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Development and Application of an Eccentric Force-Velocity Profile in Rugby Union Athletes

A thesis
submitted in fulfilment
of the requirements for the degree
of
Doctor of Philosophy in Health, Sport, and Human Performance
at
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by
Conor Michael Fenton McNeill



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Abstract

Resistance training has long been utilised as a strategy for improving sport performance in competitive athletes dating back to early civilizations. In modern times, much emphasis has been placed on better understanding the application of specific training methods to optimise performance at the individual level. One such application is the concept of eccentric-based training (ECC), which has been known to researchers and practitioners for decades; however, only recently have these notions been investigated in the context of applied human performance. Direct comparison of eccentric- and concentric-only training tends to favour the former with respect to hypertrophy, strength and muscle architecture. Furthermore, the existing literature for ECC tends to emphasise heavy- or tempo-controlled exercises. Current research has suggested that relatively fast ECC may provide a superior stimulus for eliciting adaptation in measures of strength and explosive ability compared to slow ECC. The purpose of this thesis was to examine the theoretical and applied underpinnings for ECC in practical training environments, develop an assessment tool for prescribing ECC, and to investigate the effects of ECC on practical measures of performance in competitive athletes.

Evidence suggests that neuromuscular adaptations resulting from eccentric-based training methods could benefit athletic populations competing in team sports. The purpose of Chapter 2 is to review existing literature on the effects of eccentric-based training on performance qualities in team sport athletes. Variables related to strength, speed, power and change of direction ability were extracted and effect sizes were calculated. Eccentric-based resistance

training appears to be an effective stimulus for developing trivial to large effect size differences in strength, speed, power, and change of direction in team sport athletes. However, the range of effect sizes, testing protocols, and training interventions suggest more research is needed to better implement this type of training in athletic populations.

According to the findings of our literature review, eccentric-based training (ECC) is an effective training strategy in athletes; however, despite the theoretical benefits the uptake by practitioners is currently unknown. The purpose of Chapter 3 was to survey strength and conditioning practitioners about their use of ECC with athletes. Our survey adds to the existing body of literature showing implementation of ECC by practitioners in the field to improve physical performance through strength, hypertrophy, and power. Sport performance (64%) was the top ranked reasons to include ECC, and specifically targeted the improvement of strength (35%), hypertrophy (19%), and power (18%). ECC intensity was prescribed as percentage of concentric 1RM (34%), RPE (20%) or velocity (16%). A majority of respondents did not monitor ECC load (58%) or use eccentric-specific testing (75%). The methodology between practitioners is generally non-uniform and tends to follow existing guidelines for traditional or concentric-based training despite major physiological differences between the two modes of muscle action. The efficacy of ECC is well supported, yet there appears to be a lack of defined protocol for integrating ECC research into practice. Therefore, the prescription of ECC may be improved through the development of a framework for strength and conditioning practitioners to use for specific programming outcomes. A greater

understanding of eccentric contribution to sport performance may help define testing and monitoring procedures for the prescription of ECC interventions.

Several gaps in practice were identified in Chapter 2 and Chapter 3, namely the lack of protocol for including ECC in a team sport environment. The purpose of Chapter 4 was to investigate the reliability of an incremental eccentric back squat protocol with trained rugby union athletes. Force plates and a linear position transducer captured force-time-displacement data across six loading conditions, separated by at least seven days. Eccentric peak force demonstrated good intraclass correlation coefficient (≥ 0.82) and typical error values ($\leq 7.3\%$) for each load. Variables based on mean data were generally less reliable (e.g., mean rate of force development, mean force, mean velocity). These findings indicate this lower body, multi-joint protocol meets common standards reliability for longitudinal monitoring of eccentric force and velocity characteristics in trained athletes.

In Chapter 5, the eccentric force-velocity relationship was investigated in an applied setting with a multi-joint movement. The purpose of this study was to investigate the force-velocity-load relationship in an incremental eccentric back squat test with professional male rugby union athletes. Each increase in barbell load tended to result in a linear change in relative eccentric mean force (REMF), eccentric mean velocity (EMV), and eccentric peak velocity (EPV). The direction of this change was dependent on the variable being measured with linear positive changes noted in REMF, and linear negative changes in EMV and EPV. We

observed a plateauing effect for relative eccentric peak force (REPF) as load increased. These results show that for “peak” variables lighter loads produced similar magnitudes of force, but generally moved at higher velocities than heavier loads. These observations suggest that the eccentric force-velocity-load relationship may vary depending on individual characteristics and the parameters used. Individual characteristics explain large proportions of variance in eccentric capacity, thus the individualisation of ECC appears justified. Further research may investigate the responsiveness of these qualities to different types of eccentric training and athletic performance.

