13 †M105, †H501, †H105	-7.37%* (-13.829 - -0.421)	1% (-0.829 – 2.859)	8.40% (3.95 – 12.70)	1.77% (0.88 – 2.82)	0.23 (-0.645 – 0.763)	0.93 (0.737 – 0.979)
Moderate intensity 105	2.06 ± 0.05	1.92 ± 0.03	1.96 ± 0.07 †M501, H501	-3.27%* (-9.563 – 3.453)	0.95% (-0.769 – 2.698)	6.43% (2.88 – 9.27)	1.67% (0.82 – 2.63)	0.47 (-0.334 – 0.853)	0.95 (0.794 – 0.984)
High intensity 501	1.88 ± 0.08	1.86 ± 0.09	1.88 ± 0.10 M501, M105, †H105	4.17% (-3.497 – 12.438)	0.63% (-1.195 – 2.480)	9.83% (4.07 – 13.10)	4.42% (2.06 – 6.63)	0.60 (-0.122 – 0.894)	0.97 (0.866 – 0.990)
High intensity 105	1.94 ± 0.07	1.92 ± 0.08	1.95 ± 0.09 †M501, †H501	4.74% (-3.401 – 13.555)	0.59% (-1.144 – 2.353)	7.88% (3.24 – 10.45)	1.60% (2.59 – 0.80)	0.50 (-0.286 – 0.863)	0.96 (0.854 – 0.989)
Stationary 505	2.84 ± 0.03	2.61 ± 0.07	2.65 ± 0.08 †F505	-4.84%* (-10.282 – 0.929)	0.76% (-0.916 – 2.473)	6.31% (2.95 – 9.47)	1.59% (0.77 – 2.47)	0.32 (-0.543 – 0.798)	0.90 (0.623 – 0.968)
Flying 505	2.36 ± 0.06	2.35 ± 0.06	2.38 ± 0.07 †S505	4.20%* (-2.010 – 10.811)	0.41% (-1.193 – 2.041)	6.19% (2.62 – 8.42)	1.46% (0.73 – 2.35)	0.59 (-0.144 – 0.890)	0.96 (0.839 – 0.988)
Total Time	5.23 ± 0.14	4.98 ± 0.14	5.03 ± 0.19	-3.77% (-6.279 - -1.191)	0.51% (-1.156 – 2.205)	3.59% (1.71 – 5.49)	1.53% (0.75 – 2.40)	0.70 (0.085 – 0.924)	0.93 (0.737 – 0.979)

** = significance difference between session p < 0.05, † = significant differences between phases in session 3 p < 0.001. A1 = Significantly different to Acceleration 1, R1 = Significantly different to Reacceleration 1, A2 = Significantly different to Acceleration 2, AR2 = Significantly different to Reacceleration 2, C1 = Significantly different to COD1, C2 = Significantly different to COD2, M501 = Significantly different to Moderate Intensity 501, M105 = Significantly different to Moderate Intensity 105, H501 = Significantly different to High Intensity 501, H105 = Significantly different to High Intensity 105, S505 = Significantly different to Stationary 505, F505 = Significantly different to Flying 505.*

4.5 Discussion

In the assessment of COD tests, determining COD performance from absolute performance time is a unique challenge, where independent qualities (i.e. acceleration and deceleration, reacceleration and COD) are components contributing to the performance assessed (Nimphius et al., 2016). Of interest to the authors was whether an advanced diagnostic protocol could be utilised to assess performance for distinctive phases of the pro-agility shuttle. In doing so, two true acceleration measures, two reacceleration measures, two COD phases and six additional assessments were identified as sub-tests that could provide informative data, in addition to total time measure for the pro-agility shuttle. Prior to any utilisation of the sub-tests in the field, it was crucial to determine the reliability of the different phases. The main findings of this study were: 1) acceleration phase performance measures of REA1, ACC2, and REA2, 501_{HI}, 105_{HI} and total time variables were reliable across all testing sessions; 2) all phases and sub-tests measured met the acceptable thresholds for reliability between sessions 2-3; and 3) there appeared to be a learning effect between sessions 1-2. Given these results, the application of an advanced diagnostic protocol to assess different phases and sub-tests within the pro-agility shuttle may be of utility to strength and conditioning coaches.

Previous research (Forster et al., 2021b) has suggested reliability of phases within the pro-agility may be improved with the addition of timing lights placed at equal distances between the COD and start/finish lines. Evidence of our findings confirm this in finding all pro-agility phases to be reliable. Each phase and sub-test measures different qualities within the pro-agility shuttle. Measures of ACC1 and ACC2 are not influenced by deceleration or a COD, due to the nature of phases initiating from either a stationary or flying start. Although similar in that ACC1 and ACC2 are measures of accelerative ability, the force-velocity requirements differ between initial 0-5 m and flying acceleration i.e. 5-10 m (Callaghan, Jeffriess, Mackie, Jalilvand, & Lockie, 2015; Lockie, Jalilvand, Callaghan, Jeffriess, & Murphy, 2015). The reliability of the acceleration phases of the pro-agility shuttle in this study closely align with previous findings that 5 m (ICC = 0.65-0.87 and CV = $\leq$ 3.3%) (Comfort, Stewart, Bloom, & Clarkson, 2014; Enright et al., 2018) and 10 m (ICC = 0.85-0.62 and CV = $\leq$ 2.6%) (Enright et al., 2018; Standing & Maulder, 2017) sprints times are reliable performance metrics in athletes. However, in comparison Forster et al. (2021b) found measures of acceleration to be "moderate" (ICC = 0.51 – 0.71) when timing lights are placed at 1 m from COD.

Subjects in this study were found to be significantly faster in Acceleration 2 than in ACC1 (0.43 ± 0.02 and 0.70 ± 0.01 s, *p* = <0.00, respectively). The difference in performance may be explained by the flying start enabling higher movement velocities to be reached in ACC2, than from initiation of movement from a stationary position, as measured in ACC1. Additionally, variability in mean change and relative consistency (ICC) scores in ACC2 (-0.38%, ICC = 0.97) were observed to be marginally higher compared to ACC1 (0.24%, ICC = 0.98). These findings are in line with previous literature, that higher movement velocity associated with the flying start may attribute to the increased variability, reducing the reliability of the measurement (Barber et al., 2016; Duthie, Pyne, Marsh, & Hooper, 2006; Hader, Palazzi, & Buchheit, 2015). Therefore, the difference in times between ACC1 and ACC2 indicate assessment of musculotendinous capabilities at different velocities and can be used to determine linear accelerative capabilities (Cavagna, Komarek, & Mazzoleni, 1971; Falch et al., 2020; Lai, Schache, Brown, & Pandy, 2016; Vescovi & McGuigan, 2008).

After making a directional change, athletes must reaccelerate. REA1 and REA2 were deemed to reliably measure low and high load initial reaccelerative ability, respective of COD entrance velocity. Once more, there were no significant differences (*p* = 0.66) in performance between the low and high load reaccelerative session 3 conditions. It appears the reacceleration phases are similarly reliable (CVs = 0.95 – 1.00%; ICCs = 0.99), regardless of entry distance prior to COD. In contrast, Forster et al. (2021b) found measures of reacceleration to be unreliable (CV = 11.5 – 16.3; ICC = -0.15 - 0.48) with timing gates placed at 1 m from COD. Furthermore, reacceleration ability was found to be as reliable as acceleration from stationary and flying starts, though significantly (*p* < 0.001) faster than ACC1 and slower than ACC2. Research has shown reacceleration to differ from "pure" acceleration, in that elastic energy, stored during deceleration, increases force output during the propulsive phase (Ettema, 2001; McCarthy, Wood, Bolding, Roy, & Hunter, 2012; Spiteri et al., 2013), therefore improving post-COD reaccelerative ability (Spiteri et al., 2013). Therefore, given the differences in times between acceleration phases and reacceleration phases, yet similar reliabilities, strength and conditioning coaches can confidently distinguish between different forms of acceleration ability in their athletes.

It should be noted that, like the acceleration performance measures, both low and high velocity COD measures were found to have excellent levels of absolute and relative consistency between session 2-3 (CV $\leq$ 2.03, ICC $\geq$ 0.96). Interestingly, there was no significant difference between mean performance times of COD1 and COD2 in session 3 (1.44 ± 0.12 and 1.45 ± 0.12 s, *p* = 0.18, respectively). These findings were unexpected, as the higher entry velocity into COD2 would be thought to increase movement variability, due to higher braking force and eccentric strength requirements to decelerate and maintain optimal body positioning during the turn (Dos' Santos et al., 2018; Spiteri et al., 2013; Spiteri et al., 2014) (as identified above). Though COD1 and COD2 resulted in similar time and reliability, it is unknown whether there were differences between the acceleration and deceleration components within these phases. For example, since ACC2 was faster than ACC1, it is possible that there were higher entry velocities and slower exit velocities in COD2 than COD1. However, continuous timing technology such as radar or laser are needed to explore this posit.

Finally, all sub-tests were established as reliable measures of the different performance components comprising the pro-agility shuttle (Table 19). Modifying the pro-agility enabled the measurement of both stationary and flying 5-0-5 performance, which was found to be similarly reliable to previous research into the stationary start (ICC = 0.97) (Barber et al., 2016) and flying start 5-0-5 tests (ICC = 0.88 and 0.95; CV = 2.40%) (Barber et al., 2016; Stewart et al., 2014). 501_{MI} and 501_{HI}, and 505_{Static} and 505_{flying} are highly reliable measures, however, the completion times in session 3 should be noted. That is, sub-test performance with moderate intensity eccentric loading capabilities (501_{MI} and 505_{Static}) exhibited longer times (0.25 – 0.27 s, $p < 0.001$) to complete than the higher intensity sub-tests (501_{HI} and 505_{flying}), due to the faster entry velocities in the latter tests (Barber et al., 2016). The differences in these sub-test measures are primarily explained by whether the subject is moving or stationary when they enter the testing phase (i.e., ACC1 and ACC2, respectively). The addition of sub-test measures provides a means for practitioners to assess a multitude of athletic fitness qualities using a single test.

To the researchers' knowledge, this study is the first to empirically test whether an advanced diagnostic protocol could be used to reliably distinguish between different sub-tests within the pro-agility shuttle. However, coaches and practitioners should be aware of several limitations of the current study: 1) timing lights were set at 0.75 m in this study, in practice we suggest adjusting timing light height to be appropriate relative to the population being assessed, as for those who exhibit a very low COD position a timing light height of 0.75 m may not be appropriate, 2) Subjects only turned on their preferred leg, therefore it is unknown whether there are differences between the phases, sub-tests, or reliability measures between the legs, and 3) Using a timing light set-up at 2.28 m either side of the COD lines was unable to completely isolate deceleration and immediate reacceleration. Therefore, to further the diagnostic capabilities of the pro-agility shuttle, it would be recommended that future researchers compare performance between the preferred and non-preferred leg and investigate the use of alternative technologies which use constant timing, such as laser or radar technology to include velocity profiling to detect changes in velocity over the different phases of the pro-agility (i.e., acceleration, reacceleration, and COD). While the subject sample for reliability in this study was small (*n* = 10), Buchheit, Lefebvre, Laursen, and Ahmaidi (2011) asseverate that in finding good reliability, an expansion in sample size may not affect the results. To expand, an increase in sample size may improve the power of our findings, by reducing the margin of error. However, in findings good reliability, this does not mean it would improve our findings (Mokkink, de Vet, Diemeer, & Eekhout, 2023). However future research should look to use larger sample size to reduce the margin of error. Finally, we suggest that two familiarisation sessions are required prior to performance testing, to ensure consistent and accurate data is captured.

4.6 Practical Applications

The advanced analysis using multiple timing lights can be used to consistently differentiate between phases of acceleration, reacceleration, and COD performance, and sub-tests within the pro-agility shuttle. Based on the findings of this research, we recommend that two familiarisation sessions be conducted to mitigate any learning effects and allow for reliable performance measurement. The ability to distinguish between the speed components of the pro-agility and utilising the established sub-tests have the potential to provide novel information relating to the different athletic capabilities of performance within the pro-agility shuttle. However, this contention needs to be investigated and a correlational analysis is needed to determine how much shared variance there is between the new measures and thereafter refine the testing battery to provide high level diagnostic information to guide better programming.

Chapter Five. Radar Profiling of Multi-phase Pro-agility Shuttle Performance.

5.0 Preface

A main finding of Chapter 2 was the common use of timing light and stopwatch technology to assess pro-agility shuttle performance. Yet, profiling of velocity surrounding 180° COD remained unexplored. Given the numerous accelerative, decelerative, reaccelerative and COD moments, it may be that other technologies can give more granular and insightful information than timing lights. With this in mind the reliability of radar velocity profiling of the different phases of the pro-agility shuttle served as the purpose for Chapter 5.

Chapter Five. Radar Profiling of Multi-phase Pro-agility Shuttle Performance.

5.1 Introduction

In many sporting instances, athletes may only sprint for two to three seconds before a directional change is required (Spencer, Bishop, Dawson, & Goodman, 2005). An athlete's ability to perform a COD is an important performance component that is required in many court and field sports. The performance of a COD to maneuver around opponents can occur during critical situations and can attribute to success in sport (i.e. distance covered or possession) (Sheppard & Young, 2006). Therefore, highlighting the importance of measuring an athlete's COD ability. One such test is the pro-agility shuttle, regularly used for athlete identification and as a measure of 180° COD performance (McGee & Burkett, 2003; Sierer et al., 2008). The pro-agility shuttle involves two 180° direction changes and is conducted over a total of 18.3 m, using timing gates to measure total pro-agility shuttle time (Harman, Garhammer, & Pandorf, 2008; Nimphius et al., 2013). In the traditional assessment protocol used for the pro-agility (Harman et al., 2008; Nimphius et al., 2013), there are multiple decelerative and accelerative phases required within the test, which are viewed as critical qualities relating to COD speed and performance (Clarke et al., 2020; Dos' Santos, Thomas, Jones, & Comfort, 2017; Hewit, Cronin, Button, & Hume, 2011; Lockie, Schultz, Callaghan, Jeffriess, & Berry, 2013). This implies that approach velocity and acceleration are determinants of better COD performance (Dos' Santos et al., 2017; Dos'Santos, Thomas, McBurnie, Comfort, & Jones, 2021), specifically athlete eccentric loading capacity when decelerating into the COD and propulsive force application ability during acceleration out of a 180° COD (Jones et al., 2017; Samozino et al., 2016). However, research into COD suggests the use of "total time" as a measurement of athlete COD performance is misinterpreted, as total time is biased to linear sprint ability and does not measure other athletic performance components of acceleration and deceleration within COD assessments (Nimphius et al., 2016).

It has been reported that 29% of total time during the pro-agility is spent making a COD, with linear phases comprising the remaining 71% of the time (Nimphius et al., 2013). Therefore, performance phases that make up COD are independent and should be examined as such (Nimphius et al., 2016; Nimphius et al., 2013; Salaj & Markovic, 2011; Vescovi & McGuigan, 2008). In this regard, assessment protocols must be developed and utilized to provide practitioners with better-quality diagnostic information relating to the different performance components involved in COD assessment (i.e., acceleration and deceleration). Recently, an advanced diagnostic protocol was established for the pro-agility shuttle, which included two additional timing lights placed 2.28 m before the COD lines (Forster et al., 2021a) (Chapter 4). This allowed for the identification of two acceleration phases, two reacceleration phases, two COD phases, and six sub-test measures, of which phases of acceleration, reacceleration, and COD were deemed reliable (CV = < 4.42%; ICC = < 0.90). With the advancement of COD assessment protocols to provide greater diagnostic value to practitioners through multi-phase analysis, we postulated in a previous study (Forster et al., 2021a) that other technologies, such as radar, may be used to enhance our understanding of pro-agility performance.

Velocity profiling for COD speed has commonly used timing gates (ICC = 0.78 – 0.99) (Barber et al., 2016; Buchheit, Haydar, & Ahmaidi, 2012; Dos' Santos et al., 2018; Forster et al., 2021a; Nimphius et al., 2016) and global positioning systems (GPS) sampling between 5-15 Hz (ICC = -0.02 – 0.73) (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010; Vickery et al., 2014). Conversely, there are limitations to the use of these technologies. For example, the use of a single timing light, as per traditional protocol for the pro-agility shuttle and 5-0-5 COD tests, lacks the ability to assess different phases of running within COD assessment. Additionally, GPS technology has exhibited poor reliability and validity to assess the velocity of short and fast movement patterns during COD (Buchheit et al., 2014; Hader et al., 2015; Jennings et al., 2010). Within recent years, center of mass (COM) velocity profiling for overground running has been used by researchers and applied practitioners using timing gates, motorized linear position encoder, and radar technology (Cahill et al., 2020; Carlos-Vivas, Marfn-Cascales, Freitas, Perez-Gomez, & Alcaraz, 2019; Helland et al., 2019; Westheim, Gløersen, Harper, Laugsand, & Eriksrud, 2023). Despite the use of equipment such as radar for velocity profiling of linear running, there is little use of this technology for velocity profiling of COD (Hader et al., 2015; Westheim et al., 2023). It would be of interest to investigate the reliability of velocity profiling for multi-phase analysis in the pro-agility shuttle using radar technology.

Velocity-profiling for 45° and 90° directional changes (ICC = 0.15, CV = 4.90 and ICC = 0.72, CV = 2.80, respectively) (Hader et al., 2015) and repeated sprint ability (Jiménez-Reyes et al., 2019) has been investigated, however, there seems to be limited or no research regarding velocity profiling for specific 180° COD assessments (i.e., pro-agility shuttle). Therefore, this study aims to determine the reliability of radar velocity profiling on pro-agility performance and determine whether the multiple performance phases within the pro-agility shuttle can be assessed. We hypothesize that radar will be a consistent method to assess pro-agility performance. Additionally, it is hypothesized that the greatest reliability will be observed in the later accelerative phases, while we expect greater variability to be seen during early acceleration and COD phases.

5.2 Methods

5.2.1 Experimental Approach to the Problem

This study used a repeated measures experimental approach to assess the reliability of an advanced diagnostic protocol for the pro-agility shuttle using radar technology. Seventeen male novice team sport athletes performed three maximal effort attempts of the pro-agility shuttle on three testing occasions, separated by seven days. Subject number were determined via G*power calculation using a repeated measures within-factors design, based on an alpha level of 0.05 and a statistical power of 0.80, a minimum sample size of ten was determined. A repeated measures ANOVA was conducted on the velocity outcome measures to determine the variation of between-day performance. To determine the reliability of total time and sub-test measures, multi-phase analysis using absolute consistency and absolute agreement were assessed between consecutive testing occasions.

5.2.2 Subjects

Seventeen male novice team sport athletes (age: 18.18 ± 2.88 years, height: 175.56 ± 16.62 cm, body mass: 85.74 ± 19.05 kg) participated in this study. Subjects were required to be healthy and free of injury at the time of testing. After reading the provided information sheet and being orally briefed on the study methods, subjects provided their written informed consent prior to participating in this study. Subjects were notified that they were free to withdraw from the study at any point. This research was approved by the Institution’s Ethics Committee and conforms to the Declaration of Helsinki.

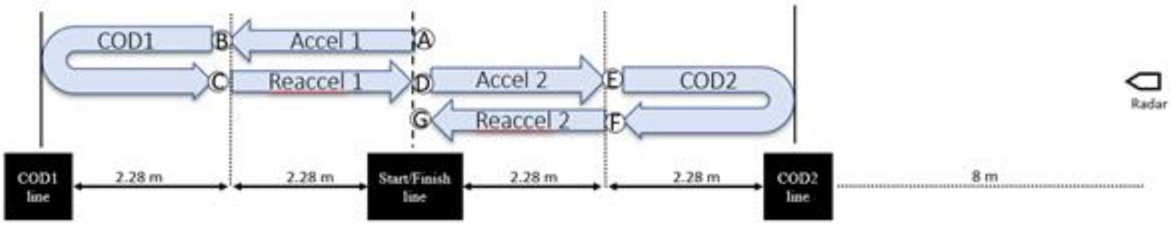

Figure 8: Radar pro-agility shuttle protocol.

5.2.3 Procedures

Testing was conducted on an indoor hardwood floor. Wearing the same clothing and footwear, subjects were required to attend four sessions: one familiarisation session where the subjects were accustomed to the pro-agility shuttle followed by three testing sessions. Testing session one occurred seven days after the familiarisation session and testing sessions were conducted seven days apart, at the same time of the day, under the same experimental conditions. Approximately one hour was required for each testing session. A standardized warmup consisting of progressive sprint and COD drills interspersed with dynamic lower-body stretching, followed by three pro-agility shuttle trials at 70%, 90%, and 100% preceded each session, similarly to a recent study (Forster et al., 2021a) (Chapter 4). For the pro-agility protocol, subjects started 30 cm behind the centreline facing perpendicular to the running lane. As illustrated in Figure 8, the subjects sprinted 4.55 m (5 yards) away from the radar, touched the COD line with their hand, changed direction 180° on their preferred side, then sprinted 9.10 m (10 yards) back towards the radar, touched the second COD line with their hand, made a second 180° COD on their preferred side, and sprinted 4.55 m (5 yards) back to finish the test as they crossed the centreline. Three trials on each testing session were used to gather average performance data and minimise the effect of best performances confounding the results (Meylan et al., 2009; Simperingham et al., 2019). By asking the subjects to come in for three testing sessions, this allowed researchers to compare velocity between consecutive sessions (i.e., session 1 and 2 and session 2 and 3) and determine the reliability of the new diagnostic setup using the radar. Three minutes of passive rest was provided between trials to limit performance fluctuations resultant from fatigue and decrease the risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008).

5.2.4 Equipment

To quantify COD performance, a radar gun (Stalker ATS Pro II, Texas, USA) with a sampling rate of 47 Hz using a Ka-Band transmitter, was set 12.56 m from the start/finish line, linear to the running line, at a height of 1 m to approximate for athlete COM (see Figure 8). This set-up enabled athletes' velocity to be tracked over the total shuttle distance (i.e., 18.28 m) and accompanying split phases to be quantified (see Table 20).

Table 20: Pro-agility phase and sub-test variable description, calculation, and quality.