Fast eccentric contraction velocities have been suggested to alter muscle architecture and improve fast twitch muscle fibre composition to a greater extent than slow eccentric contractions. These findings may have implications for improving physical performance in athletes, although most research involving ECC has been conducted with either specialized equipment or with untrained participants. The purpose of Chapter 6 was to compare the effects of fast-tempo and controlled-tempo ECC using a traditional exercise on strength, speed, and jumping ability in trained athletes. Nineteen semi-professional rugby union athletes completed 6-weeks of an off-season ECC resistance training program. Within-group differences from pre- to post-test showed trivial to small improvements ($g = 0.01$ to 0.45) in both groups across all performance variables. The observed differences in physical performance between- and within- groups are largely similar following 6-weeks of ECC in trained athletes. Differences in the execution and prescribed intensity (%1RM) of the ECC

exercises suggest that performance may change to a similar extent through different mechanisms. These findings indicate that the individualised prescription of ECC is warranted and such an approach may help to optimise performance outcomes in trained athletes. This thesis deepens the understanding of ECC and its effect on physical performance in trained athletes, and adds new knowledge to the field allowing practitioners to prescribe ECC relative to individual capabilities. Future research should examine how to prospectively optimise ECC on the basis of individual eccentric force and velocity characteristics.

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Research Outputs Arising from The Doctoral Thesis

Published and submitted manuscripts presented in the thesis

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2019). Eccentric training interventions and team sport athletes. *Journal of Functional Morphology and Kinesiology*, 4(4), 67.

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McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Eccentric Force-Velocity Characteristics during a Novel Squat Protocol in Trained Rugby Union Athletes—Pilot Study. *Journal of Functional Morphology and Kinesiology*, 6(2), 32.

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Conference presentations arising from this thesis

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McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2019). Survey of Eccentric-based Strength and Conditioning Practices in Sport. Presented at the Sport and Exercise Science New Zealand Annual Conference, Palmerston North, New Zealand. (Poster presentation).

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2020). Eccentric force-load-velocity characteristics and relationships with performance measures in trained rugby union athletes. Presented at the Sport and Exercise Science New Zealand Annual Conference, Christchurch, New Zealand. (Oral presentation).

SECTION 1

CHAPTER 1:

General Introduction

1.1 Introduction

Human movement consists of three phases in which muscle tissue is either lengthened (eccentric), shortened (concentric), or held constant (isometric). Eccentric muscle action generally occurs when external forces exceed the force produced by a muscle which leads to kinetic energy being transferred into the muscle fibres. The energy is then absorbed and dissipated as heat or stored as elastic potential energy depending on the time course and intent of the movement (Lindstedt et al., 2001). Abbot et al. (1952) were among the first to directly compare the implications of eccentric muscle action to concentric muscle action noting the differences in metabolic cost (Figure 1). Approximately 60 years later, the high force production and relatively low energetic cost of eccentric muscle action is still under investigation (Beaven et al., 2014). This continued effort to research one of the basic phases of human movement highlights the importance of eccentric muscle action to clinicians and practitioners alike.