Split	Name	Variable Description	Calculation	Quality
1	Acceleration 1 (ACC1)	Average velocity during ACC1 – from movestart (start/finish line, A) to midpoint before COD1 (A to B)	Mean of the filtered /forced velocity signal during ACC1 – from movestart (start/finish line, A) to midpoint before COD1 (A to B)	Initial acceleration ability
2	COD 1	Average velocity during COD1 – from midpoint before COD1 to midpoint after COD1 (B-C)	Mean of the filtered /forced velocity signal during COD1 – from midpoint before COD1 to midpoint after COD1 (B-C)	Moderate-intensity entry COD ability
3	Reacceleration 1 (REA1)	Average velocity during REA1 – from midpoint after COD1 to midpoint of test (start/finish line) (C to D)	Mean of the filtered /forced velocity signal during REA1 – from midpoint after COD1 to midpoint of test (start/finish line) (C to D)	Moderate-intensity reaccelerative ability
4	Acceleration 2 (ACC2)	Average velocity during ACC2 – from midpoint of test (start/finish line) to midpoint before COD2 (D to E)	Mean of the filtered /forced velocity signal during ACC2 – from midpoint of test (start/finish line) to midpoint before COD2 (D to E)	Final accelerative ability
5	COD 2	Average velocity during COD2 – from midpoint before COD2 to midpoint after COD2 (E to F)	Mean of the filtered /forced velocity signal during COD2 – from midpoint before COD2 to midpoint after COD2 (E to F)	High-intensity entry COD ability
6	Reaccelertion 2 (REA2)	Average velocity during REA2 – from midpoint after COD2 to end of test (start/finish line) (F to G)	Mean of the filtered /forced velocity signal during REA2 – from midpoint after COD2 to end of test (start/finish line) (F to G)	High-intensity reaccelerative ability
Sub-Test				
1+2	Moderate intensity 501 (501_{MI})	Average velocity from movestart (start/finish line, A) to midpoint after COD1 (A – C)	Mean of the filtered /forced velocity signal from movestart (start/finish line, A) to midpoint after COD1 (A – C)	Moderate-intensity entry and COD ability
2+3	Moderate intensity 105 (105_{MI})	Average velocity from midpoint before COD1 (B) to midpoint of test (start/finish line, D).	Mean of the filtered /forced velocity signal from midpoint before COD1 (B) to midpoint of test (start/finish line, D)	Moderate-intensity COD and accelerative ability
4+5	High intensity 501 (501_{HI})	Average velocity from midpoint of test (star/finish line, D) to midpoint after COD2 (F)	Mean of the filtered /forced velocity signal from midpoint of test (start/finish line, D) to midpoint after COD2 (F)	High-intensity entry and COD ability
5+6	High intensity 105 (105_{HI})	Average velocity from midpoint after COD2 (F) to finish of test (start/finish line, G)	Mean of the filtered /forced velocity signal from midpoint after COD2 (Gate 3, F) to finish of test (start/finish line, G)	High-intensity COD and accelerative ability
1+2+3	Static 5-0-5 (505_{Static})	Average velocity from movestart (start/finish line, A) to midpoint of test (start/finish line, D) (505_{Static})	Mean of the filtered /forced velocity signal from movestart (start/finish line, A) to midpoint of test (start/finish line, D) (505_{Static})	Moderate-intensity entry, COD, and accelerative ability
4+5+6	Flying 5-0-5 (505_{Flying})	Average velocity from midpoint of test (start/finish line, D) to finish (start/finish line, G) (505_{Flying})	Mean of the filtered /forced velocity signal from midpoint of test (start/finish line, D) to finish (start/finish line, G) (505_{Flying})	High-intensity entry, COD, and accelerative ability
1+2+3+4+5+6	Total time	Average velocity throughout entire test from movestart (start/finish line, A) to finish	Mean of the filtered /forced velocity signal from movestart (start/finish line, A) to finish (start/finish line, G)	All the above

5.2.5 Data Treatment

A description of all the variables of interest is presented in table 20. As can be seen in the table, multi-phase analysis identified four linear phases, and two COD phases within the pro-agility shuttle (see Figure 8). These phases assessed different physiological stresses often dependent on the entry velocity and therefore the decelerative-accelerative capability of the subjects (Spiteri et al., 2013; Spiteri, Newton, & Nimphius, 2015).

Speed radar data were obtained from the Stalker program (STATs software, Stalker ATS II Version 5.0.2.1, Texas, USA). Data was manually processed in the Stalker program software to remove unexpected high or low data points, likely resultant of limb movement, on the velocity-time curve (Simperingham et al., 2019). To prevent inter-observer variance, all trials were analyzed by the same person (J.F). After outliers were removed, files were imported into Matlab (MATLAB and Statistics Toolbox Release 2020a, The MathWorks inc., Natick, Massachusetts, USA) for further processing (S.D). Speed data was filtered using a 3Hz low pass 4th order Butterworth filter. Onset of movement and COD points were manually identified in the speed data. Speed data prior to the onset of movement, as well as any speed data points with a value less than that at the onset of movement were forced to zero. Distance data was obtained by integration of the processed speed data and used to determine the midpoint of the test, as well as the finish of the test (Figure 9). All further points of interest (i.e., phases and sub-tests) were identified from the distance data. Thus, each trial was processed independently, and all split velocities were relative to that trial specifically.

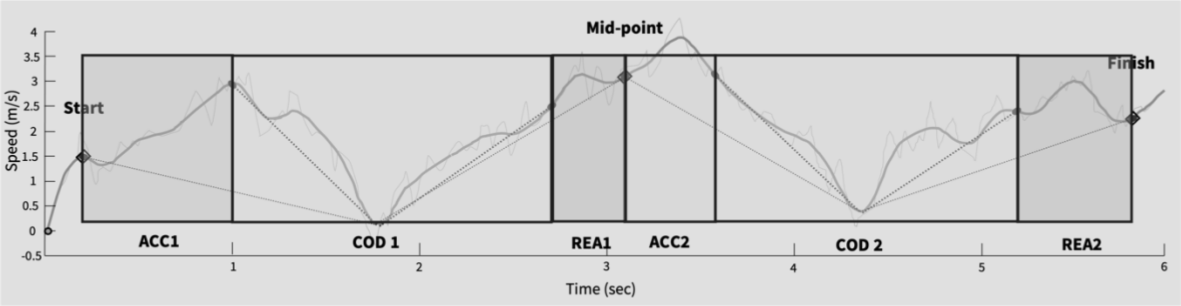

Figure 9: Pro-agility shuttle velocity-time curve.

5.2.6 Statistical Analysis

All statistical analysis was conducted using RStudio IDE (Version 1.4.869, 2009 – 2020 RStudio, PBS). The statistical analysis explored the intra-session, pairwise reliability of multi-phase pro-agility performance. A minimum of two eligible trials were averaged and within-subject variability measures were calculated. Normality of each outcome measure was confirmed using the Shapiro-Wilks test and homogeneity was confirmed by Levene's test. Descriptive statistics for each split represent the centrality and spread of the data that would be expected within a similar coach-led training setting (Bezodis, Salo, & Trewartha, 2012; Cahill et al., 2020). The percent change in mean, within-subject CV, ICC (two-way, mixed effects, absolute agreement, single measures), and ES (Hedges *g*) (Dankel & Loenneke, 2021; Koo & Li, 2016) were used to explore systematic change, absolute consistency, absolute agreement, and magnitude of change, respectively. Within-subject CVs were calculated using the root mean square approach (Bland & Altman, 1996). CVs of less than 10% were deemed acceptable as a percent of typical error (Uthoff et al., 2018). Categorisation of ICC was deemed as follows: 'very poor' (< 0.20), 'poor' (0.20 to 0.49), 'moderate' (0.50 to 0.74), 'good' (0.75 to 0.90) or 'excellent' (> 0.90) (Buchheit & Mendez-Villanueva, 2013). Magnitudes (g) were reported according to the following criteria: < 0.2 = trivial; 0.2-0.5 = small; 0.5-0.8 = moderate; > 0.8 = large (Cohen, 1988). Using IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA) a one-way ANOVA using repeated measures was used to determine whether between-day performance differed for total-time, each of the six phases and six sub-tests. A secondary one-way ANOVA was used to compare between phase performances of relative distances (e.g., ACC1 vs ACC2 and 505_{Flying} vs 505_{Static}) within session 3. To determine if systematic differences were presented between testing sessions 1-2 and sessions 2-3, and between phases of session 3, a Bonferroni pairwise comparison was used. For all outcome measures, 95% confidence levels were calculated, and statistical significance was established at $p <$ 0.05.

5.3 Results

The mean ± SD for each session's average velocity measures are displayed in Table 21. Multi-phase analysis revealed significant differences existed for REA2 ($p = 0.05$) and HI105 ($p = 0.04$) between session 1-2 ($p = 0.05$ and 0.04, respectively), and between sessions 2-3 ($p = 0.05$ and 0.04, respectively). Between sessions 1-2 mean change in average velocity for the pro-agility shuttle ranged from -4.19% to 1.94% and between sessions 2-3 the change in mean was between -0.93% to 4.25% for all variables. Change in mean was smaller, though not significant, between session 2-3 compared to session 1-2 for measures COD1 (-1.52% and 0.93%), 501_{MI} (-0.55% and 0.09%), 505_{Static} (-0.59% and -0.09%), and Total time (-1.06% and 0.85%).

Table 21: Pro-agility and sub-test descriptive statistics.

Split	**Mean (±SD) (m/s)**			**% change of mean (95% CL)**		**CV% (95% CL)**		**ICC (95% CL)**		**ES *g* (95%CI)**	
	Day 1	*Day2*	*Day3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*	*Day1-2*	*Day2-3*
Acceleration 1	2.73 ± 0.28	2.69 ± 0.19	$2.64 \pm 0.26^{\dagger A2, \dagger R1, \dagger R2}$	1.94 [-4.25, 8.13]	2.54 [-2.64, 7.73]	7.75 [1.72, 10.82]	7.07 [1.57, 9.88]	0.11 [-0.40, 0.56]	0.14 [-0.37, 0.58]	0.13 [-0.34, 0.59]	0.16 [-0.31, 0.63]
COD1	2.88 ± 0.19	2.93 ± 0.17	2.96 ± 0.15	-1.52 [-4.31, 1.28]	-0.93 [-2.81, 0.95]	4.47 [0.99, 6.25]	3.16 [2.29, 3.84]	0.58 [0.17, 0.82]	0.76 [0.46, 0.90]	-0.29 [-0.76, 0.19]	-0.25 [-0.72, 0.22]
Reacceleration 1	4.71 ± 0.31	4.72 ± 0.26	$4.76 \pm 0.36^{*R2, \dagger A1, *A2}$	-0.24 [-3.46, 2.97]	-0.59 [-3.90, 2.73]	4.47 [3.24, 5.43]	4.47 [3.24, 5.43]	0.51 [0.03, 0.79]	0.52 [0.06, 0.80]	-0.06 [-0.52, 0.41]	-0.14 [-0.60, 0.33]
Acceleration 2	5.00 ± 0.267	5.03 ± 0.18	$5.01 \pm 0.38^{\dagger A1, *R1, \dagger R2}$	-0.51 [-2.61, 1.60]	0.74 [-2.63, 4.10]	3.16 [2.29, 3.84]	4.47 [0.99, 6.25]	0.61 [0.19, 0.84]	0.32 [-0.20, 0.69]	-0.12 [-0.59, 0.34]	-0.04 [-0.42, 0.51]
COD2	2.91 ± 0.22	2.94 ± 0.18	2.88 ± 0.22	-0.71 [-3.82, 2.41]	2.18 [-0.901, 5.26]	4.47 [0.00, 6.62]	4.47 [0.99, 6.25]	0.58 [0.15, 0.83]	0.69 [0.35, 0.88]	-0.13 [-0.59, 0.34]	0.35 [-0.14, 0.82]
Reacceleration 2	4.36 ± 0.33	4.57 ± 0.41	$4.41 \pm 0.47^{*R1, \dagger A1, \dagger A2}$	-4.19* [-8.46, 0.08]	4.25* [0.41, 8.08]	7.07 [1.57, 9.88]	5.48 [3.31, 7.00]	0.70 [0.33, 0.88]	0.32 [-0.10, 0.67]	-0.49 [-0.98, 0.01]	0.53 [0.02, 1.04]
Sub-Test											
Moderate intensity 501	2.82 ± 0.16	2.84 ± 0.13	$2.84 \pm 0.14^{\dagger M105, \dagger H501, \dagger H105}$	-0.55 [-3.31, 2.22]	0.09 [-2.69, 2.86]	3.16 [0.70, 4.42]	3.16 [0.70, 4.42]	0.49 [0.02, 0.78]	0.34 [-0.18, 0.70]	-0.11 [-0.58, 0.35]	-0.01 [-0.48, 0.45]
Moderate intensity 105	4.71 ± 0.31	4.72 ± 0.26	$4.76 \pm 0.36^{\dagger M501, *H105, \dagger H501}$	-0.24 [-3.46, 2.97]	-0.59 [-3.90, 2.73]	4.47 [3.24, 5.43]	4.47 [3.24, 5.43]	0.51 [0.03, 0.79]	0.52 [0.06, 0.80]	[-0.06 [-0.52, 0.41]	-0.14 [-0.60, 0.33]
High intensity 501	3.39 ± 0.23	3.42 ± 0.178	$3.37 \pm 0.22^{\dagger M501, \dagger H105, \dagger M105}$	-0.87 [-3.31, 1.56]	1.68 [-0.70, 4.05]	3.16 [0.70, 4.42]	3.16 [0.70, 4.42]	0.68 [0.32, 0.87]	0.73 [0.41, 0.89]	-0.18 [-0.65, 0.29]	0.34 [-0.15, 0.81]
High intensity 105	4.36 ± 0.33	4.57 ± 0.41	$4.41 \pm 0.47^{*M105, \dagger H501, \dagger M501}$	-4.19* [-8.46, 0.08]	4.25* [0.41, 8.08]	7.07 [1.57, 9.88]	5.48 [3.31, 7.00]	0.32 [-0.10, 0.67]	0.70 [0.33, 0.88]	-0.49 [-0.98, 0.01]	0.53 [0.02, 1.02]
Static 505	3.09 ± 0.17	3.11 ± 0.13	$3.12 \pm 0.15^{\dagger F505}$	-0.59 [-3.05, 1.87]	-0.09 [-2.56, 2.39]	3.16 [0.70, 4.43]	3.16 [0.70, 4.42]	0.53 [0.07, 0.80]	0.42 [-0.08, 0.75]	-0.13 [-0.60, 0.34]	-0.04 [-0.51, 0.42]
Flying 505	3.58 ± 0.24	3.64 ± 0.19	$3.57 \pm 0.23^{\dagger S505}$	-1.59 [-3.89, 0.72]	2.08 [-0.40, 4.55]	3.16 [0.00, 4.93]	3.16 [0.00, 4.93]	0.69 [0.34, 0.87]	0.70 [0.35, 0.878]	-0.34 [-0.81, 0.14]	0.41 [-0.08, 0.89]
Total-Time	3.30 ± 0.18	3.33 ± 0.14	3.31 ± 0.17	-1.06 [-2.97, 0.85]	0.85 [-1.26, 2.97]	3.16 [2.29, 3.84]	3.16 [2.29, 3.84]	0.69 [0.35, 0.88]	0.64 [0.24, 0.85]	-0.28 [-0.75, 0.20]	0.17 [-0.30, 0.64]

* = significance difference $p < 0.05$, † = significant differences $p < 0.001$. A1 = Significantly different to Acceleration 1, R1 = Significantly different to Reacceleration 1, A2 = Significantly different to Acceleration 2, AR2 = Significantly different to Reacceleration 2, C1 = Significantly different to COD1, C2 = Significantly different to COD2, M501 = Significantly different to Moderate Intensity 501, M105 = Significantly different to Moderate Intensity 105, H501 = Significantly different to High Intensity 501, H105 = Significantly different to High Intensity 105, S505 = Significantly different to Stationary 505, F505 = Significantly different to Flying 505.

Absolute consistency ranged from 3.16% to 7.75% for both days. Averaged CV between sessions 1-2 was 4.52% and between sessions 2-3 was 4.22%. All variables presented absolute consistency <10% across all sessions. Absolute agreement ranged from “very poor” to “moderate” (ICC = 0.11 to 0.70) between sessions 1-2 and ranged from “very poor” to “good” (ICC = 0.14 to 0.76) between sessions 2-3. Average absolute agreement was “moderate” between both sessions 1-2 and 2-3 (ICC = 0.54 vs 0.52, respectively).

A one-way ANOVA showed significant differences in session 3, between ACC1 and ACC2 ($p < 0.001$), REA1 and REA2 ($p \leq 0.01$). Significant differences were reported for 501_{MI} when compared with 105_{MI}, 501_{HI}, and 105_{HI} ($p < 0.001$), between 105_{MI} and 105_{HI} ($p = 0.01$), and between 501_{HI} and 105_{HI} ($p < 0.001$). 505_{Static} and 505_{Flying} were also found to be significantly different ($p < 0.001$) in session 3.

5.4 Discussion

This is the first article to report the reliability of a multi-phase analysis for the pro-agility shuttle using radar technology. It was of interest to the authors to determine whether velocity profiling, using radar technology, was able to assess performance for phases of the pro-agility shuttle. In doing so, two acceleration, two reacceleration, two COD, and six additional sub-test measures were identified, together with overall performance (i.e., total time) in the pro-agility shuttle for team sport athletes. The main findings of this study were that only REA2 and 105_{HI} showed significant differences between sessions 2-3, all variable measures met the acceptable thresholds for absolute consistency between sessions 2-3, all measures showed “very poor” to “good” absolute agreement between sessions 2-3, and sub-test measures of relative distances and phases (i.e., ACC1 vs ACC2, REA1 vs REA2, and $105_{HI/MI}$ vs $501_{HI/MI}$) were significantly different ($p \leq 0.01$). It was hypothesized that radar technology would provide reliable measures when assessing multi-phase pro-agility shuttle performance, with greatest reliability being observed in the later linear phase (REA2/ACC2), but the variance in absolute agreement unequivocally dispute this.

Measures of absolute agreement (i.e., ICC) demonstrated that there is high variance between-subject performance, this demonstrated “very poor” to “good” reproducibility in the rank order of the subjects. Showing radar can be used to assess multi-phase performance in pro-agility shuttle with similar confidence as GPS for COD (ICC = -0.02 – 0.73) (Jennings et al., 2010; Vickery et al., 2014). However, given the importance of obtaining both absolute agreement and absolute consistency, solely using ICC or CV as an indicator of reliability may not provide ample power (Atkinson & Nevill, 1998). The observed ICC and CV values may be due to efficacy and error of the radar gun in this context. The acceptable absolute consistency (CV), yet the less than “moderate” levels of ICC during the ACC1, ACC2, and REA2 phases may be due to the change in distance of the lumbar point, where radar is focused, and subject COM height as they change posture during the different phases of the test (Bezodis et al., 2012). This would contribute to performance reliability between trials, attributed to the noise in the radar data and post-processing techniques (Simperingham, Cronin, & Ross, 2016).

Although the sub-test measure of 105_{HI} showed acceptable absolute consistency (CV <10%) and moderate agreement (ICC = 0.70), velocity was found to be significantly different between sessions 1-2 and 2-3. This was also seen in the REA2 phase, between sessions 2-3 ($p < 0.05$). This would be expected as the 105_{HI} subtest includes the REA2 phase of the pro-agility shuttle, contributing to the reported performance and reliability of findings. Nonetheless, pro-agility outcome measures possessing “moderate” or better ICC values (i.e., COD1, REA1, COD2, 105_{MI}, 501_{HI}, 105_{HI}, 505_{Flying} and Total time) may be used to reliably rank performance between testing occasions (Mungovan, Peralta, Gass, & Scanlan, 2018). Mungovan et al. (2018), also identified outcome measures (Net-Test) possessing acceptable absolute consistency values may be consistently used for player selection, talent identification, and isolated monitoring. Therefore, indicating multi-phase analysis of the pro-agility can consistently identify intra-individual variation over repeated testing sessions (i.e. changes in performance between testing occasions).

Radar works on the Doppler effect, which calculates velocity based on the altered frequency of the returned signal of radio waves (Gander et al., 1994; Simperingham et al., 2019). Meaning, that if subjects do not run directly in-line to the position of the radar, then an angle error will result in the measured velocities that are variable to the actual velocity of the subject. Reliability differences between ACC1 compared to ACC2 and REA1 compared to REA2 may be attributed to a variation in movement line and change in body position when entering and exiting a COD at different velocities. For example, lower entry velocities from ACC1 compared to ACC2 lead to better reaccelerative ability out of the COD in REA1 compared to REA2. Further, variation from movestart where the subject turns 90° as they may not move in a straight line and try to correct themselves would also result in error, evident in the variable results of ACC1.

Variation in the location at which deceleration and maximal acceleration occur between subjects is probable and would contribute to variations in performance (Ashton & Jones, 2019). While variation was predominantly consistent, the significant differences between phases suggest that each phase measures different components within the pro-agility shuttle. For instance, the significant average velocity differences between the first and second phases of acceleration ($p<0.001$) and reacceleration ($p<0.05$), could be explained by the different accelerative and decelerative requirements experienced throughout the pro-agility shuttle, and may be due to individual muscular or mechanical capabilities of subjects (Dos' Santos et al., 2017; Green, Blake, & Caulfield, 2011; Spiteri, Newton, Binetti, et al., 2015). Therefore, we suggest that the phases are separate athletic qualities and should be measured as such. By doing so, practitioners can identify which phases within the COD assessment an athlete needs to work on, and programme effectively to improve it. Regarding the reliability of findings, previous research (Simperingham et al., 2019) has found radar to consistently measure sprint performance over 20 m (ICC = 0.91, CV = 1.2), and multi-phase analysis of the pro-agility has been found to be reliable when using timing lights (Forster et al., 2021a). Therefore, it is difficult to truly decipher whether performance variation is resultant of biological or technological variability. Nonetheless, velocity-profiling of the pro-agility shuttle phases and sub-tests using radar possessed lower ICC when compared with the findings of timing lights by Forster et al. (2021a) (Chapter 4) for all measures (ICC = 0.14 – 0.76 vs. 0.90 – 0.99, respectively). Although similar populations were used in the current study and that of Forster et al. (2021a), the conflicting findings of multi-phase analysis between radar and timing light technologies indicate that contemporarily timing lights provide the most consistent measures of phases and sub-tests within the pro-agility shuttle. We suggest timing lights be used over radar technology until improved filtering techniques or laser technology can be used.

Practitioners should be aware of the limitations of this study and using radar. This study did not measure the differences between force-dominant or velocity-dominant individuals (Simperingham et al., 2016). Although not assessed in the current study, differences in the location at which deceleration and maximal acceleration occur in each individual are probable and may contribute to variations in performance. Therefore, it is suggested future research identify phases based on the acceleration and deceleration data of the velocity-time curve. The ability for radar to assess the pro-agility shuttle is based on subject COM displacement and not test distance. This presents the greatest limitation of the technology in this context and therefore in this study. While subjects reach in and touch the line, which would be the correct technique, the displacement is measured from the COM (i.e., before the COD line). Therefore, during COD actions, the COM does not travel the full distance equating to the total pro-agility distance, creating a deficit in distance covered. Additionally, when it comes to providing practitioners with information, radar presents the need for post-processing before measures can be reported and explained. Therefore, timing lights are the preferred method at this time, until software and alternative technologies (i.e. linear position encoder) can be developed to more reliably assess COD performance. It is recommended that further research is required into velocity profiling multi-phase analysis of the pro-agility shuttle, using radar technology, to determine velocity changes in the different phases of the pro-agility shuttle.