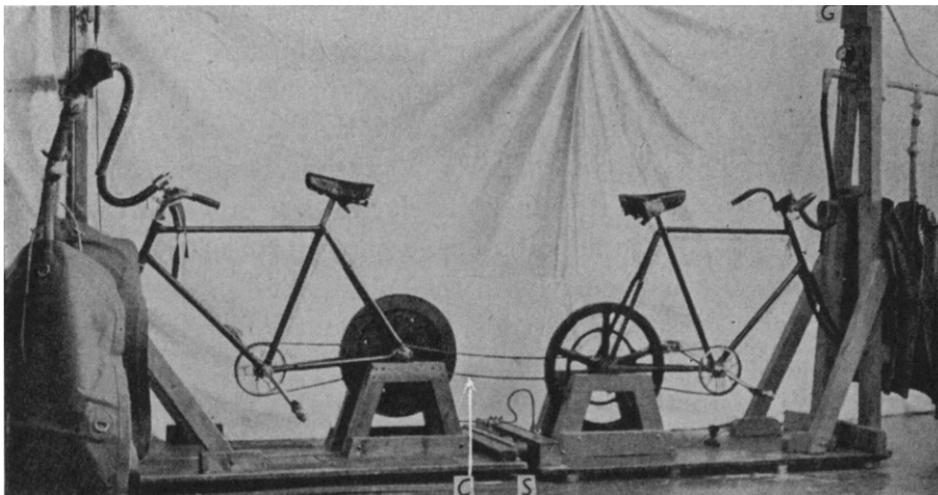


Figure 1. Pioneering eccentric research investigating the metabolic demands of eccentric exercise (Abbott et al., 1952).

Eccentric-based training (ECC) is a general strategy for improving physical performance that emphasises the lengthening action and seeks to overload the muscle-tendon unit (MTU) through the manipulation of parameters such as force, velocity, duration, or utilising specialised equipment during an exercise (Guilhem et al., 2010; Isner-Horobeti et al., 2013). Eccentric-based training is an effective stimulus for altering muscle function and architecture (Douglas et al., 2017b). Namely, altered motor unit recruitment strategies, reduced neuromuscular inhibition, increases in fascicle length, increases in tendon stiffness/ cross-sectional area, and improvements in fast-twitch muscle fibre hypertrophy resulting from ECC are reported to improve strength, force production, and rate of force development (Douglas et al., 2017a). These adaptations may benefit team sport athletes who are required to utilise elastic potential energy built up during the eccentric phase to produce rapid, explosive movement.

Much of the research involving eccentric physiology is based on observations of single fibre or single joint movement where the force-velocity relationship is inferred from a relatively isolated lengthening action (Alcazar et al., 2019). In multi-joint movement, different agonist-antagonist muscle groups may be shortening, lengthening, or co-contracting simultaneously, and thus for practical purposes the eccentric phase is generally considered to be the “lowering” action of an exercise. For example, Figure 2 illustrates the eccentric and concentric phases and associated ground reaction forces observed during a barbell countermovement jump in which the quadriceps would lengthen during knee flexion and shorten during knee extension.

When a lengthening or active stretch of the MTU occurs immediately prior to a shortening action, it is referred to as a stretch-shortening cycle (SSC). The SSC has been shown to augment the force production of the concentric phase that is evident in activities like running and hopping (Komi, 2000). Eccentric-based training has been shown to improve components of the SSC as well as muscle hypertrophy and neuromuscular control in athletes (Friedmann-Bette et al., 2010; Núñez et al., 2018). The importance of the eccentric phase has also been shown in studies investigating the force-angle relationship and injury rate (C. L. Brockett et al., 2001; Brughelli et al., 2010; Petersen et al., 2011) making eccentric strength development especially interesting for strength and conditioning practitioners as a strategy for both performance and injury prevention. Despite these findings, a recent review highlighted that relatively little research has been performed involving ECC in moderately trained or elite sport participants (Douglas et al., 2017b). More research is needed to explore how eccentric training methods affect performance in well-trained athletes.