5.5 Conclusion and Practical Applications

While radar can be used to differentiate between athlete's performance in sprinting, it is not a reliable enough measurement to determine inter-individual performance for all phases in the pro-agility shuttle. Although, radar may be used to assess inter-individual and intra-individual pro-agility shuttle performance in phases measures COD1, COD2, REA1, 105_{MI}, 105_{HI}, 501_{HI}, 505_{Flying}, and total time. However, based on the findings of this research, we recommend coaches interpret findings presenting less than or equal to moderate absolute agreement with caution. Due to the limitations in post-processing of the data required when using radar technology, timing light technology may be preferred for practitioners. The present findings demonstrate that multi-phase analysis of the pro-agility using radar velocity profiling can be used consistently to measure individual performance variation between testing sessions (intra-individual performance) and can be used for isolated monitoring. However, practitioners should consider the error that is present with changes to the COM displacement during COD. Further radar is not reliable enough to identify changes in rank-order between athletes (inter-individual performance) across all phases. The ability to discern between phases within the pro-agility shuttle, via multi-phase analysis, provides useful information about an athlete's ability to accelerate and change direction from different velocities. That information can then be used to guide individual training programmes. However, velocity profiling of the pro-agility shuttle needs to be investigated further and correlational analysis is required to determine the variance between the use of radar and timing light technologies.

Chapter Six. The Acute Effect of Forearm and Shank Wearable Resistance on Pro-agility Shuttle Performance in Team Sport Athletes.

6.0 Preface

Chapter 3 highlighted the specific and non-specific training methods which had been utilized to enhance pro-agility shuttle performance. As evident from the literature, both non-specific resistance training and specific speed and plyometric training methods can be used to promote the desired adaptations. Yet, no evidence attested to the effect of external resistance applied to the limbs on pro-agility shuttle performance. Therefore, the purpose of Chapter 6 was to conduct a cross-over design to investigate the acute effects that forearm and shank WR loading have on pro-agility shuttle performance. This provided practitioners with information relating to how limb-loading influenced the phases of the pro-agility shuttle and how it may be utilized within a COD training programme.

Chapter Six. The Acute Effect of Forearm and Shank Wearable Resistance on Pro-agility Shuttle Performance in Team Sport Athletes.

6.1 Introduction

Change of direction (COD) is an important physical quality required for athlete performance. The pro-agility shuttle is a test used to assess COD performance, and is utilised by practitioners for talent identification, monitoring of athlete performance and team selection (Sierer et al., 2008; Vescovi & McGuigan, 2008) in sports such as American football (Sierer et al., 2008), basketball (Banda et al., 2019), and rugby (La Monica et al., 2016). The pro-agility shuttle features a total of 18.28 m (20 yards) of linear sprinting and two 180° direction changes, with COD performance quantified as total time. Given that the pro-agility test incorporates accelerative, decelerative, and COD components, total-time as a single measure of performance lacks practicable diagnostic value in terms of providing insight into the individual components of performance within the test (Forster et al., 2021a; Nimphius et al., 2016; Nimphius et al., 2013). By simply inserting extra timing lights into the pro-agility test, Forster et al. (2021a) developed an advanced diagnostic protocol that was found to provide reliable measurement of acceleration, reacceleration, and COD phases as well as moderate- and high-intensity sub-tests (ICC >0.90, CV <4.42%) (for delineation see Chapter 4, Table 18). Practically, this information provides coaches and researchers with a reliable tool to assess more nuanced athlete physical capabilities and variations in performance.

Given the different physical and technical requirements of the phases comprising the pro-agility shuttle, it is important that training methods should be implemented appropriately, relative to the demands of the different phases and mimic specific actions performed for optimal transfer of adaptation (Falch et al., 2019; Forster, Uthoff, Rumpf, & Cronin, 2022b; Istvan Rydså & van den Tillaar, 2020). A recent review compared different training methods for developing pro-agility shuttle performance (Forster et al., 2022b) (Chapter 3), the main finding being that different types of training may lead to preferential improvements in the acceleration, deceleration, or COD phases of the pro-agility shuttle. Specifically: resisted or inclined sprinting may develop the linear acceleration phases; unilateral resistance training may promote increased strength to overcome the imposed forces during the deceleration and COD phases; multiplanar plyometrics could help enhance stretch-shortening cycle capabilities across different force vectors; and, a combination of two or more of these methods may enable simultaneous development of each of these qualities. However, it may be that muscle and movement specific overload, as in the use of WR, provides better adaptive outcomes for all phases of the pro-agility test.

WR is a method utilising light-weight body loading and has been shown to provide overload to high-velocity sport-specific tasks, with minimal disruptions to technique (Dolcetti et al., 2018; Macadam, Simperingham, & Cronin, 2018). One research group has looked at the effects of vest loading on pro-agility shuttle performance, (Inacio, Dipietro, Visek, & Miller, 2011) and reported a 3.1% slower pro-agility shuttle completion time when loads as little as 2% BM were attached to the torso. However, no research group has investigated the effects of limb loading on pro-agility shuttle performance. Loading the limbs is a highly modifiable resistive WR method leading to increased rotational overload, due to a multitude of loading patterns (Dolcetti et al., 2018; Feser et al., 2023; Macadam, Simperingham, et al., 2018; Marriner, Cronin, Macadam, & Storey, 2018; Martin, 1985). Compared to loading of the trunk, WR attached to the limbs can provide direct overload by altering the rotational inertia of the articular and muscular systems (Martin, 1985; Martin & Cavanagh, 1990). The influence of forearm (Macadam et al., 2019; Macadam, Simperingham, et al., 2018; Uthoff et al., 2020) or shank WR (Feser, Bezodis, et al., 2021; Feser, Macadam, Nagahara, & Cronin, 2018; Feser et al., 2023; Macadam, Simperingham, & Cronin, 2016; Simperingham et al., 2022) has primarily been investigated during linear sprint running, with loads ranging from 1-3% BM used over 5 to 20 m. Regarding shank loading, 2% BM loading has shown to significantly increase sprint time over 5 and 10 m (ES: 0.44 and 0.33, $p < 0.02$) (Feser, Bezodis, et al., 2021), and influence stride frequency and knee kinematics during the initial steps of acceleration (-2.1 to -15.5%, ES: 0.22 to 0.50, $p < 0.05$) (Feser et al., 2018; Feser et al., 2023). Furthermore, 3% BM shank loading has shown to significantly increase ground contact time (GCT) during the initial 1-2 steps of acceleration (5%, ES: 0.41 to 0.49), with significant increases in GCT, and stride frequency (5%, ES: 0.56 and -2%, ES: 0.32, respectively) during acceleration phase (steps 3-8) (Simperingham et al., 2022). When 2% BM was attached to the forearms, significant increases to step length (4.01%, ES=1.04) and 10 m acceleration time (2.1 to 2.7%, ES=0.46 to 0.54) were observed, with the findings attributed to the additional rotational inertia during arm swing promoting greater horizontal forward momentum (Macadam et al., 2019; Macadam, Simperingham, et al., 2018; Uthoff et al., 2020). Additionally forearm loading has shown significant increases in flight time, GCT, and step length (-5.3, 6.5%, and 2.1%, ES=-0.22, 0.73, and 0.22) respectively, and decreased step frequency (-4.1%, ES=-0.67) over a 20 m sprint (Macadam, Simperingham, et al., 2018), which is similar total distance to that of the pro-agility shuttle. Regarding limb loading and COD performance, recent investigation by Istvan Rydså and van den Tillaar (2020) found load of 2-3% BM attached to the shank significantly increased 90° COD split time ($p < 0.01$) in national level male football athletes.

It is the belief of the authors that WR loading may be used as a specific means to overload COD performance without unduly altering acute movement technique. To the authors' knowledge however, no researchers have compared upper versus lower body limb-loading or investigated the phase-specific influence of WR on pro-agility shuttle performance. Therefore, the aim of this study was to investigate the acute effects of arm and shank loading on pro-agility shuttle, phase, and sub-test performance to provide practitioners with practical applications for training with WR. It is hypothesised that shank loading will affect the linear phases the most given greater rotational inertia.

6.2 Methods

6.2.1 Experimental Approach to the Problem

Using an acute repeated measures cross-over experimental design, twenty-eight male team sport athletes performed three maximal effort trials of the advanced pro-agility shuttle using unloaded, loaded 1.5% BM WRf, and 1.5% BM WRs conditions over two testing occasions separated by seven days. Results of the loaded conditions were compared to unloaded, and WRf compared to WRs. A repeated measures ANOVA was used to assess whether differences exist between unloaded, WRf, and WRs pro-agility shuttle and phase performance.

6.2.2 Subjects

Twenty-eight male team sport athletes (age: 16.9 ± 0.85 years, height: 177 ± 7.21 cm: 70.6 ± 12.5 kg) volunteered to participate in this study. After being orally briefed on the methods and reading the information sheet, subjects provided their written informed consent, prior to participating in this study. Subjects were notified that they were free to withdraw from the study at any point. Inclusion criteria included: 1) healthy and free of injury, 2) actively participate in a field or court sport, and 3) have performed resistance training regularly (minimum of twice weekly) for six months prior. None of the athletes reported any musculoskeletal injuries prior to, or during the study. This research was approved by the Auckland University of Technology Ethics Committee and conformed to the Declaration of Helsinki.

2.2.3 Procedures

All athletes were familiar with the testing procedures and had worn the WR garments in training prior to volunteering to participate in this research. Testing was conducted on an indoor hardwood gym floor. Subjects attended two testing sessions. At the beginning of each testing session, the subjects completed a standardized warmup consisting of lower body muscle activation exercises, progressive sprint and COD drills interspersed with dynamic lower-body stretching, followed by three unloaded pro-agility trials at 70%, 90%, and 100% of maximum effort (Forster et al., 2021b). Thereafter, subjects randomly performed three pro-agility trials unloaded and three trials under a loading condition with either 1.5%BM attached to the forearm (WRf) or the shank (WRs). The order of loading conditions were randomised between testing occasions.

For the execution of the pro-agility run, subjects started in a three-point position with their left foot on a centreline, facing perpendicular to the running lane (Forster et al., 2021a). Timing started when the subject turned 90 degrees and sprinted 4.57 m (5 yards) to the left and ran through centre start/finish timing gate, touched the COD line with their left hand, the subject then immediately turned and ran 9.14 m (10 yards) to the other side and touched the COD line with their right hand, turning and running 4.57 m (5 yards) back through the middle line, finishing the test. Three minutes of passive rest was provided between trials to limit performance fluctuations from fatigue (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008).

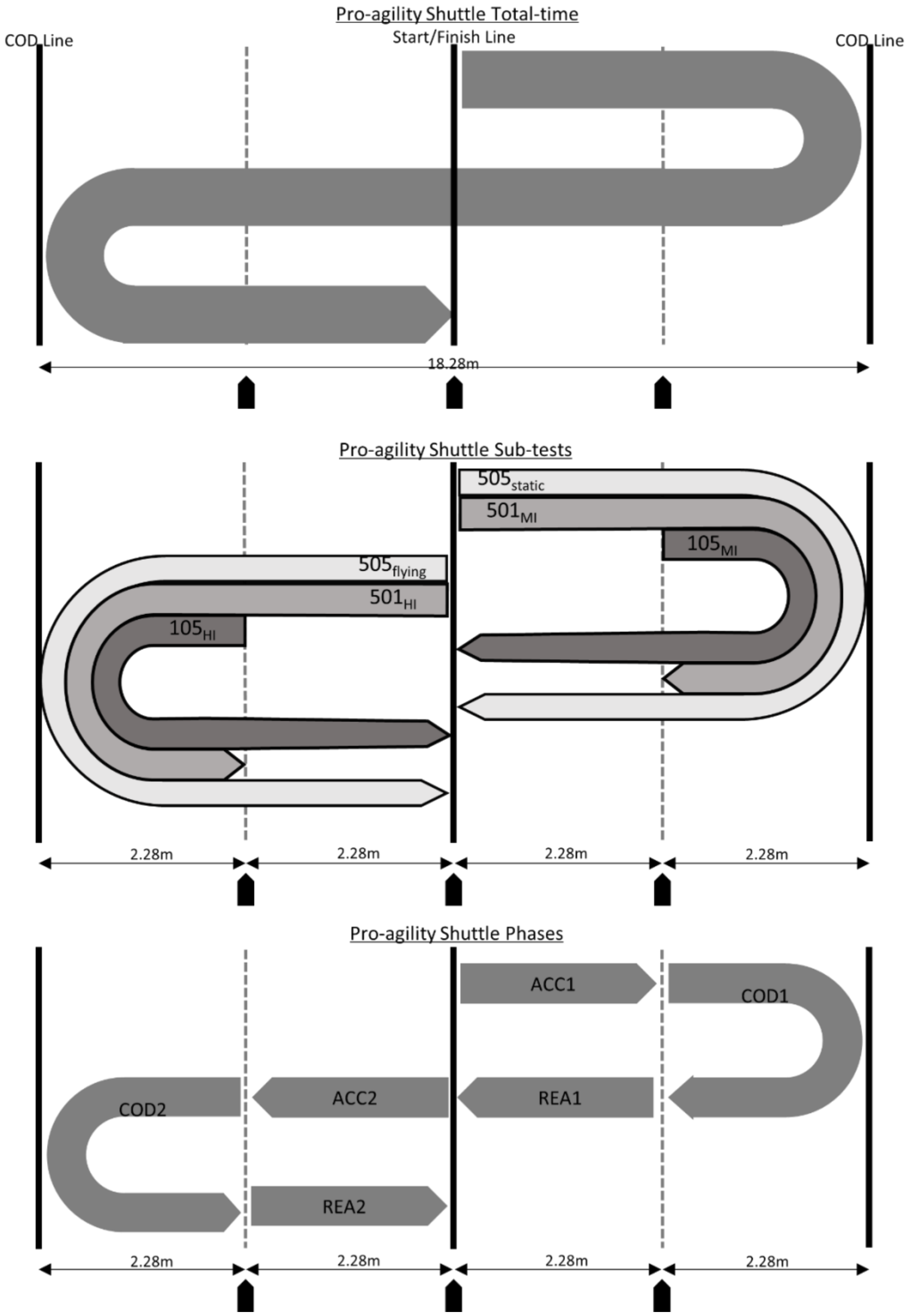

Figure 10: Advanced pro-agility shuttle diagnostic protocol

Lila™ Exogen™ Exoskeleton compression forearm and shank sleeves were worn with combinations of 50g, 100g, and 200g loads attached via Velcro. Loading was relative to subject BM for each condition (i.e. 1.5% forearm and 1.5% shank) (Figure 11). Timing lights (Smartspeed, Fusionsport, Finland) were set at the start/finish line and

2.28 m either side of the start line (i.e., 2.28 m between the start/finish and each COD line) (Figure 10). Timing light height was set at 0.85 m for the start/finish to correspond with approximate centre of mass and timing lights 2.28 m from each COD line were set at 0.75 m to account for subjects lower centre of mass during the COD (Morrison et al., 2015).

Use of the advanced pro-agility diagnostic protocol enabled total time (i.e., 18.3 m), phases, and associated moderate-intensity and high-intensity sub-tests (Table 18) to be measured via timing lights to determine individual measures (Forster et al., 2021a) (Chapter 4). A multi-phase analysis was used to partition the pro-agility shuttle into four linear and two COD phases (Figure 10), enabling performance values for 13 distinct measures to be ascertained and quantified from the timing light data. Six of the 13 were inclusive of 2 acceleration, 2 COD, and 2 reacceleration phases. Another six were sub-tests inclusive of 3 moderate intensity, and 3 high-intensity measures, and lastly, a single measure of total time. The reliability of these measures have been established previously reporting a CV of <4.42% across all variables and ICC ranging from 0.90 to 0.99 (Forster et al., 2021a).

Figure 11: Wearable resistance (WR) loading condition location.

6.2.4 Statistical Analysis

Statistical analysis were conducted via Microsoft Excel (version 16.0; Microsoft Corporation, Seattle, WA, USA) and IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA). Descriptive statistics (mean and standard deviation) were calculated, derived from the average of the two fastest trials from each condition for all variables of interest and used for subsequent analysis. Shapiro-Wilks test and Levene's statistic were used to assess and confirmed normality and homogeneity of variance (Garson, 2012). Between-condition effects were assessed using a one-way ANOVA using repeated measures. If a significant F-value was observed, Bonferroni post hoc analysis was used to determine pairwise differences between conditions. To quantify relative average individual change and magnitude of change in performance between conditions, percent change (%) and Cohen's *d* ES statistics were calculated (Cohen, 1988), and evaluated according to the following criteria: < 0.2 = trivial; 0.2-0.5 = small; 0.5-0.8 = moderate; > 0.8 = large (Cohen, 1988). The level of significance was set at $p < 0.05$ and 95% confidence intervals (CI) were used where appropriate.

6.3 Results

Descriptive statistics, percentage change, and ES for each loading condition and their comparisons can be observed in Table 22. In terms of the phase analysis and comparisons to the unloaded condition, forearm loading was found to effect one variable significantly, forearm loading resulting in a significantly slower ACC2 phase (6.98%, $d = 0.47$, $p = 0.03$). Shank loading was found to significantly effect one variable, resulting in significantly faster COD1 phase (-12.8%, $d = -0.49$, $p = 0.007$). Between forearm-shank comparisons revealed forearm loading to result in significantly slower performance in COD1 and ACC2 phases (6.52 to 14.0%, $d = 0.33$ to 0.54, $p = <0.048$), whereas, shank loading was significantly slower than forearm in COD2 (-12.0%, $d = -0.51$, $p = 0.038$).

With regards to the sub-test analysis and comparisons to the unloaded condition, shank loading was found to significantly effect four variables, resulting in significantly faster 501_{MI}, 105_{MI}, and 505_{static} sub-tests (-6.95 to -10.1%, $d = 0.41$ to 0.49, $p < 0.009$) and a slower 505flying time (5.88%, $d = 0.44$, $p = 0.005$). No significant changes were found for sub-tests in the forearm-control comparison. The between forearm-shank comparisons revealed forearm loading to result in significantly slower performance in 501_{MI}, and 505static sub-tests (9.74 to 12.6%, $d = 0.41$ to 0.49, $p = 0.003$), whereas, shank loading was significantly slower than forearm in 105_{HI} (-7.30%, $d = -0.50$, $p = 0.038$).

Regarding total-time, shank loading was found to be significantly faster than the unloaded condition (-10.6%, *d* = -0.90, *p* = 0.01). No significant differences were observed between forearm-unloaded or forearm-shank comparisons.

Table 22: Pro-agility shuttle, phases, and sub-test descriptive statistics

	Condition (Mean ± SD) (s)			**% Change in Mean**			**Effect Size (95% CI)**		
	Unloaded	*Forearm*	*Shank*	*Forearm - Unloaded*	*Shank - Unloaded*	*Forearm - Shank*	*Forearm - Unloaded*	*Shank - Unloaded*	*Forearm - Shank*
Total-time	5.36 ± 0.48	5.06 ± 1.02	4.79 ± 0.78	-5.60	-10.6*	5.34	-0.45 (-0.99 to 0.11)	-0.90 (-1.46 to -0.33)	0.24 (-0.78 to 0.30)
Pro-agility Phases									
Acceleration1	0.66 ± 0.13	0.65 ± 0.09	0.66 ± 0.09	-1.52	0.00	-1.54	-0.16 (-0.70 to 0.38)	0.12 (-0.66 to 0.42)	-0.05 (-0.49 to 0.59)
COD 1	1.41 ± 0.41	1.43 ± 0.44	1.23 ± 0.31	1.42	-12.8*	14.0†	0.06 (-0.48 to 0.59)	-0.49 (-1.04 to 0.05)	0.54 (-1.08 to 0.01)
Reacceleration 1	0.50 ± 0.07	0.51 ± 0.11	0.52 ± 0.09	2.00	4.00	-1.96	0.05 (-0.48 to 0.59)	0.24 (-0.30 to 0.77)	-0.15 (-0.34 to 0.86)
Acceleration 2	0.43 ± 0.02	0.46 ± 0.06	0.43 ± 0.05	6.98*	0.00	6.52†	0.47 (-0.10 to 1.04)	0.07 (-0.49 to 0.62)	0.33 (-0.09 to 0.22)
COD 2	1.37 ± 0.37	1.33 ± 0.37	1.49 ± 0.23	-2.92	8.76	-12.0†	-0.12 (-0.65 to 0.42)	0.37 (-0.17 to 0.91)	-0.51 (-0.03 to 1.05)
Reacceleration 2	0.41 ± 0.07	0.42 ± 0.08	0.44 ± 0.07	2.44	7.32	-4.76	0.29 (-0.26 to 0.83)	0.51 (-0.04 to 1.06)	-0.18 (-0.36 to 0.71)
Pro-agility Sub-tests									
Moderate-Intensity 501	2.09 ± 0.46	2.15 ± 0.49	1.88 ± 0.35	2.87	-10.1*	12.6†	0.01 (-0.54 to 0.55)	-0.54 (-1.08 to 0.01)	0.49 (-0.06 to 1.04)
Moderate-Intensity 105	1.91 ± 0.37	1.94 ± 0.51	1.75 ± 0.40	1.57	-8.38*	9.79	0.07 (-0.47 to 0.60)	-0.42 (-0.13 to 0.95)	0.42 (-0.13 to 0.95)
High-Intensity 501	1.80 ± 0.28	1.83 ± 0.34	1.89 ± 0.20	1.67	5.00	-3.28	0.01 (-0.55 to 0.57)	0.39 (-0.18 to 0.95)	-0.33 (-0.87 to 0.21)
High-Intensity 105	1.81 ± 0.39	1.78 ± 0.41	1.91 ± 0.25	-1.66	5.52	-7.30†	-0.12 (-0.66 to 0.43)	0.38 (-0.18 to 0.92)	-0.50 (-1.04 to 0.05)
505_{static}	2.59 ± 0.43	2.67 ± 0.54	2.41 ± 0.44	3.09	-6.95*	9.74†	0.04 (-0.50 to 0.59)	-0.43 (-0.99 to 0.10)	0.41 (-0.13 to 0.96)
505_{flying}	2.21 ± 0.33	2.28 ± 0.39	2.34 ± 0.26	3.17	5.88*	-2.63†	0.07 (-0.50 to 0.64)	0.44 (-0.13 to 1.01)	-0.31 (-0.85 to 0.23)

*: Significantly different to unloaded <0.05, †: Significantly different between loaded conditions <0.05

6.4 Discussion

The aim of this study was to determine the acute effects of 1.5% BM WR loading of the forearm and shank on COD pro-agility phases and total-time. The main findings were: 1) shank loading was found to significantly improve COD performance; 2) forearm loading was found to significantly reduce acceleration performance; 3) the sub-tests that were found to differ significantly to the unloaded condition were influenced by COD1; and 4) a greater reduction in total-time was observed with shank loading as compared to the unloaded condition.

Shank loading was found to significantly decrease COD1 time (-12.8%, *d* = -0.49) as compared to the unloaded condition. This finding was unexpected as it was hypothesised that shank loading would overload the linear phases of the pro-agility shuttle and result in slower times. However, this was not the case, the shank loading enhanced COD performance (decreased time), compared to both unloaded and forearm performance. When comparing the change observed in COD1 to the ACC1 and REA1 phases it was evident that the non-significant differences to the unloaded conditions indicated that the accelerative or reaccelerative phases were reasonably unaffected by the shank loading, so the effect was attributed to the turn itself. The authors are unaware of a finding like this being documented previously, and given 2-D kinematics were not recorded it is difficult to explain this finding, nonetheless it can be concluded that loading of the shank effected technique in some manner. We speculate that the shank loading resulted in the braking leg being pushed out further in front of the COM, creating a larger braking force, an earlier COD, resulting in a faster turn. A videographic approach, however, would be needed to determine the veracity of such a contention.