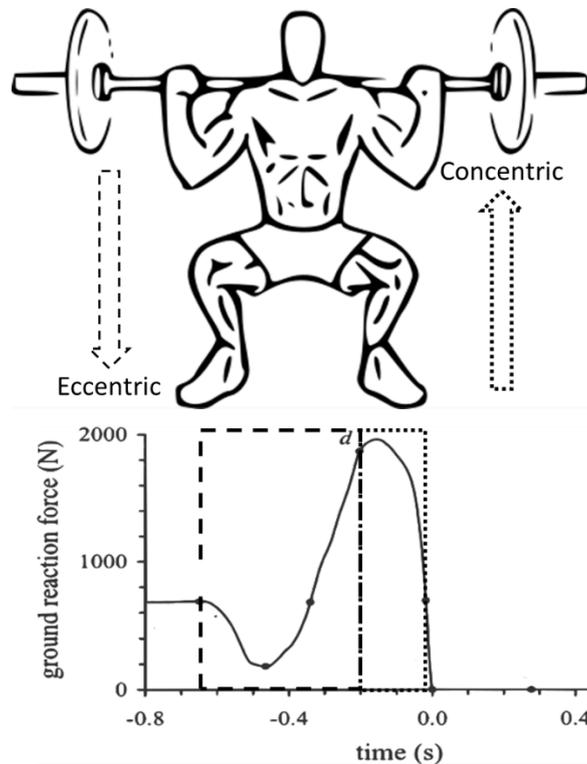


Figure 2. Eccentric (dashed) and concentric (dotted) phases of a barbell countermovement jump and the resultant ground reaction forces with an anatomical depiction of these phases in a multi-joint movement.

Extensive research has investigated the effects of ECC training using isokinetic dynamometry (Higbie et al., 1996; Hortobágyi et al., 1996). Numerous publications undertaking isokinetic ECC have reported significant improvements in strength, muscle fibre composition, rate of force development, and neuromuscular control (Oliveira et al., 2016a; Paddon-Jones et al., 2001; Papadopoulos et al., 2014). Isokinetic dynamometers are capable of exerting high force on the involved muscle fibres under high-velocity conditions, and this particular feature may explain the efficacy of this equipment on strength and power adaptations. Higher eccentric contraction velocities, possibly occurring under high-force conditions, has been reported to affect fast-twitch Type II muscle fibre to a greater degree

than slow-twitch muscle fibre, either through preferential recruitment or the lowering of thresholds required to activate these larger motor units (Douglas et al., 2017a; Henneman et al., 1965; Paddon-Jones et al., 2005). High-velocity isokinetic ECC may lead to greater neuromuscular adaptations possibly improving both eccentric- and concentric-specific strength more so than low-velocity ECC (Isner-Horobeti et al., 2013). Unfortunately, the cost and time requirements may make this equipment impractical for wide spread use in athletic settings (Meylan et al., 2008). Alternatively, limited evidence does suggest that iso-load or dynamic constant external resistance may be at least as effective as isokinetic training (Coratella et al., 2015; Guilhem et al., 2010). Given that high-velocity conditions in the eccentric phase tend to produce greater neuromuscular adaptation, future research should investigate the effects of ECC velocity on performance in applied training environments.

Only limited research has been performed with team sport athletes investigating the effects of ECC using accentuated or iso-inertial exercises. The existing literature employs bodyweight, flywheel, and traditional resistance training modalities to investigate the effects on strength, speed, power, injury rates, and change of direction (Cook et al., 2013; de Hoyo et al., 2015, 2016; Mjølshnes et al., 2004; Rey et al., 2017; Sabido et al., 2017). Prior research has also examined the eccentric phase and the contribution to concentric performance and change of direction (Cormie et al., 2010; de Hoyo et al., 2016; Spiteri et al., 2013, 2014; Tous-Fajardo et al., 2016). The Nordic hamstring exercise and inertial flywheel exercise are prominent in the literature and have been shown to improve performance metrics, even in

well-trained athletes (Askling et al., 2003; Krommes et al., 2017; Maroto-Izquierdo, García-López, & de Paz, 2017). Suchomel et al. (2019a, 2019b) have suggested various practical applications for ECC; however, these recommendations fall short of a clear framework for the programming and periodization of ECC in athletes. From a kinetic and kinematic perspective, little work has been done to quantify the mechanical outputs of these and other ECC exercises. Further, research has shown that the response to ECC may be different in trained and untrained participants (Newton et al., 2008) warranting further investigation into how ECC stimuli might differentially affect adaptation in athletes of differing ability. Future research should quantify the eccentric force and velocity relationship in iso-inertial multi-joint movements, and how this relationship can be applied to individualised training.

1.2 Thesis aims

Existing eccentric research focuses largely on muscle damage, ergogenic aids, and clinical rehabilitation with limited investigations on trained athlete populations. As a result of unique neural and structural adaptations, ECC provides a potent stimulus for musculoskeletal remodelling. Researchers investigating ECC have recruited participants with limited resistance training or competitive sport experience (Douglas et al., 2017b). Furthermore, while research on athletic populations does exist, the novel nature and exercise equipment of the training interventions may not represent the actual training environment (Meylan et al., 2008).

In order to expand the current body of literature to include well-trained athletic populations it is also necessary to quantify the dose-response relationship for eccentric-based training and subsequent adaptations. There is limited research available on well-trained athletes that clearly defines the goals, procedures, and rationales behind longitudinal eccentric training interventions. This lack of established protocols makes it difficult for practitioners to assess eccentric capability and replicate what has been demonstrated in the literature. The purpose of this thesis is to provide strength and conditioning practitioners with a practical foundation for implementing ECC as a method for improving physical performance in athletes. Across the following sections and chapters, we aim to:

- Investigate the use of ECC as a general strategy for improving physical performance in team sport athletes from a scientific and applied perspective.
- Explore the underlying eccentric force-velocity-load relationship in the context of a traditional exercise.
- Examine the reliability of eccentric characteristics in dynamic movement and their association with physical performance.
- Understand how the application of ECC methods affect physical performance at the individual level.

The objectives of this PhD project are to better understand ECC in practice and how it may improve the physical performance of trained athletes. The research explores novel means of

assessing eccentric ability and provides new knowledge regarding the objective prescription and application of this training methodology. Finally, this thesis aims to assist practitioners with the quantification of training interventions and subsequent adaptations in athletic populations.

1.3 Thesis structure

The thesis is made up of 4 sections containing 8 chapters in total (Figure 3). Section 1 is an introduction to the scope and purpose of the thesis. Section 2 contains Chapter 2 and Chapter 3 which together illustrate the theoretical and practical foundations of eccentric-based training. Chapter 2 is a systematic literature review of ECC specific to improving physical performance in team sport athletes. Chapter 3 describes the uptake of ECC in practice through a survey of strength and conditioning practitioners. Section 3 builds on the gaps in practice identified in Chapter 3 through the development of a novel eccentric testing protocol (Chapter 4), which was implemented with a cohort of trained athletes to better understand the kinetic and kinematic properties of ECC (Chapter 5). The association between these ECC properties and common measures of physical performance were then explored in semi-professional athletes (Chapter 6). Two different ECC programs were then developed based on what is commonly implemented in practice (Chapter 3) and the findings of our eccentric testing protocol (Chapter 5). The effects of these two ECC programs on physical performance were then examined over a 6-week training program (Chapter 7). Lastly, the findings of the thesis are summarised along with directions for future research.