It appears that loading of the forearm significantly reduced linear speed performance during the ACC2 phase (6.98%) compared to unloaded. This may be attributed to 1.5% BM load being a larger relative load considering the mass of the forearm, compared to the mass of the shank. Since arm swing works to coordinate leg mechanics (Macadam, Cronin, Uthoff, Johnston, & Knicker, 2018; Uthoff et al., 2020) and transfers the horizontal momentum to and from the body (Macadam, Simperingham, et al., 2018), the greater inertial mass would require more muscular activation to decelerate the arms during ACC2 preceding the COD. Furthermore, greater inertia and consequently more momentum in the system, increases need for deceleration to occur earlier, reducing average velocity and increasing time during the ACC2 phase. Additionally, this lower entry speed (increased time) from ACC2 then meant that the deceleration demands leading into COD2 were lower than the

WRs and unloaded condition, hence explaining the trivial (*d* = 0.12) improvement in COD2 with WRf (-2.92%), and faster 105_{HI} and 505_{Flying} (-2.63 to -7.30%, *d* = -0.50 to -0.31) compared to the WRs condition.

Both the WRf and WRs conditions had faster pro-agility shuttle performance than the unloaded group, though only the WRs condition was significant. This indicates that although forearm loading was able to significantly alter the ACC2 phase, it seems differences during the COD phase had greater influence on total-time than the linear phases. It was interesting to note the utilisation of 1% BM shank loading had been found to significantly increase total-time performance in a 25 m COD test involving two 45° and two 90° CODs (Istvan Rydså & van den Tillaar, 2020). This dichotomy to the present findings indicates shank loading may differ in effect depending on the angle of COD, WRs may result in greater overload during smaller degrees of directional change i.e. less braking and propulsive requirements surrounding the smaller COD.

Differentiation between phases and sub-test measures within the pro-agility shuttle can provide practitioners with more information than a singular measure of total-time. This information can be used to identify areas of strength/power development and guide athlete training strategy and cueing. Forearm and shank WR were found to result in acute changes in pro-agility shuttle total-time, sub-test, and phase performance, and provided a non-invasive, velocity-specific modality for eliciting changes and overloading pro-agility shuttle performance. This is important as light-loading schemes during high-velocity movements can serve as an advantageous complimentary training method for athletes less skilled in traditional resistance training movements (Marriner et al., 2018). Limb-loading may enhance an athlete's control over movement, potentially resulting in better transferability of movement from training to performance in the athlete's sport (Dolcetti et al., 2018). However, practitioners should be aware that individual athlete responses may differ due to training history and neuromuscular capabilities (Macadam, Simperingham, et al., 2018). Furthermore, the reader should be cognizant of the limitations of this study. Firstly, only adolescent male subjects were included and therefore the effects of WR on pro-agility shuttle performance in other populations (e.g. females) is yet to be determined. Secondly, the study did not investigate the kinetic (e.g. horizontal propulsive and braking forces) and kinematic (e.g. joint segment changes) implications of different WR loading locations on components which constitute the pro-agility shuttle (i.e. acceleration, deceleration, high and low entry velocity COD). Further research is needed in these area.

6.5 Practical Applications

It appears that forearm and shank loading of 1.5% BM can be used to overload pro-agility shuttle performance. Loading of the forearms can be utilised to overload the acceleration phase of the pro-agility shuttle, without eliciting change ($p < 0.05$) in total-time performance, whereas, shank loading can be used to enhance moderate intensity COD ability and significantly affect total-time. While we recommend that caution be taken when interpreting individual athlete response to loading strategies, the use of this novel loading technology provides a unique training method for developing the linear phases and promoting faster COD performance within the pro-agility shuttle. Strength and conditioning practitioners may use this information to guide training strategy specificity and enhance transferability of training adaptation into sports performance on the field.

Chapter Seven. The Chronic Effects of Shank and Forearm Wearable Resistance training on 180° Change of Direction Performance.

7.0 Preface

In Chapter 6 it was determined that WRs and WRf loading may offer a novel training modality for development of pro-agility shuttle linear and COD phases. Additionally, long-term WR training may further enhance strength/power qualities and bolster the transferability of adaptation to COD performance. Therefore, the overarching intention of this chapter was to investigate the chronic effects of WRs and WRf COD training on pro-agility shuttle and associated power capabilities in athletes. The findings advance the knowledge and inform strength and conditioning practitioners as to how WRs and WRf can be implemented to further improve COD related adaptations.

Chapter Seven. The Chronic Effects of Shank and Forearm Wearable Resistance training on 180 Change of Direction Performance.

7.1 Introduction

The ability to change directions effectively is essential for field and court sport athletes (Eriksson et al., 2015; Sheppard & Young, 2006), with the assessment of this physical quality used for athlete development and selection (McGee & Burkett, 2003; Reilly et al., 2000). Specifically, the ability to change direction 180° is an integral action, regularly used in key game situations within sports like soccer, rugby, and American football (Bloomfield et al., 2007; Bourgeois et al., 2017; Dos'Santos, McBurnie, Thomas, Comfort, & Jones, 2020; Vescovi et al., 2007). As such, the pro-agility shuttle has been widely used within sports to determine athlete 180° COD ability (Forster et al., 2022a) (Chapter 2). For example, being one of six performance tests in the American football National Football League combine (McGee & Burkett, 2003; McKay et al., 2020), the pro-agility shuttle provides insights into an athlete's COD ability and can be used as a predictor of player performance, having great implications for draft number and earnings (McGee & Burkett, 2003). Therefore, effectively performing the repetitive accelerations, decelerations, and 180° CODs required in pro-agility shuttle may indicate an athlete's preparedness for performing at a high-level on the court or field.

Until recently, performance in the pro-agility shuttle was assessed on the total time to complete the test (Forster et al., 2021a). However, partitioning the speed and COD components within the pro-agility shuttle into distinct phases and sub-test measures has provided insight into athletic capabilities relating to acceleration and deceleration, reacceleration, and 180° COD (Forster et al., 2021a) (Chapter 4). This enables strength and conditioning practitioners to efficiently assess multiple athletic qualities within a single test, differentiating linear speed and COD performance. Further, practitioners can identify athlete strength and weaknesses during distinct moments within a COD movement (Forster et al., 2021a), and appropriately devise training strategies to enhance relative contraction-dependent (concentric, eccentric, and isometric) capabilities and technical demands of the pro-agility shuttle, thereby improve specific transference of training adaptations (Campos-Vazquez et al., 2015; Reilly et al., 2009).

A rise in popularity of WR training has emerged following several studies highlighting the transferability of this training method to athletic performance (Bustos et al., 2020; Feser, Bayne, Loubser, Bezodis, & Cronin, 2021; Istvan Rydså & van den Tillaar, 2020; Li, Li, Cui, & Wong, 2021; McMaster, Cronin, & McGuigan, 2009; Soria-Gila, Chirosa, Bautista, Baena, & Chirosa, 2015). Advancements in WR loading strategies is revolutionizing the way strength and conditioning (S&C) coaches think about how exercise is prescribed for athletic movement. One such method involves using light-limb loading with external loads as light as 50 g attached to distal segments of the body to provide a unique stimulus via increasing the rotational inertia of the involved limbs (Feser, Bezodis, et al., 2021). Researchers have demonstrated that attaching external load to an extremity provides a specific stimulus to train high-velocity athletic movements, such as sprinting (Bustos et al., 2020; Feser, Bayne, et al., 2021; Uthoff et al., 2020). Training high-velocity movement with WR loads as little as 1-2% body mass (BM) attached to the lower extremities (i.e. shank) have been found to significantly (*p* <0.05) decrease step frequency and step velocity (Hurst, Kilduff, Johnston, Cronin, & Bezodis, 2018). Whereas, significant increases in 10 m sprint time, step length, and GCT have been reported when loads are attached to the forearms during short accelerations (Macadam, Simperingham, et al., 2018; Uthoff et al., 2020). Previous researchers have demonstrated acute loading of the forearm or shank to overload COD ability (Chapter 6) (Forster, Uthoff, Rumpf, & Cronin, 2023; Istvan Rydså & van den Tillaar, 2020). With regards to chronic adaptations of WR, most studies have investigated the effect on linear sprinting (Bustos et al., 2020; Feser, Korfist, et al., 2021; Pajié, 2011). For example, 5% BM WR attached to the ankle found to significantly increase stride length (5.3%, ES = 0.43) and decrease stride frequency (-5.6%, ES = 0.54) in 25-50 m sprint performance after 6-weeks of training (Pajié, 2011). While, 1% BM shank loading has been found to increase velocity over a period of 9-weeks, although not statistically significant to the control group (Feser, Korfist, et al., 2021).

Previous researchers have reviewed the effectiveness of different training methods on the trainability of the pro-agility shuttle (Forster et al., 2022b) (Chapter 3). Resisted strength training has been found to be effective in enhancing pro-agility shuttle performance (0.28-3.14%, ES = 0.09-0.87) (Abt et al., 2016; Millar et al., 2020; Schilling et al., 2013; Speirs et al., 2016). However, more specific COD training, similarly resembling the biomechanics and contraction-dependent actions performed during COD action, was found to be similarly effective at enhancing pro-agility shuttle performance (2.61-3.96%, ES = 0.29-54) (Šišková et al., 2021; Wagner et al., 2014). Given these findings, there is clear benefit for using WR to modify the inertial properties of the limb, resulting in overload to muscles proximal to the WR. This may provide a specific means to provide stimulus to the musculotendinous structures during sport-specific movements, developing linear sprint performance and for specific COD training to develop COD ability (Dolcetti et al., 2018). Thus, it is of special interest to know if COD training with WR can benefit the development of COD ability in the pro-agility shuttle.

Provided that WR loading of the shank and forearm deliver unique overload to high-velocity movements, and COD-specific training is beneficial to enhancing pro-agility shuttle performance, including shank or forearm WR, a COD-specific training protocol may provide additional advantage to the enhancement of COD performance. Therefore, to understand this under explored area of research, the authors aimed to investigate the effects of COD-specific training utilizing upper or lower limb WR on pro-agility shuttle, sprint, strength and jumping performance in male youth athletes. It is hypothesized that forearm and shank WR would improve acceleration and COD performance as measured by the pro-agility shuttle, and associated multi-directional force capabilities, more so than without WR.

7.2 Methods

7.2.1 Experimental Approach to the Problem

To compare the effectiveness of a COD training programme utilising shank and forearm loaded WR, amateur team sport athletes participated in 6 weeks of COD training with forearm or shank WR. A third group of the same demographic served as the control and participated in the same COD training without any external load. Using a repeated measures experimental design, pre- and post-intervention data was collected for COD, speed, strength and jump performance for all groups. Specifically, an advanced pro-agility shuttle diagnostic was used to assess COD ability and linear sprint to assess athlete speed performance. As COD is multi-directional, countermovement jump (CMJ) and squat jump (SJ) were used to assess vertical force production, horizontal jump (HJ) was used to assess horizontal force production, left and right lateral jump (LJL and LJR) were used to assess lateral force production, and isometric mid-thigh pull (IMTP) was used to assess isometric peak force capabilities. Variables were selected based on their application to COD performance.

Table 23: Subject physical characteristics

Condition	N	Age M ± SD	Height M ± SD	Weight M ± SD
CG	14	16.6 ± 0.85	175.1 ± 9.71	69.2 ± 7.17
WRs	14	16.7 ± 0.86	176.2 ± 6.96	65.0 ± 5.76
WRf	14	17.1 ± 0.83	180.1 ± 6.75	77.4 ± 14.5
CG = control group, WRs = shank loaded group, WRf = forearm loaded group.				

7.2.2 Subjects

Forty-two male youth team sport athletes (age: 16 to 18 years, height (cm): 164.0 to 191.6 cm, weight (kg): 54.4 to 112.5 kg), were recruited to participate in this study (Table 23). Based on an effect size of 0.25, an alpha level of 0.05, statistical power of 0.8 using repeated measures within-between interaction design, a sample size of forty-two was determined to provide adequate power for this study. To be eligible for participation, subjects were: 1) of at least 16 years of age, healthy and free of injury for at least one month prior to the commencement of the study; 2) had not sustained any injuries in the past 6 months that could be aggravated by the tests and negatively affect their performance during testing and the training intervention; 3) actively participated in a field or court sport; and, 4) had performed resistance training regularly (2+ times per week) for six months prior to the commencement of the intervention. Upon completion of the pre-intervention testing session, yet prior to the start of the intervention, subjects were matched to on pro-agility shuttle total-time performance and then randomly assigned to either a control group (CG; N = 14), a forearm loaded WR group (WRf; N = 14), or a shank loaded WR (WRs; N=14) group. Before data collection, all subjects provided written informed consent, which was reviewed by the Auckland University of Technology Ethics Committee and conforms to the Declaration of Helsinki.

7.2.4 Pre- and Post-intervention Testing Procedures

Subjects of this intervention were required to attend pre-training and post-training testing sessions, 1-week before and after the 6-week training block for pre-intervention and post-intervention testing. Subjects were asked to refrain from intense exercise 48 h before each testing session. Prior to the intervention, subjects attended a familiarisation session where they were familiarised with the tests, the subjects were briefed on the study procedures and subject characteristics (i.e., age, height, BM, and level of competition) were collected, seven days prior to the commencement of pre-intervention testing. A standardized warmup consisting of progressive sprint and COD drills interspersed with dynamic lower-body stretching, followed by three pro-agility shuttle trials at 70%, 90%, and 100% (Forster et al., 2021b) preceded each session.

7.2.4.1 Pro-agility Shuttle

During each testing session, three trials of the advanced pro-agility shuttle (Figure 12) were performed and setup as previously described (Forster et al., 2021a). Three pairs of timing gates (SmartSpeed, Vald Performance, Australia) were set at the start/finish line and 2.28 m either side of the start line between each COD line. The start/finish line gate was set at 0.85 m to correspond with approximate height of centre of mass, while gates placed 2.28 m either side of the start line were set at 0.75 m, accounting for subjects' lower centre of mass during COD (Morrison et al., 2015). The subjects started on a centreline facing perpendicular to the running direction (Gillen et al., 2018). The subjects sprinted 4.55 m in their preferred direction to the 1st COD line touching the 1st COD line with their hand, then sprinted 9.10 m in the other direction, touching the 2nd COD line with their hand, and sprinted 4.55 m back to finish the test as they crossed the centreline, always turning on their dominant leg (Forster et al., 2021a). Movement prior to the initiation of the test (e.g. rocking back and forth) was not permitted. The only cue provided was encouragement of the subjects to complete the test as fast as possible. Three minutes of passive rest were provided between trials to limit performance fluctuations resultant from fatigue and decrease risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008). The advanced diagnostic of the pro-agility shuttle has shown good test-retest reliability (ICC = 0.90 to 0.99) (Forster et al., 2021a).

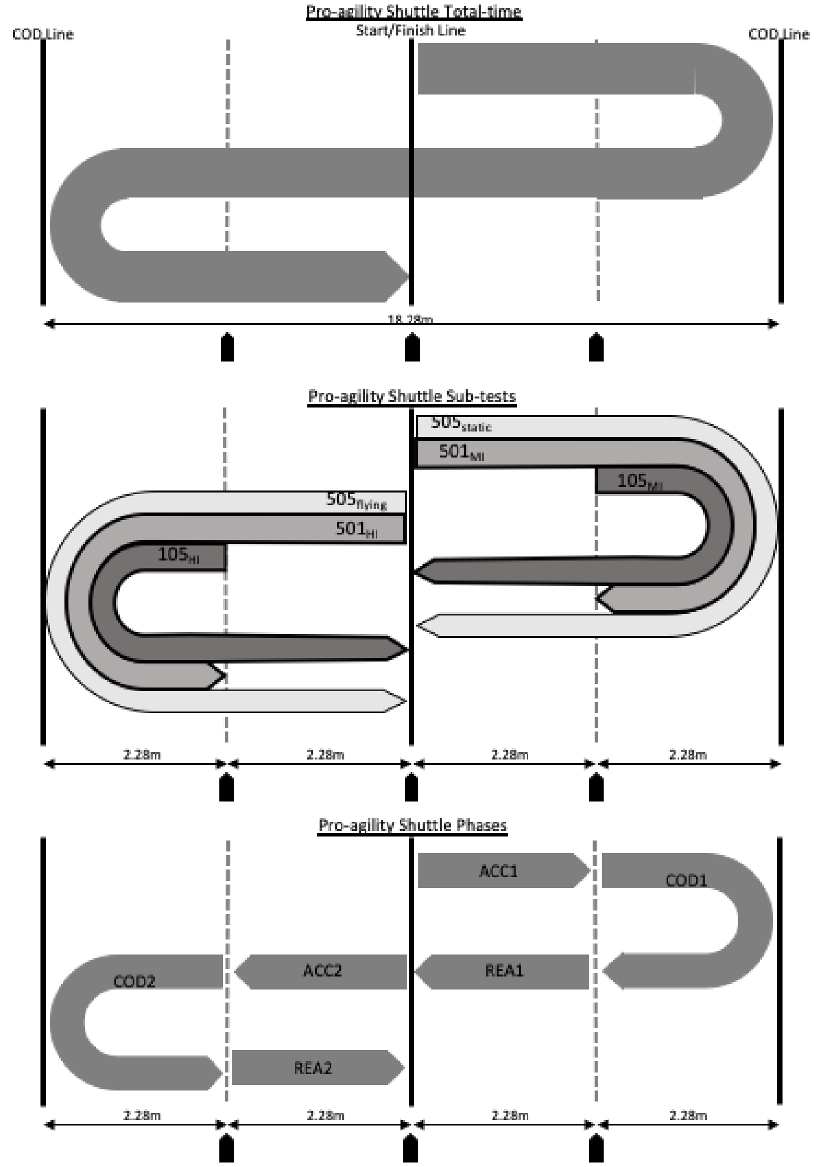

Figure 12: Advanced pro-agility shuttle set-up.
Total-time = pro-agility shuttle test; ACC1 = initial acceleration ability; COD1 = moderate-intensity entry COD ability; REA1 = moderate-intensity reaccelerative ability; ACC2 = final accelerative ability; COD2 = high-intensity entry COD ability; REA2 = high-intensity reaccelerative ability; 501_{MI} = moderate-intensity entry and COD capability; 105_{M}I = moderate COD and accelerative ability; 501_{HI} = high-intensity entry and COD capability; 105_{HI} = high COD and accelerative ability; 505_{static} = moderate-intensity entry, COD, and accelerative ability; 505_{flying} = high-intensity entry, COD, and accelerative ability (Forster et al., 2021a).

7.2.4.2 Linear Sprint

Three maximal intensity linear sprints over 18.28 m (corresponding distance of the pro-agility shuttle) were assessed using three timing lights (SmartSpeed, Vald Performance, Australia) to measures changes in sprint performance times for splits 0-2.28 m, 2.28-18.28 m, and 0-18.28 m. Each sprint was initiated from a two-point split stance position with the toes of their front foot placed 30 cm behind the first timing gate to prevent early triggering. Subjects were cued to sprint as fast as possible. Three minutes of passive rest was provided between trials to limit performance fluctuations resultant from fatigue and decrease risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008). 18.28 m linear sprint has shown good test-retest reliability (ICC = 0.88 to 0.91) (Gillen et al., 2018).

7.2.4.3 Isometric Mid-Thigh Pull

To measure lower-body isometric strength changes, isometric mid-thigh pull (IMTP) was used to measure peak force (Khamoui et al., 2011) via a strain gauge (Auckland University of Technology, Auckland, NZ), using hip and knee angles of 145° with knee angles determined using a handheld goniometer. A steel bar was positioned corresponding to the subjects second pull power clean position (approximately half-way between the iliac crest and the midpoint of the patella) (Dos'Santos, Thomas, Jones, McMahon, & Comfort, 2017). IMTP was initiated using the countdown “3, 2, 1, pull” with subjects ensuring that maximal effort be applied for five seconds (Haff, Ruben, Lider, Twine, & Cormie, 2015). Three minutes of passive rest was provided between trials to limit performance fluctuations resultant from fatigue and decrease risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008). IMTP has shown good test-retest reliability (ICC >0.86) (Dos'Santos et al., 2017).

7.2.4.4 Vertical, Horizontal, and Lateral Jump

Multi-planar jumping performance was assessed via four jumps: vertical squat (SJ) and countermovement (CMJ) jumps, horizontal (HJ), and lateral (LJ) jumps. Three trials of each jump type were performed, with the average performance used for subsequent analysis. A Vertec (Swift Performance Equipment, Wacol, Australia) was used to measure vertical jumping capabilities, whereby the CMJ was performed from a standing position with a preliminary countermovement (ICC = 0.89) (Papia, Bogdanis, Apostolidis, & Donti, 2018), and the SJ was initiated from a static squatting position (i.e., 4 second pause at the bottom of the eccentric phase) with a knee angle of approximately 90^{O} (ICC = 0.80) (Papia et al., 2018). A HJ test was used to assess bilateral horizontal force production capabilities (ICC = 0.95) (Markovic, Dizdar, Jukic, & Cardinale, 2004). Athletes started standing upright with the toes of both feet on a line and hands on their hips. They then jumped forward from the line as far as possible and landing in a stable bilateral position. Upon landing, distance was measured using a measuring tape affixed to the floor (Yamayo Measuring Tools, Tokyo, Japan) from the heel of the rearmost foot (Haff & Triplett, 2015). A LJ test (ICC = 0.97) (Meylan et al., 2009) was performed unilaterally to assess changes in lateral force production capabilities (Hewit, Cronin, & Hume, 2012). Athletes started the test by standing with one leg on a line with their hands on their hips and alternate leg flexed to approximately 90° at the hip and knee. They then jumped laterally (away from the direction of the stance leg) as far as possible, alongside the affixed measuring tape, landing bilaterally (Hewit et al., 2012). Upon landing, distance was measured from the lateral side of the rearmost foot (same leg used to jump). Three minutes of passive rest was provided between each jumping trial to limit performance fluctuations resultant from fatigue and decrease risk of injury (Lockie, Davis, et al., 2016; Vescovi & McGuigan, 2008).

Table 24: Periodized 8-week wearable resistance loading strategy for both WRf and WRs groups.

Week	Load placement (WRf and WRs groups)	Load (WRf and WRs groups)
1 (Pre-intervention testing)	-	-
2	Proximal	0.5% BM
3	Distal	0.5% BM
4	Proximal	1% BM
5	Distal	1% BM
6	Proximal	1.5% BM
7	Distal	1.5% BM
8 (Post-intervention testing)	-	-

4.2.4.5 Training Intervention

The training intervention lasted a total of six weeks, with pre- and post-intervention testing being conducted one week before and one week after the training period (i.e., weeks 1 and 8, respectively) (Table 24). The training intervention was performed twice per week, with sessions being separated by 48 h. The training intervention was implemented during the warm-up phase of two of their on-field training sessions over the course of the intervention. The intervention consisted of approximately 5 minutes standardised warm-up of low intensity dynamic movement combined with active stretching and 15 minutes of high-intensity acceleration, deceleration, and COD drills (Table 25).