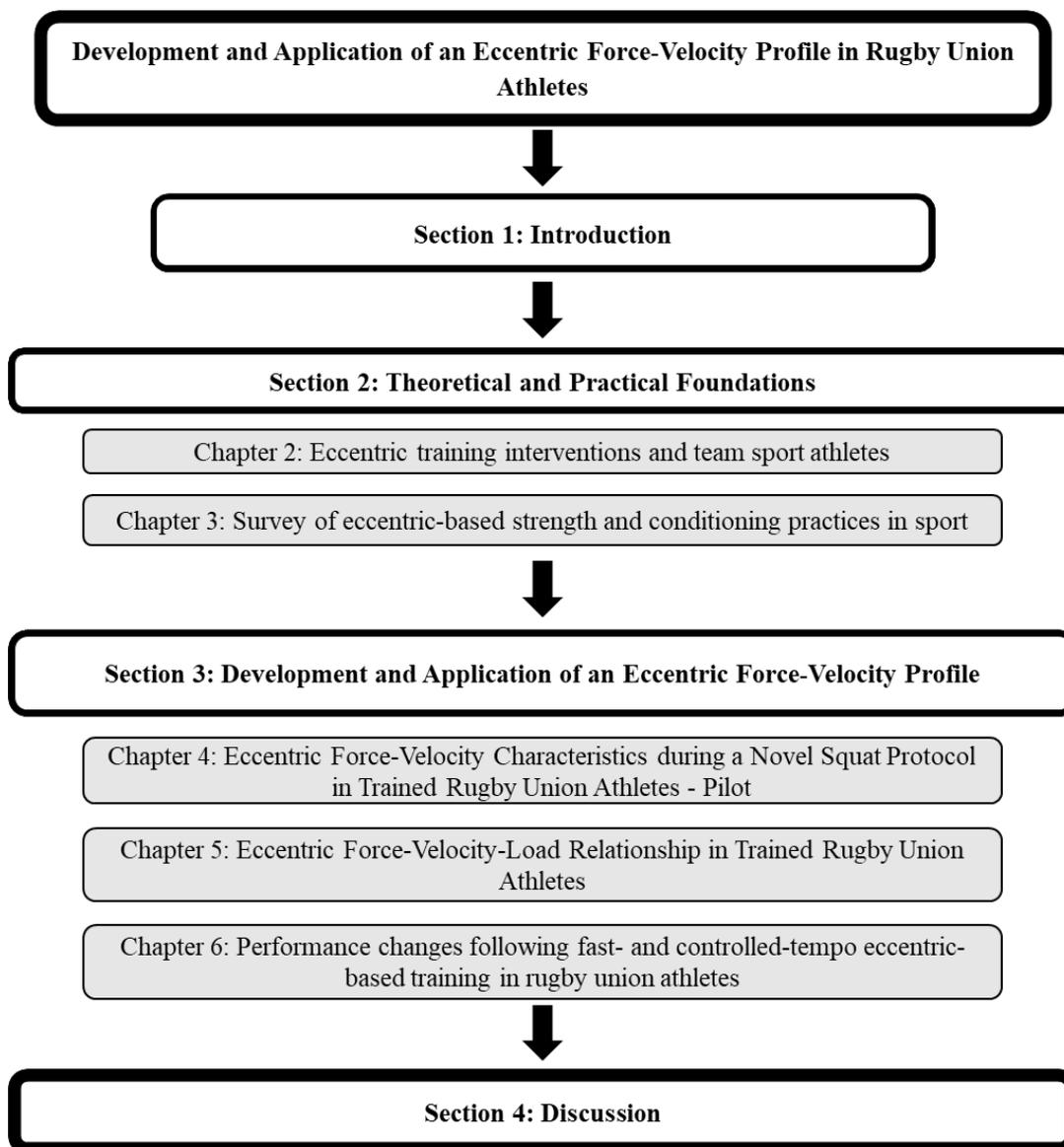


Figure 3. Structure and organisation of the thesis.

Chapters 2 through 7 (excluding Chapter 6) represent work that is either currently published or has been submitted for publication, and as a result are formatted according to journal specifications. In order to create a cohesive structure across the thesis, a short introduction is included prior to each chapter. To further aid in a coherent format, references are included as one list at the end of the thesis document.

SECTION 2

Theoretical and Practical Foundations

CHAPTER 2:

Eccentric training interventions and team sport athletes

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2019). Eccentric training interventions and team sport athletes. *Journal of Functional Morphology and Kinesiology*, 4(4), 67.

Prelude: This chapter is intended to explore the existing literature for evidence of eccentric training strategies in competitive team sport athletes. Eccentric-based resistance training has been shown to improve performance outcomes in a range of populations making it a popular choice for practitioners. The purpose of this review is to examine the current evidence related to the effects of eccentric-based resistance training on performance qualities in trained male team sport athletes.

2.1 Introduction

There is growing evidence in the literature that strongly supports eccentric resistance training as an effective stimulus for enhancing physical performance (Douglas et al., 2017b). During an eccentric contraction, kinetic energy is transferred and stored as elastic potential energy within the muscle tendon unit (Lindstedt et al., 2001), which can acutely enhance force production in the subsequent concentric contraction through the stretch-shortening cycle (Cormie et al., 2011; Komi, 2000; Wilson & Flanagan, 2008). Training methods that take advantage of the eccentric phase have been referred to in the literature as eccentric overload (EO) and accentuated eccentric loading (AEL) (Guilhem et al., 2010; Isner-Horobeti et al., 2013; Wagle et al., 2017). These terms refer to the manipulation of force and time variables during the eccentric phase of exercise through the application of relatively high force or high velocity (Chaabene et al., 2018; Schoenfeld et al., 2017; Vogt & Hoppeler, 2014). Longitudinal eccentric training may benefit team sport athletes who are required to produce force quickly during rapid movement through favourable neuromuscular and morphological adaptations (Douglas et al., 2017a). The purpose of this systematic review was to investigate the effects of EO and AEL on performance qualities in trained male team sport athletes.