Table 25: Intervention exercises

Exercise	Distance	Reps	Rest	Notes
Hip Swivels	N/A	5 each leg	90 sec	Standing in position and moving feet quickly 90° and back, working on dissociation between hips and shoulders
High knee run	10 m	3	90 sec	Thigh parallel to ground, pull toes to shin
Backwards pedals	10 m	3	90 sec	Start with slight flexion at the hip, push explosively through the ball of the foot, extending the swing leg behind.
Jump turns	10 m	3	90 sec	Facing a line, jump and turn 90° so one foot touches the line and then finish another 90° turn and sprint 10 m the way your back was initially facing
90° turn to sprint	10 m	4 each way	2 min	Alternating left and right 90° turns
Acceleration to lunge deceleration	10 m	4 each leg	2 min	Alternating left and right leg decelerations
3-step lateral shuffle to acceleration	10 m	4 each way	2 min	Alternating left and right shuffle
Crossover run to 180° COD into acceleration	10 m crossover run, 10 m acceleration	4 each way	2 min	Alternating left and right leg crossover steps. 180° turn and sprint 10 m the way your back was initially facing.

While all the groups performed the intervention, only those participating in the WRf or WRs groups performed the interventions with WR on the forearm or shank, respectively (Figure 13). Load was equally distributed across the anatomical planes (anterior, posterior, medial, and lateral) and location shifted from proximal to distal each week coinciding with an increase in load of 0.5% BM after every two weeks (Table 24). This was to ensure progressive overload could be achieved over the course of the intervention (Dolcetti et al., 2018).

Figure 13: Shank and forearm wearable resistance.

7.2.5 Statistical Analysis

Descriptive statistics (mean ± SD) were reported for all dependant variables. Shapiro-Wilks test and Levene's statistic were used to assess and confirmed normality and homogeneity of variance (Garson, 2012). Descriptive variables were quantified using IBM SPSS statistical software package (version 25.0; IBM Corporation, New York, USA). Within-group pre- and post-intervention differences in all performance tests for the CG, WRf, and WRs groups were assessed via paired t-tests. Between-group differences were assessed via a one-way repeated measures ANOVA on the change scores and Bonferroni post-hoc comparisons were used to determine between-group differences if a significant F value was observed. Practically meaningful differences within- and between-groups were assessed using percent changes in the mean, smallest worthwhile change (SWC), and ES. To depict individual responses to the training intervention, the SWC was calculated as 0.2 x pre-intervention pooled standard deviation for all groups and converted to a percentage for each performance variable. Individual responses were then identified as small (0.2 x SD), moderate (0.6 x SD), or large (1.2 x SD) (Hopkins, Marshall, Batterham, & Hanin, 2009). Cohen's *d* ES were calculated using the change score, by dividing the mean change by the pooled SD of the change score (Dankel & Loenneke, 2021) for within-group and between group changes. ES was reported according to the following criteria: < 0.2 = trivial; 0.2-0.59 = small; 0.6-1.19 = moderate; and >1.2 = large (Hopkins et al., 2009), and expressed using 95% confidence intervals. The level of significance was set at $p < 0.05$.

7.3 Results

The physical characteristics of the CG, WRs, and WRf groups did not differ significantly at baseline. The means, standard deviations, and effect sizes for each within- and between-group comparisons for the pro-agility shuttle are presented in Table 26. Graphical illustration of the within-group individual responses relative to the SWC in each condition are also presented in Figure 14.

Table 26: Within and between-group changes and effect sizes in pro-agility shuttle total-time and sub-tests.

Performance Test (seconds)	Group	Pre M(SD)	Post M(SD)	Performance Change %(SE)	Pre-Post Effect d(95% CI)	Between-Group Comparison	Intervention Effect d(95% CI)
Total-Time	CG	4.88 ± 0.17	4.90 ± 0.23	0.46% (1.07)	0.11 (-0.70 to 0.78)	WRs - CON	0.35 (-0.40 to 1.10)
	WRs	4.83 ± 0.31	4.99 ± 0.43	3.68% (2.99)	0.31 (-0.44 to 1.05)	WRf - CON	0.02 (-0.73 to 0.76)
	WRf	5.05 ± 0.31	5.01 ± 0.74	0.83% (3.36)	0.04 (-0.72 to 0.76)	WRs-WRf	0.22 (-0.52 to 0.97)
Sub-tests (seconds)							
501_{MI}	CG	2.10 ± 0.04	2.10 ± 0.15	0.31% (1.88)	0.04 (-0.73 to 0.76)	WRs - CON	-0.32 (-1.06 to 0.43)
	WRs	2.13 ± 0.10	2.05 ± 0.33	-3.39% (4.13)	-0.23 (-0.97 to 0.52)	WRf - CON	-0.37 (-1.12 to 0.38)
	WRf	2.22 ± 0.18	2.12 ± 0.30	-3.79% (4.42)	-0.26 (-0.84 to 0.64)	WRs-WRf	0.07 (-0.67 to 0.81)
105_{MI}	CG	1.89 ± 0.04	2.06 ± 0.11*	8.98% (1.48)	1.63 (-0.14 to 1.57)	WRs - CON	-0.61 (-1.36 to 0.15)
	WRs	1.92 ± 0.07	2.00 ± 0.16	4.61% (2.32)	0.54 (-0.22 to 1.29)	WRf - CON	-0.49 (-1.24 to 0.26)
	WRf	2.01 ± 0.15	2.05 ± 0.32	2.47% (4.79)	0.10 (-0.70 to 0.78)	WRs-WRf	0.17 (-0.57 to 0.92)
501_{HI}	CG	1.85 ± 0.05	1.83 ± 0.09	-1.37% (1.24)	0.38 (-0.86 to 0.63)	WRs - CON	0.05 (-0.69 to 0.79)
	WRs	1.88 ± 0.12	1.87 ± 0.22	-0.54% (3.53)	-0.07 (-0.81 to 0.67)	WRf - CON	0.78 (0.001 to 1.54)
	WRf	1.90 ± 0.09	1.99 ± 0.20	4.88% (2.78)	0.47 (-0.57 to 0.93)	WRs-WRf	-0.49 9-1.24 to 0.26)
105_{HI}	CG	1.82 ± 0.05	1.76 ± 0.17	-3.29% (2.38)	-0.36 (-0.88 to 0.61)	WRs - CON	0.28 (-0.47 to 1.02)
	WRs	1.85 ± 0.13	1.86 ± 0.267	0.89% (4.39)	0.02 (-0.72 to 0.77)	WRf - CON	0.07 (-0.67 to 0.82)
	WRf	1.90 ± 0.11	1.86 ± 0.27	-2.04% (3.91)	-0.16 (-0.80 to 0.68)	WRs-WRf	0.17 (-0.57 to 0.92)
505_{static}	CG	2.58 ± 0.05	2.69 ± 0.13*	4.22% (1.28)	0.89 (-0.42 to 1.13)	WRs - CON	-0.40 (-1.15 to 0.35)
	WRs	2.61 ± 0.09	2.65 ± 0.22	1.59% (2.16)	0.20 (-0.55 to 0.94)	WRf - CON	-0.43 (-1.18 to 0.32)
	WRf	2.72 ± 0.20	2.69 ± 0.37	-0.56% (4.14)	-0.07 (-0.77 to 0.71)	WRs-WRf	0.21 (-0.53 to 0.95)
505_{flying}	CON	2.26 ± 0.07	2.25 ± 0.19	-0.23% (2.09)	-0.03 (-0.75 to 0.73)	WRs - CON	0.14 (-0.60 to 0.88)
	WRs	2.28 ± 0.13	2.31 ± 0.24	1.54% (3.31)	0.10 (-0.64 to 0.84)	WRf - CON	0.69 (-0.07 to 1.46)
	WRf	2.32 ± 0.11	2.45 ± 0.23*	5.60% (2.43)	0.63 (-0.52 to 1.00)	WRs-WRf	-0.41 (-1.16 to 0.34)

Note: Total-time = pro-agility shuttle test; 501_{MI} = moderate-intensity entry and COD capability; 105_{M}I = moderate COD and accelerative ability; 501_{HI} = high-intensity entry and COD capability; 105_{HI} = high-intensity COD and accelerative ability; 505_{static} = moderate-intensity entry, COD, and accelerative ability; 505_{flying} = high-intensity entry, COD, and accelerative ability (Forster et al., 2021a)*; * = statistically significant* (*p* < 0.05).

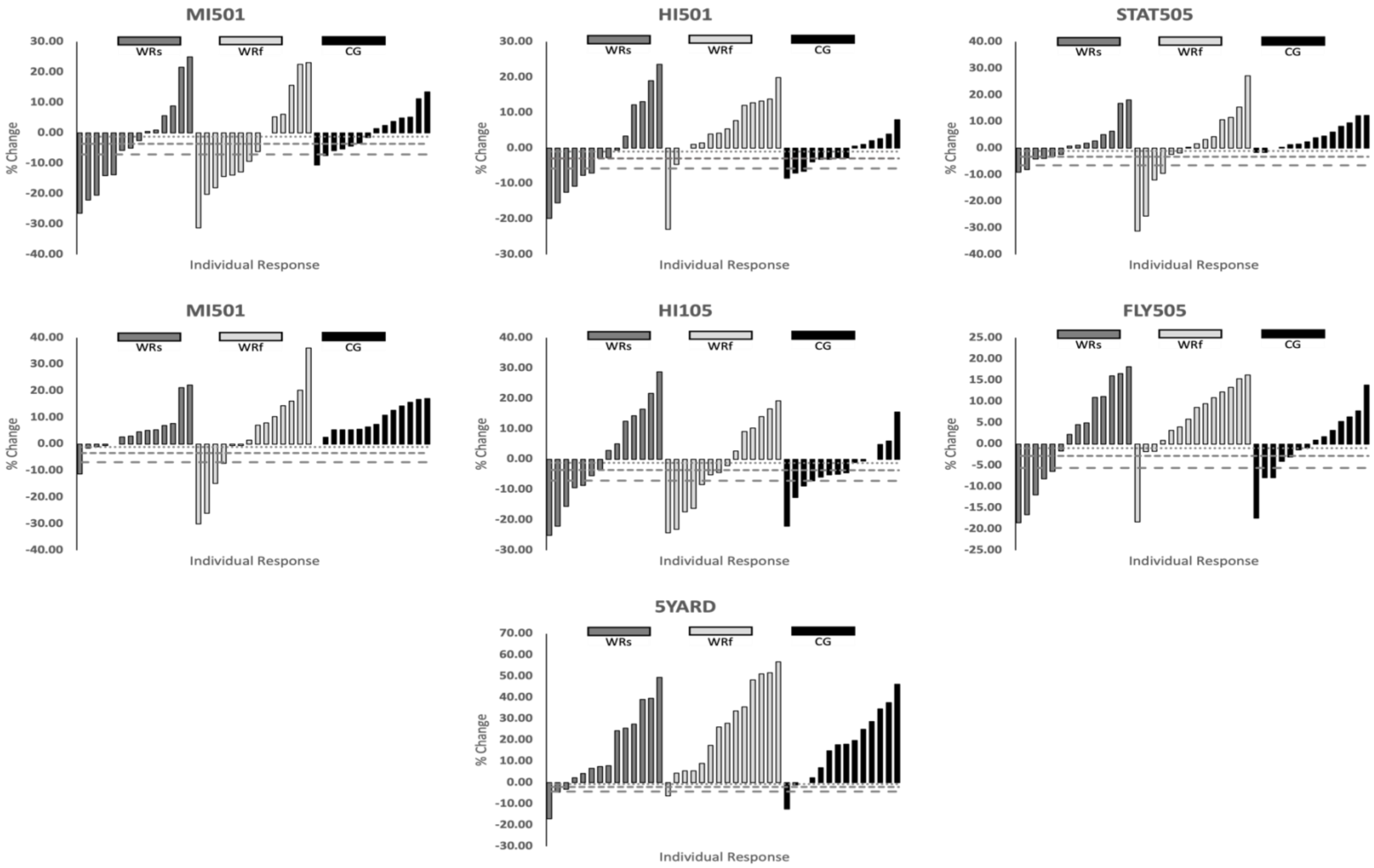

Figure 14: Pro-agility shuttle total-time and sub-test individual change score (%).

Note: •• = smallest worthwhile change (pre SD * 0.2); – – = moderate worthwhile change (pre SD * 0.6); — — = largest worthwhile change (pre SD * 1.2); Total-time = pro-agility shuttle test; 501_{MI} = moderate-intensity entry and COD capability; 105_{M}I = moderate COD and accelerative ability; 501_{HI} = high-intensity entry and COD capability; 105_{HI} = high-intensity COD and accelerative ability; 505_{static} = moderate-intensity entry, COD, and accelerative ability; 505_{flying} = high-intensity entry, COD, and accelerative ability (Forster et al., 2021a).

7.3.1 Total-Time and Sub-Tests

No significant within- or between-group effects were identified for pro-agility shuttle total time ($p > 0.05$; d = 0.02-0.35). A moderate increase in 505_{flying} (5.60%, $d = 0.63$, $p = 0.035$) was observed in the WRf group, whereas moderate to large increases in105_{MI} and 505_{static} times (4.22-17.04%, d = 0.89 to 1.63, $p < 0.005$) were noted in the CG. As can be observed from Figure 14, there are no clear trends in terms of the efficacy of WR on the variables of interest. The largest number of individuals improving above the SWC was found for WRs, 501MI (n = 8) and 501HI (n = 8), and for WRf, 501MI (n = 8) and 105HI (n = 8). Substantial improvements above the SWC were also observed for the 105HI (n = 8) and 505flying (n = 6) in the CG.

No significant between-group changes were observed for any COD variable, however, practically meaningful differences (moderate effect sizes) in 105_{MI} ($d = -0.61$, $p = 0.81$) were noted between the WRs-CG. Compared to the CG, practically meaningful decreases in 501_{HI} and 505_{flying} times (d = 0.69 to 0.78, p = 0.28 to 0.75) for the WRf group were also noted.

Table 27: Within and between-group changes and effect sizes in pro-agility shuttle phases.

Pro-agility shuttle Phases (seconds)		Pre M (SD)	Post M(SD)	% Change (SE)	Within-Group ES (95% CI)		Between-Group ES (95% CI)
ACC1	CG	0.69 ± 0.04	0.63 ± 0.03*	-8.60% (1.55)	-1.39 (-1.41 to 0.24)	WRs - CON	0.21 (-0.53 to 0.96)
	WRs	0.69 ± 0.04	0.64 ± 0.10	-6.89% (3.34)	-0.55 (-1.31 to 0.20)	WRf - CON	0.00 (-0.74 to 0.74)
	WRf	0.71 ± 0.07	0.64 ± 0.07*	-8.60 (1.55)	-1.39 (-1.41 to 0.24)	WRs-WRf	0.21 (-0.53 to 0.96)
COD1	CG	1.41 ± 0.02	1.47 ± 0.13	4.78% (2.42)	0.53 (-0.55 to 0.96)	WRs - CON	-0.45 (-1.21 to 0.30)
	WRs	1.44 ± 0.08	1.41 ± 0.25	-1.57% (5.00)	-0.10 (-0.84 to 0.64)	WRf - CON	-0.42 (-1.17 to 0.33)
	WRf	1.51 ± 0.13	1.48 ± 0.26	-1.21% (5.41)	-0.10 (-0.78 to 0.70)	WRs-WRf	0.38 (-0.73 to 0.75)
REA1	CG	0.48 ± 0.02	0.59 ± 0.11*	21.38% (5.98)	0.94 (-0.41 to 1.16)	WRs - CON	0.09 (-0.65 to 0.84)
	WRs	0.48 ± 0.02	0.60 ± 0.13*	24.11% (7.65)	0.84 (0.07 to 1.61)	WRf - CON	-0.24 (-0.98 to 0.51)
	WRf	0.50 ± 0.04	0.57 ± 0.16	14.35% (8.88)	0.40 (-0.60 to 0.90)	WRs-WRf	0.30 (-0.45 to 1.04)
ACC2	CG	0.44 ± 0.03	0.49 ± 0.06*	12.51% (3.63)	0.91 (-0.42 to 1.14)	WRs - CON	-0.57 (-1.33 to 0.18)
	WRs	0.43 ± 0.01	0.45 ± 0.05	4.93% (3.82)	0.33 (-0.41 to 1.08)	WRf - CON	0.87 (0.09 to 1.64)*
	WRf	0.42 ± 0.01	0.59 ± 0.18*	41.5% (11.8)	0.94 (-0.41 to 1.16)	WRs-WRf	-1.12 (-1.92 to -0.32)*
COD2	CG	1.42 ± 0.04	1.34 ± 0.09*	-5.61% (1.86)	-0.80 (-1.09 to 0.45)	WRs - CON	0.21 (-0.54 to 0.95)
	WRs	1.46 ± 0.12	1.42 ± 0.25	-1.90% (5.21)	-0.13 (-0.87 to 0.61)	WRf - CON	0.00 (-0.74 to 0.74)
	WRf	1.48 ± 0.09	1.40 ± 0.24	-5.10 (4.73)	-0.31 (-0.86 to 0.63)	WRs-WRf	0.16 (-0.58 to 0.90)
REA2	CG	0.41 ± 0.03	0.43 ± 0.14	5.39% (6.76)	0.15 (-0.69 to 0.80)	WRs - CON	0.20 (-0.54 to 0.94)
	WRs	0.40 ± 0.03	0.44 ± 0.09	12.33% (7.00)	0.45 (-0.30 to 1.20)	WRf - CON	0.16 (-0.58 to 0.90)
	WRf	0.42 ± 0.03	0.45 ± 0.07	9.36% (4.34)	0.56 (-0.54 to 0.97)	WRs-WRf	0.08 (-0.66 to 0.82)

Note: ACC1 = initial acceleration ability; COD1 = moderate-intensity entry COD ability; REA1 = moderate-intensity reaccelerative ability; ACC2 = final accelerative ability; COD2 = high-intensity entry COD ability; REA2 = high-intensity reaccelerative ability (Forster et al., 2021a); * = statistically significant ($p < 0.05$).

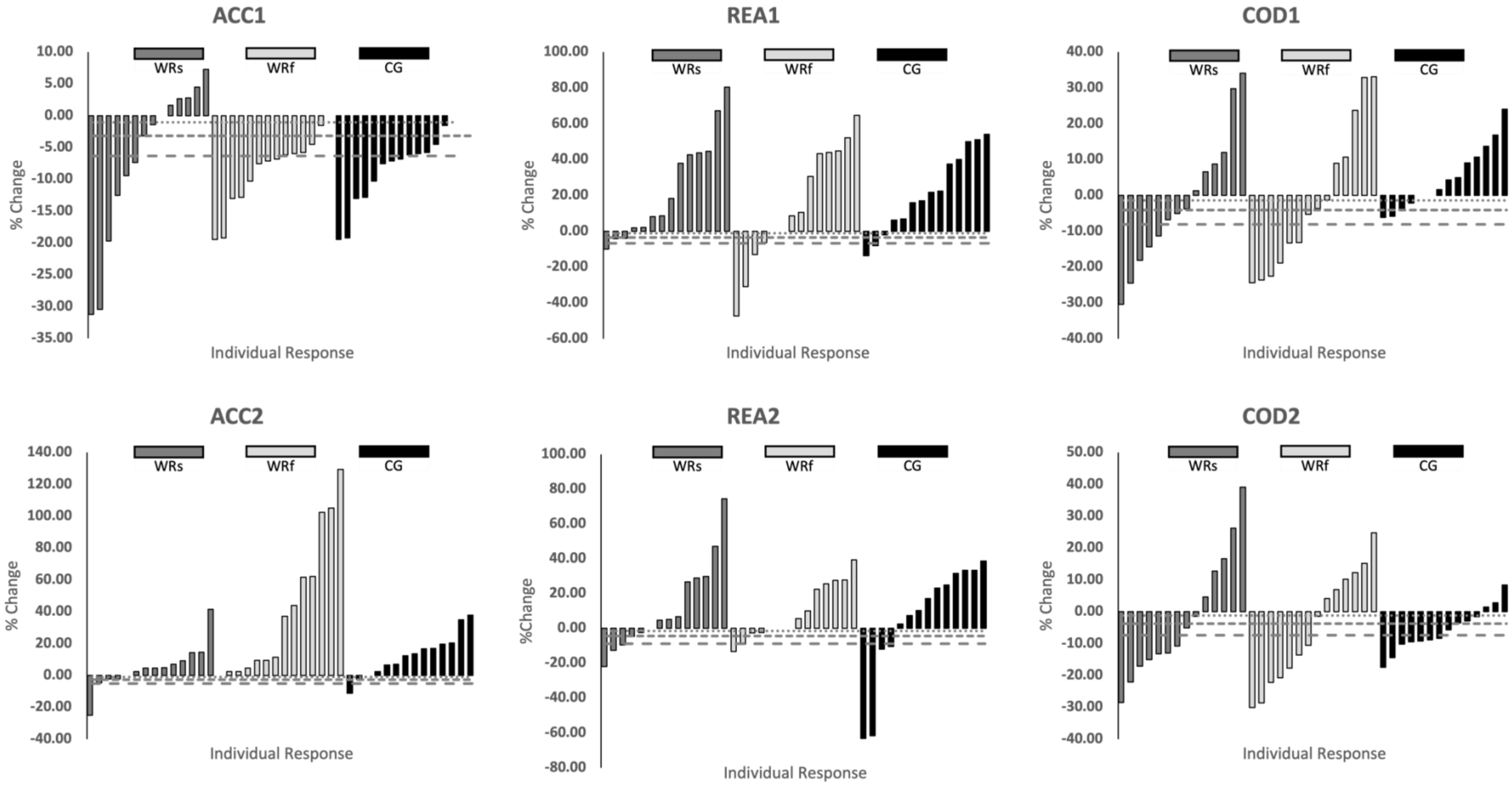

Figure 15: Pro-agility shuttle phase individual change score (%).

Note: •• = smallest worthwhile change (pre SD * 0.2); – – = moderate worthwhile change (pre SD * 0.6); — — = largest worthwhile change (pre SD * 1.2); ACC1 = initial acceleration ability; COD1 = moderate-intensity entry COD ability; REA1 = moderate-intensity reaccelerative ability; ACC2 = final accelerative ability; COD2 = high-intensity entry COD ability; REA2 = high-intensity reaccelerative ability (Forster et al., 2021a).

7.3.2 Phases

Within-group analysis of the phases is presented in Table 27. Decreases in pro-agility shuttle ACC1 time (-8.60%, *d* = 1.39, p = 0.037) and an increase in time was observed for ACC2 (41.54%, *d* = 0.94, p = 0.004) for WRf. A moderate increase in REA1 time (24.11%, *d* = 0.84, p = 0.008) was noted for WRs. Regarding the CG, moderately faster times were noted for ACC1 (-8.50%, *d* = -1.39, p <0.01) and slower times were observed for REA1 and ACC2 (12.51 to 21.38%, *d* = 0.91 to 0.94, p < 0.05). The individual changes for each of the pro-agility phases are depicted in Figure 15. There were no consistency in trends regarding efficacy of WR on the variables of interest, the largest number of individuals improving above the SWC was observed in the WRf and WRs for ACC1 (*n* = 14 and 8), COD1 (*n* = 8 and 8) and COD2 (*n* = 8 and 9) respectively. Substantial improvements above the SWC were also observed for the CG (*n* = 11) in COD1.

Moderate increases in ACC2 time (*d* = 0.87 and -1.12, *p* = 0.004 to 0.025) were noted in WRf when compared to the CG and WRs groups. Though not statistically significant, the CG increased ACC2 time (*d* = -0.57, P = 0.065) as compared to WRs .

Table 28: Within and between-group changes and effect sizes in linear sprint.

					Within-Group		**Between-Group**
Sprint (seconds)		PRE M(SD)	POST M(SD)	% Change (SE)	ES (95% CI)		ES (95% CI)
0-2.28 m	CON	0.71 ± 0.08	0.69 ± 0.06	-3.15% (2.25)	-0.37 (-0.89 to 0.61)	WRs - CON	-0.108 (-0.92 to 0.57)
	WRs	0.69 ± 0.09	0.65 ± 0.08*	-5.20% (2.37)	-0.65 (-1.41 to 0.11)	WRf - CON	-0.30 (-1.04 to 0.45)
	WRf	0.67 ± 0.07	0.62 ± 0.06*	-6.43% (1.97)	-0.93 (-1.15 to 0.41)	WRs-WRf	0.12 (-0.62 to 0.86)
2.28-18.28 m	CG	2.49 ± 0.29	2.44 ± 0.31	-1.85% (1.29)	-0.46 (-0.93 to 0.58)	WRs - CON	-0.60 (-1.36 to 0.15)
	WRs	2.48 ± 0.11	2.37 ± 0.12*	-4.20% (0.76)	-1.50 (-2.34 to -0.66)	WRf - CON	-0.12 (-0.86 to 0.62)
	WRf	2.36 ± 0.05	2.30 ± 0.06*	-2.48% (0.44)	-1.57 (-1.52 to 0.17)	WRs-WRf	-0.81 (-1.58 to -0.04)
0-18.28 m	CG	3.17 ± 0.37	3.13 ± 0.39	-1.44% (1.06)	-0.38 (-0.89 to 0.60)	WRs - CON	-0.55 (-1.30 to 0.21)
	WRs	3.12 ± 0.07	3.01 ± 0.11*	-3.50% (0.98)	-0.94 (-1.72 to -0.16)	WRf - CON	-0.26 (-1.00 to 0.48)
	WRf	2.99 ± 0.08	2.92 ± 0.08*	-2.31% (0.58)	-1.08 (-1.23 to 0.36)	WRs-WRf	-0.42 (-1.17 to 0.33)

Note: * = statistically significant ($p < 0.05$)

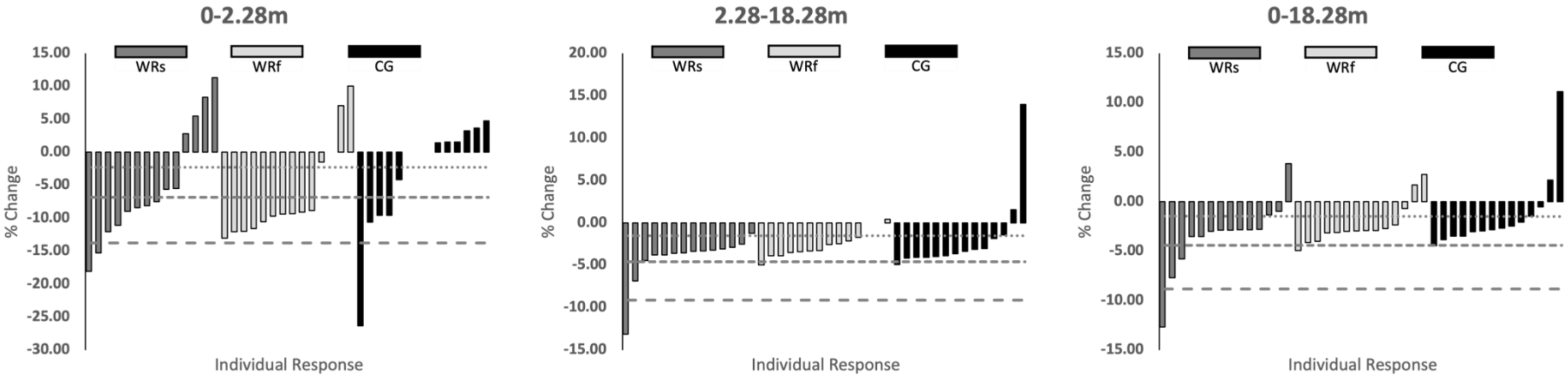

Figure 16: Linear sprint individual change score (%).

Note: •• = smallest worthwhile change (pre SD * 0.2); – – = moderate worthwhile change (pre SD * 0.6); — — = largest worthwhile change (pre SD * 1.2); 0-2.28m, 2.28-18.28m, and 0-18.28m: linear sprint; * = statistically significant (p < 0.05).

7.3.3 Linear Sprint

Decreased linear sprint times over all distances (-2.31 to -6.43%, *d* = -0.93 to -1.57, p < 0.04) were observed for WRf training, whereas moderate to large decreases in 0-2.28 m, 2.28-18.28 m, and 0-18.28 m time (-3.50 to -5.20%, *d* = -0.65 to -1.50, p < 0.03) were noted for WRs. No statistically significant or practically meaningful changes in linear sprint ability were noted in the CG. The individual changes for each of the linear sprint times are depicted in Figure 16. As can be observed a greater number of individuals improved with use of WR than without in 0-2.28 m sprint (WRs: *n* = 10, WRf: *n* = 10 vs CG: *n* = 5). The largest number of individuals improving above the SWC was found for WRs, 2.28-18.28 m (*n* = 13), and for WRf, 2.28-18.28 m (*n* = 10) and 0-18.28 m (*n* = 11). A large number of individuals improved above the SWC for 2.28-18.28 m (*n* = 11) and 0-18.28 m (*n* = 10) in the CG.

No significant between-group changes were observed for any linear sprint variable. However, compared to the CG, moderate decreases in 2.28-18.28 m and 0-18.28 m linear sprint times (*d* = -0.55 to -0.60, p = 0.069 to 0.105) were noted for WRs. There were no differences (p < 0.05) between WRf and the CG. Practically meaningful improvements in WRs 2.28 m-18.28 m time (*d* = -0.81, *p* = 0.059) was noted as compared to WRf training.

Table 29: Within and between-group changes and effects sizes in jump measures.

					Within-Group		Between-Group
Jump (cm)		PRE M(SD)	POST M(SD)	% Change (SE)	ES (95% CI)		ES (95% CI)
CMJ	CG	53.08 ± 6.65	57.05 ± 5.98*	8.26% (3.25)	0.68 9-0.50 to 1.03)	WRs - CON	-0.48 (-1.23 to 0.27)
	WRs	53.9 ± 5.94	54.94 ± 4.56	3.99% (2.21)	0.45 (-0.30 to 1.20)	WRf - CON	-0.67 (-1.43 to 0.09)
	WRf	59.25 ± 4.32	59.54 ± 6.46	0.06% (2.29)	0.07 (-0.72 to 0.77)	WRs-WRf	0.30 (-0.45 to 1.04)
SJ	CG	53.51 ± 6.83	56.00 ± 6.70	5.18% (2.93)	0.47 (-0.57 to 0.93)	WRs - CON	-0.51 (-1.26 to 0.24)
	WRs	52.57 ± 5.62	52.17 ± 4.19	0.03% (2.88)	-0.07 (-0.81 to 0.67)	WRf - CON	-0.79 (-1.56 to -0.02)
	WRf	58.02 ± 6.42	56.24 ± 8.31	-3.10% (2.68)	-0.32 (-0.87 to 0.62)	WRs-WRf	0.24 (-0.50 to 0.98)
HJ	CG	231.72 ± 16.16	235.25 ± 12.86	1.66% (0.83)	0.52 9-0.55 to 0.95)	WRs - CON	-0.08 (-0.82 to 0.66)
	WRs	216.65 ± 7.22	219.56 ± 10.05	1.36% (1.02)	0.36 (-0.39 to 1.10)	WRf - CON	-1.12 (-1.92 to -0.33)*
	WRf	233.95 ± 22.08	230.68 ± 24.01*	-1.47% (0.83)	-0.63 (-1.00 to 0.52)	WRs-WRf	0.90 (0.12 to 1.68)*
LJ RIGHT	CG	178.13 ± 21.24	182.07 ± 21.74*	2.25% (0.73)	0.83 (-0.44 to 1.10)	WRs - CON	0.07 (-0.67 to 0.81)
	WRs	165.30 ± 9.25	169.98 ± 10.61	3.11% (2.18)	0.34 (-0.40 to 1.09)	WRf - CON	1.58 (0.73 to 2.43)*
	WRf	173.26 ± 17.50	186.15 ± 17.59*	7.55% (1.03)	1.99 (0.01 to 1.82)	WRs-WRf	-0.77 (-1.54 to 0.00)*
LJ LEFT	CG	180.84 ± 15.75	184.82 ± 16.00*	2.23% (0.54)	1.09 (-0.35 to 1.24)	WRs - CON	0.77 (0.00 to 1.54)
	WRs	162.04 ± 11.62	171.36 ± 8.29*	6.05% (1.58)	1.02 (0.24 to 1.81)	WRf - CON	0.58 (-0.17 to 1.34)
	WRf	186.78 ± 26.08	195.36 ± 23.55*	5.02% (1.75)	0.81 (-0.45 to 1.09)	WRs-WRf	0.08 (-0.67 to 0.82)

Note: CMJ = countermovement jump; SJ = squat jump; HJ = horizontal jump; LJ = lateral jump; * = statistically significant ($p < 0.05$).

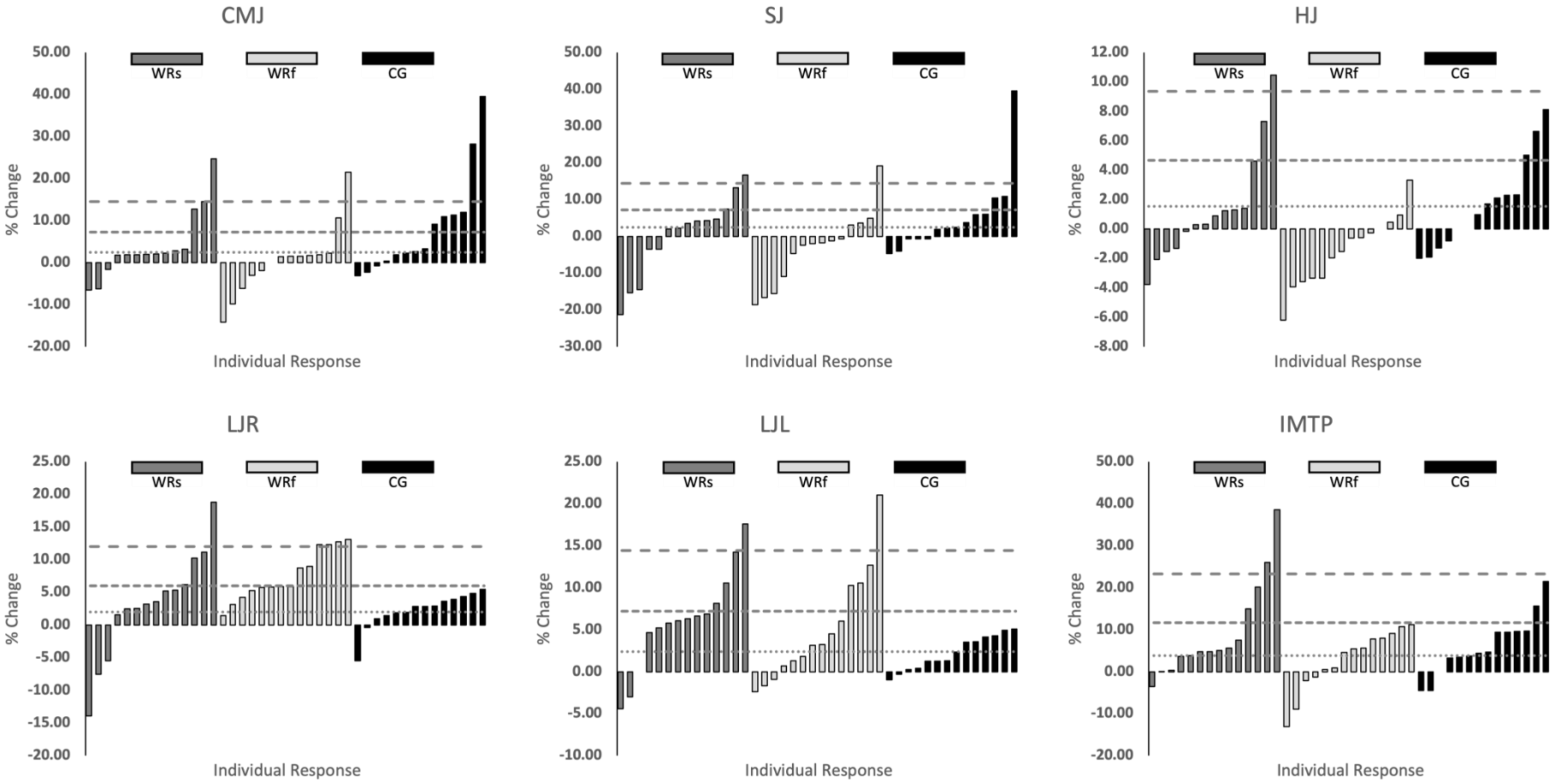

Figure 17: Jump measures and isometric peak force individual change score (%).

Note: •• = smallest worthwhile change (pre SD * 0.2); – – = moderate worthwhile change (pre SD * 0.6); — — = largest worthwhile change (pre SD * 1.2); CMJ = countermovement jump; SJ = squat jump; HJ = horizontal jump; LJR = lateral jump right; LJL = lateral jump left; IMTP = isometric mid-thigh pull.

7.3.4 Jump

Regarding jump performance (see Table 29), a moderate decreases in HJ distance (-1.47%, $d = -0.63$, $p = 0.035$) and increases in LJR and LJL distance (5.02 to 7.55%, $d = 0.81$ to 1.99, $p <0.01$) were noted for WRf, whereas, only moderately increased distances in LJL (6.05%, $d = 1.02$, $p = 0.002$) were noted for WRs. Increases in CMJ height (8.26%, $d = 0.68$, $p = 0.024$), LJR and LJL distances (2.23 to 8.26%, $d = 0.63$ to 1.09, $p < 0.024$) were observed in the CG. The individual changes for each of the jump measures are depicted in Figure 17. As can be observed there are no clear trends in terms of the efficacy of WR on the variables of interest. The largest number of individuals improving above the SWC in WRs and WRf were found for LJR ($n = 10$ and 13) and LJL ($n = 11$ and 8). Substantial improvements above the SWC in CMJ ($n = 8$), and LJR ($n = 8$) performance were noted in the CG.

Moderately shorter HJ distances ($d = -1.12$ to 0.90, $p = 0.001$ to 0.014) were noted for WRf, compared to CG and WRs, as a result of the CG and WRs group improving whereas WRf decreased HJ performance. The WRf increased in LJR distance ($d = 1.58$, $p < 0.05$) compared to the CG. Though not statistically significant, the WRf group increased LJR distance ($d = -0.77$, $p = 0.009$), compared to WRs, the CG increased CMJ height ($d = -0.67$, $p = 0.14$) compared to the WRf, and WRs increased LJL distance ($d = 0.77$, $p < 0.05$) compared to the CG.

Table 30: Within and between-group changes and effect sizes for isometric mid-thigh pull peak force.

				Within-Group		Between-Group	
IMTP		PRE M(SD)	POST M(SD)	% Change (SE)	ES (95% CI)		ES (95% CI)
Peak Force (N)	CG	1325 ± 212.70	1402 ± 216.90*	6.14% (1.90)	0.89 (-0.43 to 1.13)	WRs - CON	0.27 (-0.47 to 1.02)
	WRs	1194 ± 153.29	1300 ± 176.56*	9.42% (3.10)	0.84 (0.07 to 1.61)	WRf - CON	-0.35 (-1.10 to 0.40)
	WRf	1484 ± 311.41	1526 ± 338.51	2.76% (1.94)	0.38 (-0.60 to 0.89)	WRs-WRf	0.54 (-0.21 to 1.29)

Note: IMTP = isometric midthigh pull; * = statistically significant ($p < 0.05$)

7.3.5 IMTP

Increases in IMTP peak force (6.14 to 9.42%, $d = 0.84$ to 0.89, $p < 0.008$) were noted for the CG and WRs group. There were no significant or practically meaningful differences between-groups for IMTP peak force. A depiction of subject individual % changes relative to the worthwhile changes for IMTP is depicted in Figure 17. The largest number of individuals improving above the SWC for IMTP was in WRs ($n = 9$). Substantial improvements above the SWC were also observed for the WRf ($n = 8$) and CG ($n = 8$).

7.4 Discussion

This study was the first to investigate the effects of performing COD training with shank or forearm loading on pro-agility shuttle performance and associated linear speed, multi-directional jumping, and IMTP performance. The main findings were: 1) WRf decreased ($p < 0.05$) time in ACC1 phase time, while increased the time for ACC2 compared to the WRs and CG groups; 2) WR had no significant within- or between-group changes on COD phase time; 3) REA1 times were observed to be slower within-group for CG and WRs but not between-groups; 4) no significant between-group differences in total time were observed; 5) WR training produced significantly faster linear sprint times compared to unloaded training; 6) WRf loading significantly decreased HJ and increased LJR distance compared to the CG and WRs groups; and, 7) only significant within-group changes were observed for IMTP peak force in the WRs group, whereas no significant between-group changes were noted.

The effects of WR training on acceleration, was investigated In two phases, at the inception of the pro-agility test (ACC1) and prior to the second COD (ACC2). It was thought that WR loading would have minimal effect on the initial acceleration phase, as limb angular velocity began from zero and therefore the angular momentum of the limbs and resistive effects of WR would be the least during initial movement. For both the CG and WRf, within-group changes in ACC1 time decreased similarly, (-8.60%, d = -1.39 and -8.60, d = 1.39, respectively), while no changes ($p < 0.05$) were observed for the WRs condition. Even though the between-group differences were non-significant, it would seem that the forearm loading might be a better option as large improvements were produced in early acceleration (d = -1.39). Additionally, it was thought WR loading would have a greater effect on the final accelerative phase (ACC2), due to a higher limb velocity from the preceding run-in and greater angular momentum. This was not the case as moderate within-group increases (12.5 to 41.5%) in ACC2 times were found for the WRf and CG. Significant between group differences were noted between WRf and the other two interventions. In terms of ACC2 training WRf is not recommended, and shank loading may be a better option for overloading this phase given the non-significant changes. Overall it would appear that forearm loading is beneficial for initial accelerative performance yet detrimental to final accelerative phase performance.

Of interest was how WR training would effect COD capability, the two 180 degree CODs (COD1 and COD2) were of particular interest to the authors. The two CODs differed in terms of the entry velocities, in the second COD there was greater linear velocity on entry and therefore greater angular momentum to brake/arrest, and thereafter execute a controlled turn. The limb-loading undoubtedbly added to the angular momentum and the motor control needed to execute a 180 degree COD turn throughout the intervention. Therefore, it was thought adding resistive overload during decelerative actions around the COD that the times would be shorter especially during COD2. This contention was unsupported as no within-group or between-group differences were observed in the WR conditions and is most likely explained by the micro-loading and limb velocities (slow) during the COD providing minimal resistive overload i.e. the effects of additional angular momentum and angular kinetic energy from limb loaded WR were negligible.

The effects of WR training on reacceleration was investigated after the CODs (REA1 and REA2). The reaccelerations differ slightly from the acceleration phase as the musculotendinous system is pre-loaded with elastic strain energy due to the preceding entry deceleration and COD. Limb loading the reacceleration actions in training will naturally slow down limb angular velocity and therefore angular momentum, however, though speculative it was hoped that the greater loading of the neuromuscular system around the turn, would potentiate the force output of the musculature involved in the ensuing reacceleration (Buchheit et al., 2011; Ettema, 2001), or at the very least we would observe faster reacceleration times upon removal of the WR resistive overload. The only significant within-group changes were observed in REA1, where the CG and WRs times were slower (21.38%, 24.11%; d = 0.94, 0.84). No other within- and between-group differences were noted, our hypothesis regarding the effects of WR on reacceleration unsubstantiated. This may be explained by the WR loading parameters not being appropriate to induce the neuromuscular strength adaptation that is required to coordinate and rapidly apply higher levels of propulsive force during reacceleration. Furthermore the exercises performed throughout the intervention may not have been appropriate to develop reaccelerative capabilities.

The total time is in essence the sum of the components parts described previously. Given the preceding results and the mostly non-significant changes in the components phases/times, it was unsurprising the outcome measure of total-time was unchanged (d= 0.04 to 0.31, 0.83 to 3.68%; $p > 0.05$). This was unexpected as it was thought that velocity-specific exercise combined with a movement-specific resisted stimulus would promote neuromuscular adaptation beneficial to improving COD performance and it's component parts.

As WR is a variable overload the magnitude of which increases with limb velocity, it was thought that it would provide a substantiative overload during the longer distance linear sprints (2.28-18.28 m, and 0-18.28 m). Within-group decreased sprint times ($p < 0.05$) for all linear sprint splits (0-2.28 m, 2.28-18.28 m, and 0-18.28 m) were found for both the WRs and WRf interventions (d = -0.65 to -1.57). Despite no statistically significant between-group effects, practically meaningful differences (ES = -0.55 to -0.81) between groups were observed for 2.28-18.28 m for WRs-CG and WRs-WRf, and for 0-18.28 m between WRs-CG. Overall it would seem that shank loaded training enhanced linear speed adaptation with greater efficacy than forearm loaded and unloaded training (Feser, Korfist, et al., 2021). It would seem that adding external load to the shank and the associated increased rotational inertia and subsequent kinetic energy/work across the musculature of the ankle and calf during stance, and the knee and hip during flight stages (Couture et al., 2018), was more advantageous for improving sprint ability compared to forearm loading. These findings are in line with those of previous researchers who reported shank loaded training to reduce (ES = -0.64, $p < 0.05$) 20 m sprint times (Bustos et al., 2020), affirming shank loaded training leads to beneficial adaptations to linear speed capabilities. While these findings relate to fast SSC capabilities, it is also important to consider the effect on slower SSC actions as in jumping tasks.