2.2 Materials and Methods

2.2.1 Search Strategy

One reviewer conducted the literature search according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic reviews (Moher et al., 2009). The electronic databases PubMed, SPORTDiscus and Web of Science were searched up until 23 May 2019. No date ranges were imposed on the individual databases. Search terms included: ‘eccentric exercise’, ‘eccentric training’, ‘eccentric

contraction’, ‘strength’, ‘power’, ‘speed’, ‘velocity’, ‘force’, ‘hypertrophy’, ‘athletes’, and ‘team sports’. Boolean operators ‘AND’ and ‘OR’ were used to combine key search terms. When applicable, filters were used during the initial literature search to identify relevant articles. Full-text articles from peer-reviewed academic journals written in English were included, while articles involving animal (non-human), youth (<17 years old), and older (>44 years old) participants were excluded.

Once the initial search had been conducted, the articles were stored in reference manager software (Zotero, version 5.0.52, Corporation for Digital Scholarship, Vienna, VA, USA). Duplicate articles were manually reviewed and merged using the included “Duplicate Items” function. From the company’s website, “Zotero assesses records for duplicates based on the title, DOI, and ISBN fields to determine duplicates. If these fields match (or are absent), Zotero also compares the years of publication (if they are within a year of each other) and author/creator lists (if at least one author last name plus first initial matches) to determine duplicates” (www.zotero.org). The titles and abstracts of the remaining records were then screened. Articles not meeting the inclusion/exclusion criteria were removed, and the remaining records were assessed. Those full-text studies meeting the eligibility criteria were then assessed for inclusion in the review. An additional search was carried out using the reference lists of articles; those records identified through the additional search were then subjected to the same systematic process. Finally, all of the studies deemed to meet the criteria were assessed for methodological quality and included in the review.

2.2.2 Eligibility Criteria

Studies meeting the following inclusion criteria were included in the review:

- Participants were healthy, competitive, male team sport athletes above the recreational level (i.e., professional, national, elite) and were between 17 and 35 years of age.
- The sports included in the review following the screening process were basketball, soccer, handball, and rugby union.
- Studies investigated the effects of longitudinal (\geq three weeks) EO training interventions. Eccentric training load (volume, intensity) needed to be quantified.
- Data on at least one of the following outcome measures were reported: strength (e.g., 1RM, maximal voluntary contraction, peak torque), maximum sprint times (e.g., 10 m, 20 m, 40 m sprint), power (e.g., jump height, rate of force development), and change of direction (e.g., T-test, cutting).

Studies with the following exclusion criteria were not included in the review:

- Participants were individual sport athletes (i.e., skiing, cycling, running) or untrained (students or with less than six months training experience). Studies not listing the training experience/sport status of participants were also excluded.
- Studies investigating male and female athletes were excluded if the results were not reported separately.
- The training intervention included injured participants.
- Supplements or ergogenic aids were used in the intervention.

2.2.3. Study Selection

The eligibility assessment was performed in an unblinded manner by a single reviewer. The study selection process used is visually represented by Figure 4. Those studies identified through the initial search outlined above or identified through reference lists were then

screened for eligibility criteria. If there was uncertainty about whether a study met the standard for inclusion, an additional reviewer (C.Martyn Beaven) was consulted and an agreement was reached ($n = 5$).