The effects of WR training were investigated on vertical, horizontal, and lateral jump performance. It was thought that due to the horizontal and lateral nature of the accelerations and COD exercises, greater improvement in jump distance would be seen in these vectors than in the vertical. Within-group improvement ($p < 0.05$) in height/distance were noted for CMJ in CG (d = 0.68), LJR in CG and WRf (d = 0.83, 1.99), and LJL in all groups (d = 0.81 to 1.09), whereas a decrease in HJ distance was observed in WRf (d = -0.63). For between-group changes WRf training was observed to significantly reduce HJ distance compared to CG and WRs (d = -1.12, 0.90) interventions and increase LJR distance compared to the CG and WRs (d = 1.58, -0.77) interventions. The effects of WR on jump performance appear quite variable, but it does seem that the WRf had the greatest effects, which were vector specific, the arm loading improving lateral jump distance (right) but decreased horizontal jump performance. The detrimental effect of the WRf and lack of effect of WRs interventions on HJ distance was unexpected given the number of horizontal oriented sprint and acceleration exercises in the intervention. Contrary to our findings, Bustos et al. (2020) noted shank WR significantly increased bilateral horizontal jumping distance (4.52%, d = 0.67). This discrepancy is conceivably due to the inclusion of plyometric exercises within the intervention by Bustos et al. (2020), while ours did not. It should be noted, similar increases to HJ distance were observed in the WRs (1.36%, *d* = 0.36, *p* = 0.206 vs 0.26%, *d* = 0.04, *p* >0.05) compared to the initial four weeks of training by Bustos et al. (2020), suggesting that there may have been better adaptation with continued training in this study.

With regards to the IMTP peak force, it was thought the increase in kinetic energy/work involved with limb-loading would lead to greater force development. Significant within-group increases were observed for the CG and WRs (*d* = 0.89 and 0.84 respectively), however the WR loading parameters (load/location) used in training were not sufficient to elicit significant between-group changes in IMTP peak force. These findings were unexpected as it was presumed that compared to unloaded training, the additional inertia and therefore mechanical work across the knee and hip musculature required with shank loading, would lead to neuromuscular adaptation and associated greater peak force production. The lack of adaptation could be explained by: 1) high velocity strength improvements not translating to zero velocity strength assessments; 2) the IMTP is a measure of total overall strength i.e. legs, trunk, grip; and, 3) the training was pushing/compressive force training whereas the IMTP is a tensile/pulling assessment of peak force.

7.6 Limitations

Given the novelty of this study, discussion of the changes were problematic due to the paucity of research conducted regarding COD and WR training, subsequently, the discussion comparing our results to previous research was minimal. The use of the forearm limited comparative loading between upper and lower body, given the reduced surface area to attach the micro-loads. Training frequency and duration was dictated by the availability of facilities and the youth athletes. Given the sample is representative of adolescent male youth athletes, it is unknown if effects of WR training in other populations (e.g. elite athletes). Timing light technology is limited by not identifying changes in acceleration and decelerations due to the lack of continual velocity data, like that of laser or horizontal motorized linear position encoder. The jump measures, height/distance were outcome measures and perhaps the effects of WR could have been better understood via assessing horizontal, vertical, or lateral forces and other movement strategy variables via force plate analysis. Additionally, correlational analysis was not conducted between the changes seen in COD and other performance measures, due to the size and scope of the findings.

7.7 Practical Applications

While not significantly different to unloaded training, shank and forearm WR training can be used to produce training-related improvements in linear acceleration/speed times and LJ distance. These improvements in sprint and jump performance can be beneficial for team-sport athletes, as they are important physical qualities for success in many field and court sports. However, practitioners should carefully consider the potential negative effects of external load attached to the shank and forearm on COD, reacceleration, and HJ performance when planning WR training programs for youth team-sport athletes over a 6-week period. With the current status of knowledge on limb loaded WR for COD training in mind, it is recommended that practitioners use a combination of loaded and unloaded multi-directional COD and plyometric training to complement the positive effects on sprint and jump performance. Furthermore, practitioners should carefully plan WR training programs for pro-agility shuttle performance in team-sport athletes, and consider exercise selection and what musculature would benefit from micro-loading. Based on the limited evidence available (Brown et al., 2022), investigating muscle activity while wearing 1.5% BM WR at a running speed of 18 kilometers per hour indicates that loading of the shank appears to influence EMG activity in the muscles superior to the proximal joint (i.e. gluteus, quadricep, and hamstring muscles). However, this information is based on steady state sub-maximal running, therefore no objective advice can be provided on COD.

The reader should be aware this is a seminal study in the area of limb loaded WR and its influence on COD performance, therefore the findings need to be interpreted in this light. Most importantly it needs to be realised that even though the forearm and shank WR loading parameters used in this study did not result in a great deal of improvement in COD performance, the findings guide the practitioner and researcher as to other loading parameters that may produce better results. With this in mind and in the light of previous research with WR in sprinting, it is recommended that higher training frequencies (3 x per week) over longer training cycles (> 6 weeks) be implemented. Furthermore, it would be interesting to determine if greater inertial loading and/or the introduction of micro-loaded shorts would affect COD performance in some manner.

Chapter Seven. The Chronic Effects of Shank and Forearm Wearable Resistance training on 180 Change of Direction Performance.

Chapter 8. Summary, Practical Applications, Limitations, and Future Research Directions.

8.1 Summary

This thesis sought to answer the over-arching question, "what are the acute and chronic effects of forearm and shank loaded WR on pro-agility performance?" To answer this question, a series of systematic literature reviews, and acute and longitudinal studies were implemented. Therefore, this thesis was framed by the following sections: Section 1) Systematic reviews of the literature; Section 2) reliability investigation; Section 3) training effects of WR; and Section 4) summary.

8.1.1 Section 1: Review of Literature

Previous reviews of the COD literature had primarily focused on the overview of COD assessment and training modalities, however there was limited detail to the specific administration and diagnostic potential of the pro-agility shuttle. Therefore, a systematic review of the utility and reliability of the pro-agility shuttle was conducted (Chapter 2), and a second systematic review of the effectiveness of specific and non-specific training methods on pro-agility performance followed (Chapter 3). The main takeaways from Section 1 were as follows:

Normative values for the pro-agility shuttle were established in Chapter 2, it was evident that athletes in sports who perform the pro-agility shuttle more regularly (i.e. American football) exhibited the fastest pro-agility shuttle times (4.45 s). Similarly, when the different skill-levels were examined, elite athletes (4.61 ± 0.29 s) had faster pro-agility shuttle times than sub-elite (4.91 ± 0.44 s) and novice (5.32 ± 1.14 s) athletes. Regarding reliability, it was determined that although timing lights were reported as less reliable compared to stopwatch measures (ICC = 0.80 to 0.96; CV 0.06 to 4.95% vs. ICC 0.91 to 0.98, CV = 1.9%), the findings were most likely influenced by the limited research in the area and timing light technology may be more accurate in representing the variability in pro-agility performance. It was determined that investigation into the reliability of other technologies, such as radar to differentiate between linear speed and COD components within the pro-agility shuttle was needed. When looking at the different training effects on the pro-agility shuttle in Chapter 3, it was identified that sprint (ES: 0.108 per session), plyometric (ES: 0.092), and unilateral resistance training (ES: 0.087) methods were most effective at enhancing total-time. Additionally, concurrent utilisation of these training methods (ES: 0.078) was more effective than specific COD training (ES: 0.045) and could prove effective for simultaneous enhancement of different neuromuscular qualities.

8.1.2 Section 2: Reliability of an Advanced Pro-agility Shuttle Protocol using Timing Light and Radar Gun Diagnostics

Section 2 consisted of two chapters, which determined the reliability of an advanced protocol for the pro-agility shuttle, in recognition of the limited diagnostic value provided by a single measure of total time. In Chapter 4, the reliability of the phases and sub-tests differentiating the linear and COD components within the pro-agility shuttle using timing light technology were investigated. In Chapter 5, the reliability of velocity profiling of the pro-agility shuttle's linear and COD phases using radar technology was examined. It was determined that the linear and COD components within the pro-agility shuttle can be isolated. Phases of acceleration (ACC1 and ACC2) were found to be more reliable when measured using timing lights (ICC = 0.97 to 0.98, CV = 1.18 to 1.45%) than radar (ICC = 0.14 to 0.32, CV = 4.47 to 7.07) between sessions 2-3. Similarly, reacceleration phases (REA1 and REA2) were found to be more reliable when measured with timing lights (ICC < 0.99, CV = 0.95 to 1.00%) than radar (ICC = 0.32 to 0.52, CV = 4.47 to 5.48%). It was also established that timing lights (ICC = 0.96 t0 0.97, CV = 1.97 to 1.98%) were more reliable than radar (ICC = 0.69 to 0.75, CV = 3.16 to 4.47%) for measuring the COD phases. The established reliability of pro-agility shuttle phases, using this advanced protocol, were able to be used for assessment of different athletic capabilities relating to acceleration, reacceleration, and COD performance within the pro-agility shuttle and provided greater diagnostic value to applied practitioners. It was noted that when using radar there was considerable between-subject variability in COM location across measures, which necessitated substantial post-processing. Though radar may be used to monitor individual athlete accelerative and reaccelerative velocities between testing occasions, application of this technology was not recommended for use by practitioners due to post-processing time and resource constraints.

8.1.3 Section 3: Acute and Chronic Effects of Forearm and Shank Wearable Resistance on Pro-agility Shuttle Performance

In Chapter 3, it was identified that specific speed and plyometric training, along with concurrent unilateral resistance training, were most effective at improving pro-agility shuttle performance. While adding external load to sport-specific movements had previously proven difficult, recent advancements in WR limb-loading had proved effective at providing such overload. Section 3 was comprised of two chapters that investigated the effects of shank and forearm WR COD loading and training on pro-agility shuttle performance. In Chapter 6, the acute effects of 1.5% BM forearm and shank loading on pro-agility shuttle performance was investigated. In Chapter 7 the chronic training effects of progressive forearm and shank WR training on pro-agility shuttle performance and associated speed, and lower body power capabilities were quantified. The main finds were as follows:

Acutely and longitudinally, when WR was placed on the forearm, compared to the CG, an increase in ACC2 time ($d = 0.47, 0.87$, $p < 0.03$) was observed. Whereas, when WR was placed on the shank there was an acute decrease in total time (-10.6%, $d = -0.90$, $p = 0.01$) and COD1 time (-12.8%, $d = -0.49$, $p = 0.007$), yet shank loaded training did not lead to any significant changes as compared to the CG and WRf. It should be noted that within-group shank loading changes appeared to better maintain ACC2 performance/time (4.93%, $d = 0.33$, $p < 0.05$) and significantly reduced linear sprint times (-3.50 to -5.20%, $d = -0.65$ to -1.50, $p < 0.03$), more so than CG and WRf after chronic exposure. Furthermore, with forearm loading there was an improvement to jump performance capabilities for LJR ($d = 1.58$, $p < 0.05$), but WRf was found to reduce HJ ($d = -1.12$, $p = 0.001$) distance, compared to unloaded training. These results offered practitioners initial insights into the efficacy of chronic WRs and WRf COD training on pro-agility shuttle performance and associated speed, and lower-body jump capabilities in amateur team-sport athletes. Though WR training did not result in any significant improvement relating to pro-agility shuttle total-time, phase, or sub-tests, it was highlighted as this was the first study using limb loaded WR for COD training, that a lot more research is needed to establish the value of this training method for improving the different aspects of the pro-agility test.

8.2 Limitations

The following limitations specific to each of the chapters are acknowledged by the author:

8.2.1 Chapter 2: Pro-agility Unpacked: Variability, Comparability, and Diagnostic Value

1) Limited data was available in the literature to comprehensively establish normative pro-agility shuttle performance times, except for in the sport of American football, due to the importance of the test for selection into professional teams.
2) Some normative values were represented by few or single studies, making the inferences from the findings difficult considering the limited resources.

8.2.2 Chapter 3: Training to Improve Pro-agility Shuttle Performance: A Systematic Review

1) Drawing comparisons and identifying contrasts between studies was made difficult by the variability in intervention training methods, exercise selection, intervention length, and total workload. However, the included studies reflect the diversity of the interventions in the available literature.
2) A meta-analysis could not be performed on the basis of limited consistency in the methodological approaches used for specific and non-specific training methods. Nonetheless, the systematic review offered a summary of the effectiveness of different training methods on pro-agility shuttle performance.

8.2.3 Chapter 4: Advancing the Pro-agility Shuttle to Provide Better Change of Direction Diagnostics

1) Subjects only turned on their preferred leg, therefore it was unknown whether there were differences between the phases, sub-tests, or reliability measures between the legs.
2) Using a timing light set-up at 2.28 m either side of the COD lines was unable to completely isolate deceleration and immediate reacceleration. However, this offered the best method to assess these phases without risk of disruption from lateral displacement during the COD, if the timing lights were arranged closer to the COD line.

8.2.4 Chapter 5: Radar Profiling of Multi-phase Pro-agility Shuttle Performance

1) It was difficult to account for differences in the location at which deceleration and maximal acceleration occurred for each individual and may have contributed to poor reliability. Granted the differences are common and dependent on capabilities of each individual subject.

2) The ability for radar to assess the pro-agility shuttle was based off of subject COM, meaning distance differed based on the height and trunk angle of the subject. While subjects reached out and touched the line, which would be the correct distance, the displacement was measured from the COM (i.e. before the COD line). Therefore, this presented a limitation of radar technology to assess COD, as during COD actions the COM did not travel the full distance equating to the total pro-agility distance.
3) While average velocity over a specific distance enabled for relativity and standardization between radar and timing light technologies, it does not precisely reflect the actual velocity-time thresholds associated with different phases of the pro-agility shuttle.
4) Pragmatically, using radar necessitated intensive post-processing of data before measures were able to be reported and explained to practitioners.

8.2.5 Chapter 6: The Acute Effect of Forearm and Shank Wearable Resistance on Pro-agility Shuttle Performance in Team Sport Athletes

1) Acute joint kinematic and kinetic changes as a result of WR loading were not investigated due to the limited availability of appropriate equipment (i.e. in-ground force plates, MOCAP) within the region.

8.2.6 Chapter 7: The Chronic Effects of Shank and Forearm Wearable Resistance Training on 180° Change of Direction Performance

1) The quantity of load which could be applied to the limb was limited by the available surface area. This was particularly relevant when loading the forearm, given it was smaller than the shank.
2) Only outcome measures were determined for vertical, horizontal, and lateral jump performance. Force-time characteristics were not quantified due to the limited availability of appropriate equipment (i.e. force plates) within the region, as COVID-19 restrictions did not permit travel to Auckland.
3) The intervention was limited to 6-week duration due to the availability of facilities and subjects, and may not be a sufficient amount of time for appropriate biomechanical or physiological adaptations to have occurred. However, the duration reflected the viability of a COD training intervention to be implemented within the school term.
4) Intervention design was limited by being implemented during the warm-up periods. This limited exercise selection and the time-dose of the exercises performed within the intervention.

8.3 Practical Applications

Applied strength and conditioning practitioners continually look to improve and develop their practice. As such, challenging the way we conduct our practice leads to betterment in our understanding of diagnostic utility and knowledge around training to improve COD performance.

The overarching objective behind this thesis was to contribute to the body of evidence, which practitioners can use to improve the assessment of COD ability and enhance exercise prescription for the pro-agility shuttle. Based on the insights gained from the findings of this thesis, the following practical applications and recommendations were put forth:

1) Practitioners should use normative values as guidelines to gauge and monitor athlete performance.
2) The normative values established should be used to set attainable goals relevant to the sport, position, and skill-level of that athlete.
3) Sprint training should be used incorporated into a long-term athlete development training program to enhance accelerative capabilities in the pro-agility shuttle.
4) Multidirectional plyometric training should be implemented to enhance lower-body power which should transfer to the quick accelerative and decelerative components in the pro-agility shuttle.
5) Resistance training can enhance athlete capabilities to deal with high forces surrounding 180° COD and exercises should be performed unilaterally for specificity to the task, given the linear and COD components are performed unilaterally.
6) Simultaneous speed, plyometric, and resistance training can be used to enhance multiple neuromuscular qualities concurrently.
7) Multi-phase analysis of different accelerative, reaccelerative, and COD components of the pro-agility shuttle can consistently be measured, using multiple timing lights, in male team-sport athletes.
8) Using an advanced diagnostic protocol can provide practitioners with a method to quantify different components of COD performance (i.e. acceleration, COD, reacceleration) within the pro-agility shuttle.
9) Practitoners need to be cautious when using radar profiling of the pro-agility shuttle test, given the variability of COM displacement between athletes and large time requirement for post-processing.

10) Although intra-individual performance was reliably assessed with radar, due to the high signal noise of the radar data it was recommended timing light technology be used, to ensure better consistency of measurement.
11) Shank loading of 1.5% BM acutely reduced COD time when worn during the pro-agility shuttle, and significantly reduced pro-agility shuttle total-time. Practitioners may wish to use WRs loading parameters to promote efficient COD performance.
12) Forearm loading of 1.5% BM acutely increased ACC2 phase time, when worn during the pro-agility shuttle, without affecting athletes' ability to maintain pro-agility shuttle total-time. Practitioners may wish to use WRf parameters to provide unique overload of the acceleration phase of the pro-agility shuttle.
13) Progressively overloading WRs during 6-weeks of COD training was recommended to enhance initial acceleration, linear sprint, lateral force capabilities during unilateral jumping tasks, and isometric peak force performance, however, practitioners need to carefully consider the potential detriment to moderate-intensity reacceleration capabilities using this loading strategy.
14) Progressively overloading WRf during 6-weeks of COD training was recommended to enhance initial acceleration, and lateral force capabilities during unilateral jumping. Practitioners need to carefully consider the potential detriment to final accelerative ability and horizontal force capabilities during bilateral jumping when using this loading strategy.
15) It was suggested that an increase in the training duration to more than 6-weeks may be needed to obtain better results.
16) WRs and WRf training should not be used in substitute to resistance training in the confines of a strength and conditioning programme. WR should be implemented concurrently to compliment gym-based resistance training.
17) Practitioners should employ different loading and unloading strategies at different points of a training programme, to elicit individual-specific adaptations to different athletic qualities.

8.4 Future Research Directions

Considering the discoveries and constraints of this theses, the scope for future research directions regarding COD assessment diagnostics and the applicability of WR limb-loading as a COD training method were as follows:

1) It was determined that phases of the pro-agility shuttle can be measured reliably, using timing lights. However, it is still unknown the extent to which muscular qualities (i.e. concentric, eccentric) underpin performance in each of the different phases. Therefore, it is important to conduct a correlational analysis of the variance between phases of the pro-agility shuttle and different muscular qualities.
2) Given the time constraint required for post-processing of radar data, using radar technology for velocity-profiling the pro-agility shuttle is not practical for many in-field practitioners. Therefore, to make radar technology practically viable for practitioners, future research should attempt to determine better post-processing procedures for radar data analysis of the pro-agility shuttle. Additionally, it is important to determine the reliability of phases based on acceleration and deceleration phases and investigate the use of different measuring devices (e.g. AI generated video processing, motorized horizontal linear position encoder) that may have more efficient post-processing methods.
3) It was determined that shank and forearm WR loading resulted in changes during acute and after chronic training. Yet it is unknown as to what impact these loading schemes had on COD biomechanics. Therefore, assessing the kinematic changes on joint angles will help to determine whether limb-loading promotes desirable outcomes to COD technique. This would further determine if WR can be used to aid enhancement of athlete technical abilities in 180° COD tasks. We suggested future research should look to investigate the 2-D kinematic changes that occur in COD actions following acute and chronic WR limb-loaded training.
4) Changes to horizontal and lateral force capabilities following forearm and shank WR training were determined by the jumping tasks. However, only quantifying these changes by the outcome of the jump tasks did not consider the impact these modalities had on the mechanisms underpinning the jumps (i.e. force, impulse, flight time, or contraction time). Therefore, future research should attempt to quantify these mechanisms using force-plates in order to better understand the kinetic changes that occur following WR limb-loaded training.

5) The WR loading parameters were used to ensure load quantity was relative to body mass of the subjects. However, absolute quantification of load (e.g. 200g) is another common approach. It is yet to be determined if different loading parameters (i.e. absolute load or load location) differ in response to training adaptation. Therefore, in order to better practitioners' understanding of WR prescription and optimize adaptation to WR training, future research should look to investigate different WR loading parameters to determine optimal prescription guidelines.
6) Finally, given that chronic effects of WR training were limited to a period of 6-weeks, it is unknown whether there are continual training adaptation with longer-term exposure upwards of 6-weeks. Therefore, researchers should look to investigate the optimal period of longitudinal exposure to WR training. This will help practitioners better understand and gauge training duration required for optimal adaptation.

8.5 Conclusion:

This thesis provided original research by improving the diagnostic capabilities of the pro-agility shuttle and determining that WR COD-training produces significant effects on COD performance. Strength and conditioning practitioners can use the findings in this thesis to better diagnose their athletes' phase-specific COD performance, and are provided with initial insights into how to prescribe WR limb-loading to enhance athletic qualities related to sprinting and jumping. These findings can be used to guide athlete training strategies aimed at enhancing pro-agility shuttle and associated athletic performance capabilities. Including WR as part of athlete COD training provided a novel training strategy to overload sport-specific actions and enabled development of qualities related to COD performance, however, there is a need for future researchers to clarify the effects of different WR loading parameters on COD performance.

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Appendices

Appendix 1. Additional Research Outputs Since Starting the PhD

Macadam, P., Nuell, S., Cronin, J. B., Diewald, S., Rowley, R., **Forster, J**., & Fosch, P. (2020). Load effects of thigh wearable resistance on angular and linear kinematics and kinetics during non-motorised treadmill sprint-running. *Eur J Sport Sci*, 1-8. https://doi.org/10.1080/17461391.2020.1764629

Forster, J., Uthoff, A., Rumpf, M., & Cronin, J. (2021). Advancing the pro-agility test to provide better change of direction speed diagnostics. *Journal of Sport and Exercise Science, 5*(2), 101-106. https://doi.org/10.36905/jses.2021.02.02

Forster, J. W., Uthoff, A. M., & Cronin, J. B. (2022). Medicine Ball Deceleration Exercise for Change of Direction. *Strength & Conditioning Journal, 44*(5), 119-122. https://doi.org/10.1519/ssc.0000000000000716

Juneau, C. M., Oranchuk, D. J., Cahill, M., **Forster, J. W**., Diewald, S., Cronin, J. B., & Neville, J. (2023). Reliability and Utility of Load-Cell Derived Force–Time Variables Collected During a Constrained and Unconstrained Isometric Knee Extension Task on a Plinth. *Journal of Science in Sport and Exercise*. https://doi.org/10.1007/s42978-022-00215-8

Appendix 2. Ethics Approval Form for Chapter 4, 5, and 6

AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

27 March 2020

Aaron Uthoff
Faculty of Health and Environmental Sciences

Dear Aaron

Re Ethics Application: **20/67 The effects of wearable resistance loading strategies on change of direction performance**

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 26 March 2023.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. 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.
7. 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 and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

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

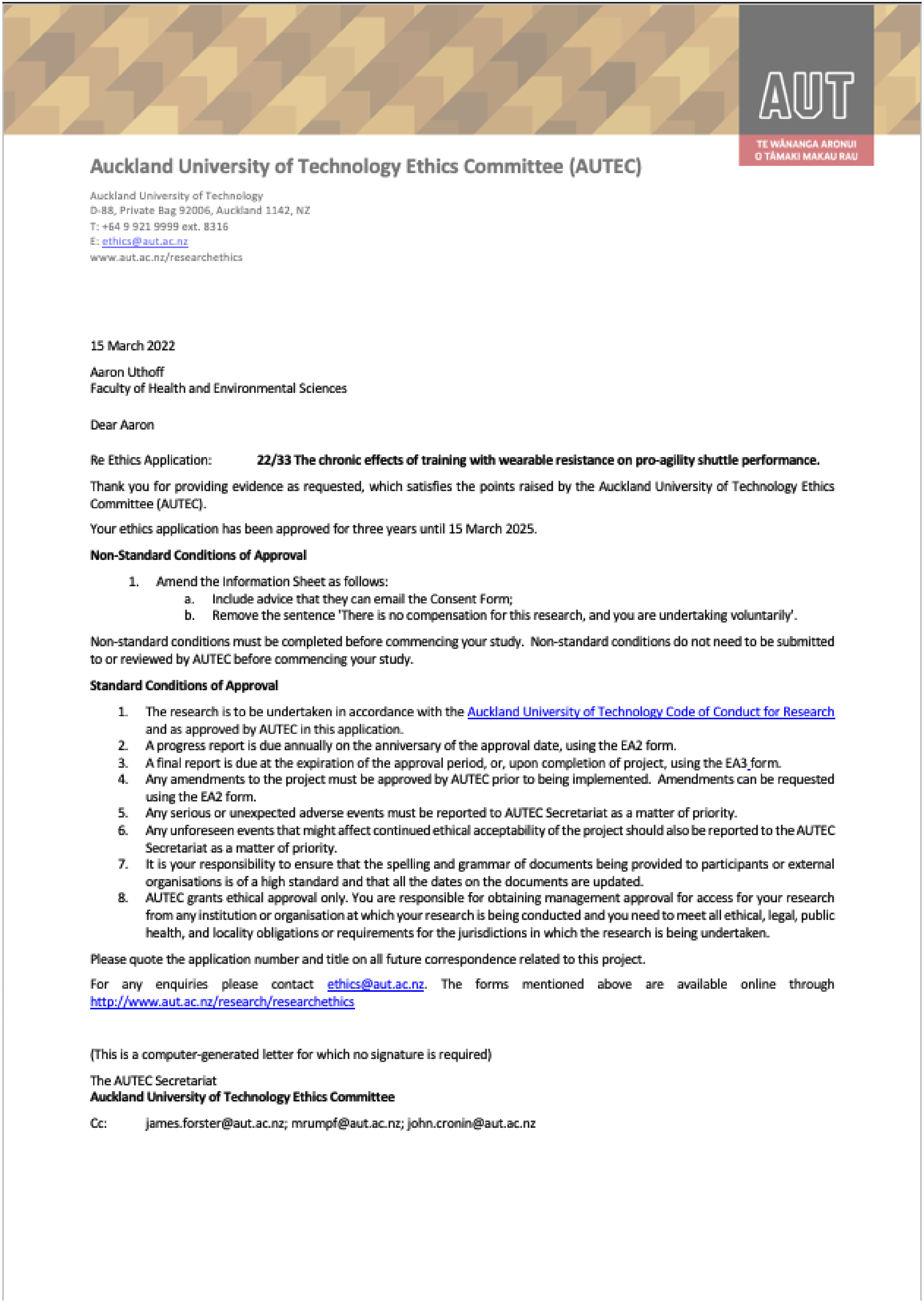
For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: james.forster@aut.ac.nz; John Cronin; mrumpf@aut.ac.nz

Appendix 3. Ethics Approval Form for Chapter 7



AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

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T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

15 March 2022

Aaron Uthoff
Faculty of Health and Environmental Sciences

Dear Aaron

Re Ethics Application: **22/33 The chronic effects of training with wearable resistance on pro-agility shuttle performance.**

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 15 March 2025.

Non-Standard Conditions of Approval

1. Amend the Information Sheet as follows:
    a. Include advice that they can email the Consent Form;
    b. Remove the sentence 'There is no compensation for this research, and you are undertaking voluntarily'.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. 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.
7. 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 and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

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

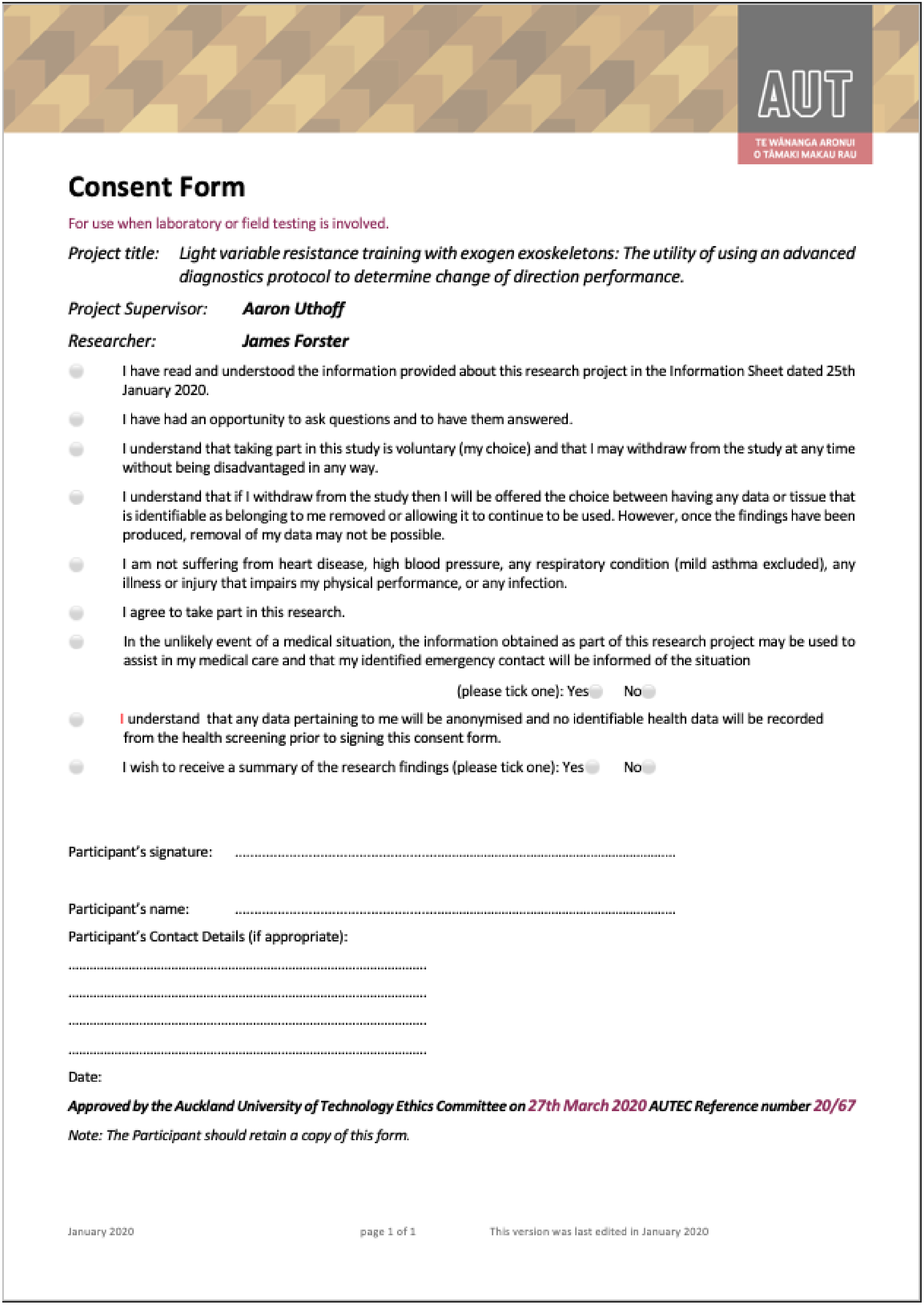
For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: james.forster@aut.ac.nz; mrumpf@aut.ac.nz; john.cronin@aut.ac.nz

Appendix 6. Informed Consent Form for Chapter 4, 5, and 6



AUT
TE WĀNANGA ARONUI
O TĀMAKI MAKAU RAU

Consent Form

For use when laboratory or field testing is involved.

Project title: *Light variable resistance training with exogen exoskeletons: The utility of using an advanced diagnostics protocol to determine change of direction performance.*

Project Supervisor: ***Aaron Uthoff***

Researcher: ***James Forster***

- ○ I have read and understood the information provided about this research project in the Information Sheet dated 25th January 2020.
- ○ I have had an opportunity to ask questions and to have them answered.
- ○ I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- ○ I understand that if I withdraw from the study then I will be offered the choice between having any data or tissue that is identifiable as 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.
- ○ 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, or any infection.
- ○ I agree to take part in this research.
- ○ In the unlikely event of a medical situation, the information obtained as part of this research project may be used to assist in my medical care and that my identified emergency contact will be informed of the situation (please tick one): Yes ○ No ○
- ○ I understand that any data pertaining to me will be anonymised and no identifiable health data will be recorded from the health screening prior to signing this consent form.
- ○ I wish to receive a summary of the research findings (please tick one): Yes ○ No ○

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

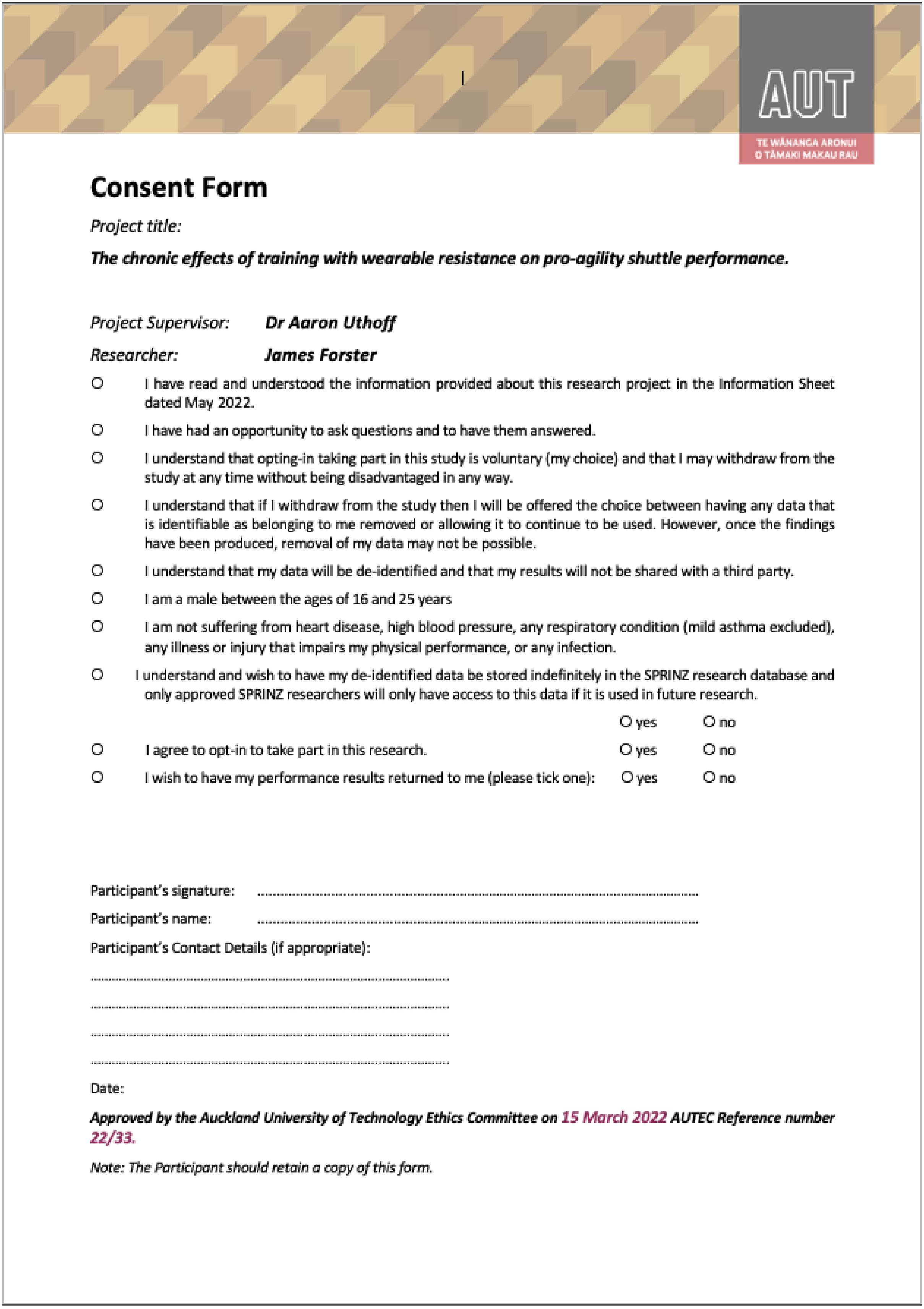
Date:

Approved by the Auckland University of Technology Ethics Committee on 27th March 2020 AUTEC Reference number 20/67

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

January 2020 page 1 of 1 This version was last edited in January 2020

Appendix 7. Informed Consent Form for Chapter 7



AUT

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Consent Form

Project title:

The chronic effects of training with wearable resistance on pro-agility shuttle performance.

Project Supervisor: ***Dr Aaron Uthoff***

Researcher: ***James Forster***

○ I have read and understood the information provided about this research project in the Information Sheet dated May 2022.

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

○ I understand that opting-in taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.

○ I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as 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.

○ I understand that my data will be de-identified and that my results will not be shared with a third party.

○ I am a male between the ages of 16 and 25 years

○ 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, or any infection.

○ I understand and wish to have my de-identified data be stored indefinitely in the SPRINZ research database and only approved SPRINZ researchers will only have access to this data if it is used in future research. ○ yes ○ no

○ I agree to opt-in to take part in this research. ○ yes ○ no

○ I wish to have my performance results returned to me (please tick one): ○ yes ○ no

Participant's signature: ....

Participant's name: ....

Participant's Contact Details (if appropriate):

....

....

....

....

Date:

Approved by the Auckland University of Technology Ethics Committee on 15 March 2022 AUTEC Reference number 22/33.

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

Appendix 10. Chapter 2 Abstract

Change of direction (COD) is an important component of athlete performance and measuring and comparing athletes is an integral aspect of strength and conditioning practice. This article aimed to determine pro-agility shuttle utility, by quantifying variability and normative values for different sports, skill-levels and positions. Limitations of the pro-agility shuttle are identified, as are future research directions. A total of 67 studies were included for review. Pro-agility shuttle reliability was reported in 10 studies across 6 sports; however, comprehensive reliability statistics were absent in most papers. Additionally, only reliability of total-time from stopwatch and timing lights were reported. Data of 32,891 subjects in 12 sports (American football, basketball, cricket, general athletes, hockey, lacrosse, recreational athletes, resistance-trained athletes, rugby, soccer, swimming, and tennis) were extracted and aggregated, establishing sport, skill-level (elite, sub-elite, and novice) and positional normative values, where practical. Elite athletes showed the fastest performance times, whereas sub-elite and novice athletes showed similar spreads in performance, suggesting similar athletic capabilities. In conclusion, the pro-agility shuttle currently has limited diagnostic value and the variability of smaller performance sub-components within pro-agility shuttle should be examined. Furthermore, the value of other technologies such as smart phone, inertial sensor or radar should be investigated.

Appendix 11. Chapter 3 Abstract

Effective directional change in sport is imperative to success in key game situations. Change of direction (COD) ability is underpinned by various athletic qualities which can be developed through specific and non-specific training methods. This review examined the effect of specific and non-specific training methods on pro-agility performance, by analysing the intervention type and resulting magnitude of training effects on pro-agility shuttle performance. A total of 20 studies were included for review. Data from 638 subjects and 29 intervention groups involving seven different training methods were extracted and analysed in relation to training method classification and primary outcome measures. Interventions involving sprint training, plyometric training, resistance training, and combined resistance, plyometric, and sprint training were found to produce statistically significant positive change on pro-agility performance per session ($p < 0.05$). Sprint training (0.108 ES), plyometric training (0.092 ES), resistance training (0.087 ES), and combined resistance, plyometric, and sprint training (0.078 ES) methods were found to have the highest per session training effect. While total time is the typical unit of measure for this test, different types of training may lead to preferential improvements in either acceleration, deceleration, or COD phases of the pro-agility shuttle. Specifically, resisted or inclined sprinting may develop the linear acceleration phases, unilateral resistance training may promote increased strength to overcome the imposed forces during the deceleration and COD phases, multiplanar plyometrics can help enhance stretch-shorten cycle capabilities across different force vectors, and a combination of two or more of these methods may enable simultaneous development of each of these qualities.

Appendix 12. Chapter 4 Abstract

The pro-agility shuttle is commonly used by practitioners to assess change of direction (COD) performance in athletes. The metric of total time is influenced by accelerative and decelerative ability and makes “true” COD ability difficult to quantify. The aim of this study was to determine whether an advanced diagnostic protocol, with three timing lights, could be used to reliably measure different components of pro-agility shuttle performance. The traditional set-up was adapted, and additional timing lights were placed 2.28 m from each COD line, enabling different phases of COD performance to be quantified. Ten subject s (age: 16.1 ± 0.32 y, height: 1.81 ± 0.11 m, body mass: 76.6 ± 18.04 kg) completed three sessions, consisting of three trials, separated by one week. Absolute and relative consistency was assessed using CV and ICC, respectively. A one-way ANOVA was performed to determine whether between-day performance differences existed. Systematic changes were identified between sessions 1-2 for COD1, Moderate Intensity 501, Moderate intensity 105, Stationary 5-0-5 and Flying 5-0-5 (-7.37% - 4.20%, $p < 0.05$). However, between session performance stabilised and no significant differences were observed between sessions 2-3 in any of the COD phases. Comparisons between sessions 2-3 resulted in low typical error (CV $\leq$ 4.42%) and excellent relative consistency (ICC $\geq$ 0.90) for all sub-tests. It would seem that the components of the pro-agility test can be measured reliably and therefore can provide valuable diagnostic information to the practitioner to guide COD programming.

Appendix 13. Chapter 5 Abstract

Typically, pro-agility performance is quantified as the total time to complete a test using timing lights, however, it may be that radar profiling might be able to provide greater diagnostic information via a multi-phase analysis. The aim of this study, therefore, was to determine the variability associated with a multi-phase pro-agility approach using radar velocity profiling. Seventeen male novice team sport athletes (age: 18.18 ± 2.88, height: 175.56 ± 16.62 cm, body mass: 85.74 ± 19.05 kg) completed three sessions, consisting of three trials, separated by one week. A repeated measures analysis to investigate the variability of a multi-phase velocity profiling using radar on pro-agility shuttle performance. A repeated measures one-way analysis of variance (ANOVA) identified significant systematic changes in high-intensity accelerative ability ($p < 0.05$) between sessions 1-2, and between sessions 2-3 ($p < 0.05$). Absolute consistency for all variables across all sessions was less than 10%. Absolute agreement for all variables ranged from “very poor” to “moderate” (ICC = 0.11 to 0.70) between sessions 1-2 and ranged from “very poor” to “good” (ICC = 0.14 to 0.76) between sessions 2-3. Phases of moderate and high change of direction (COD), initial reaccelerative ability, moderate and high-intensity reacceleration, flying acceleration, and total-time can consistently rank performance between testing occasions and may be used to measure variability for talent identification, player selection, and performance monitoring.

Appendix 14. Chapter 6 Abstract

The pro-agility shuttle is commonly used by practitioners to assess change of direction (COD) performance in athletes. Wearable resistance (WR) provides light-weight overload to limbs during high-velocity actions, yet there is diminutive research into the acute effects of WR on COD performance. The aim of this study was to determine the effects of using WR on pro-agility performance using an advanced diagnostic protocol. Twenty-eight subjects (age: 16.9 ± 0.85 y, height: 177 ± 7.21 cm, body mass (BM): 70.6 ± 12.5 kg) performed the advanced pro-agility shuttle under three conditions (i.e. unloaded, 1.5% body mass (BM) on the shank, and 1.5% BM on the forearm). Compared to the unloaded condition, shank loaded performance was found to statistically ($p < 0.05$) differ in total time and moderate intensity COD phase, moderate-intensity reaccelerative ability (105_{MI}) and eccentric loading capabilities (501_{MI}), and 505_{Flying} sub-test performance (-12.8 to 5.88%, $d = -0.54$ to 0.44, $p < 0.05$). Forearm loading was found to differ ($p < 0.05$) in the Acceleration 2 phase (6.98%, $d = 0.47$, $p < 0.05$) as compared to the unloaded condition. Significant differences between WR placement were found for COD1, Acceleration 2, COD2 501_{MI}, 105_{HI}, 505_{Static}, and 505_{Flying} (forearm-shank: -12.0 to 14.0%, $d = -0.51$ to 0.54, $p < 0.05$). These findings provide foundational information for coaches who seek to use WR to overload COD movements. It appears load of 1.5% BM attached to the forearm can overload accelerative ability, while load attached to the shank enhances COD phase and total-time performance. Therefore, different loading strategies can be used to enhance or overload different phases within the pro-agility shuttle.

Appendix 15. Chapter 7 Abstract

The aim of this study was to investigate the effects of change of direction (COD) training with shank and forearm wearable resistance (WR) in amateur team-sport athletes. Forty two male amateur team sport athletes (age: 16.7 ± 0.85 y, height: 177 ± 7.21 cm, and weight: 70.6 ± 12.5 kg) were recruited for the study, matched for COD performance and randomly allocated to a WR shank (WRs), WR forearm (WRf), or control group (CG). Subjects were tested on pro-agility shuttle, speed, and power measures one week before and after a 6-week training block. Training-related improvements in initial first-step quickness (ACC1) (-8.60 to -6.89%, *d* = -1.39 to -0.55) and linear acceleration (0-2.28m, 2.28-18.28m, and 0-18.28m) (-6.43 to -2.31%, *d* = -1.57 to -0.65) were observed in both WRs and WRf groups as compared to the CG. However, no significant between group differences were observed in pro-agility shuttle total-time. Additionally, WR loading improved ($p < 0.05$) lateral jump, and peak force (IMTP) in the WRs group (6.05%, *d* = 1.02 and 9.42%, *d* = 0.84), and lateral jumping ability (LJR, and LJL) in the WRf group (7.75%, *d* = 1.99 and 5.02%, *d* = 0.81). It appears that WR results in varying effects on COD, sprint, and jumping performance, which are unique to the loading placement. Practitioners should be cognizant that the lack of changes in total-time associated with COD training with or without WR infers that while some phases of COD performance improve, other phases are negatively affected. Therefore, these findings can assist strength and conditioning practitioners in making informed decisions when planning COD training programs for team-sport athletes.