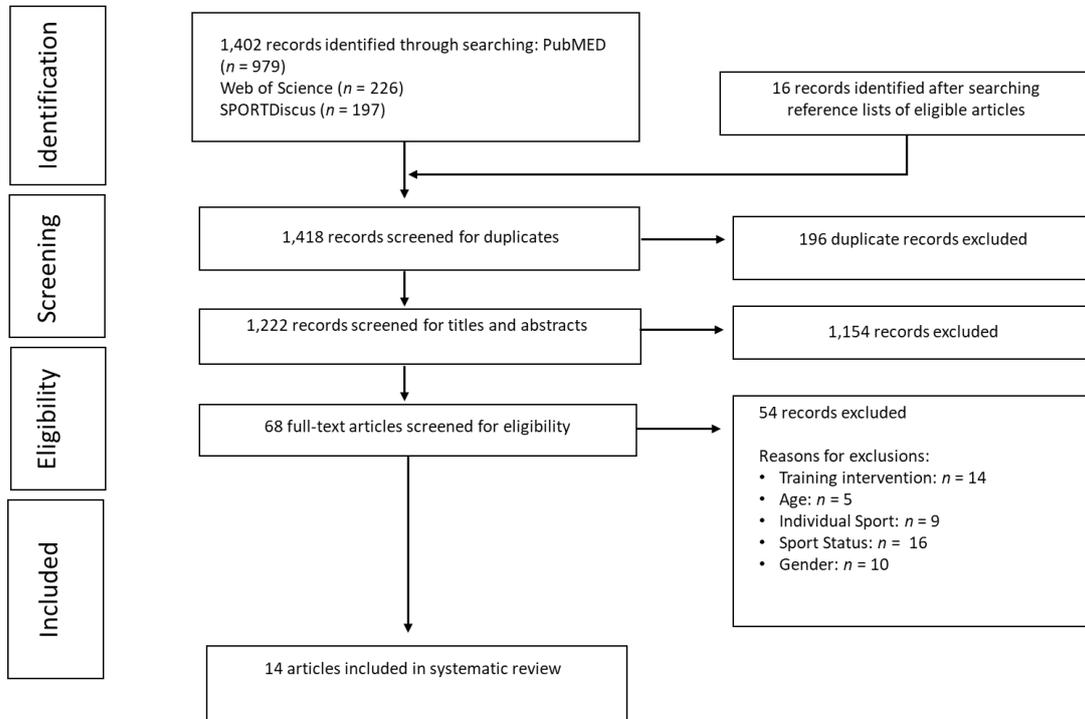


Figure 4. Flow chart of the literature search process using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.2.4. Analysis of Results

The remaining 14 articles were evaluated using a 10-item scale designed for exercise training studies (Brughelli et al., 2008). The goal of the scale was to assess the quality of strength and conditioning interventions, which might otherwise score poorly in assessments designed for healthcare research and interventions. This scale includes a 10-item scale (range 0 to 20) designed for rating the methodological quality of exercise training studies (Table 1). Two authors conducted the quality assessment independently; any discrepancies between the scores were discussed and a consensus was reached ($n = 8$). The score for each criterion was as follows: 0 = “clearly no”, 1 = “maybe”, and 2 = “clearly yes”.

The items included:

- 1 Inclusion criteria were clearly stated;
- 2 Participants were randomly allocated to groups;
- 3 Intervention was clearly defined;
- 4 Groups were tested for similarity at baseline;
- 5 Use of a control group;
- 6 Outcome variables were clearly defined;
- 7 Assessments were practically useful;
- 8 Duration of intervention was practically useful;
- 9 Between-group statistical analysis was appropriate;
- 10 Point measures of variability.

Table 1. Quality assessment for each study included in the literature review.

Author	Inclusion Criteria	Random Allocation	Intervention Defined	Groups Tested for Similarity at Baseline	Control Group	Outcome Variables Defined	Assessments Practically Useful	Duration of Intervention Practically Useful	Between-Group Stats Analysis Appropriate	Point Measures of Variability
Askling et al. (2003)	2	2	2	2	2	2	1	2	2	2
Brughelli et al. (2010)	1	2	1	1	2	2	1	2	2	2
Cook et al. (2013)	0	2	2	1	2	2	2	2	1	2
de Hoyo et al. (2015)	2	0	2	0	2	2	2	2	2	2
de Hoyo et al. (2016)	2	0	2	0	2	2	0	2	2	2
Iga et al. (2012)	0	2	2	2	2	2	1	2	2	2
Ishøi et al. (2018)	2	2	2	0	2	2	1	2	2	2
Krommes et al. (2017)	2	2	2	0	2	2	2	2	0	2
Maroto-Izquierdo et al. (2017)	2	2	2	0	2	2	2	2	2	1
Mendiguchia et al. (2015)	2	2	2	1	2	2	1	2	2	2
Mjøltnes et al. (2004)	0	2	2	0	2	2	1	2	1	2
Sabido et al. (2017)	0	0	2	2	2	2	2	2	2	2
Suarez-Arrones et al. (2018)	2	0	2	0	0	2	2	2	1	1
Sanchez-Sanchez et al. (2019)	0	2	2	0	2	2	2	2	2	2

One reviewer created a data extraction form based on several existing literature reviews (Douglas et al., 2017b; Isner-Horobeti et al., 2013; Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017; Roig et al., 2009) and variables of interest related to the research questions. This extraction form was created using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA). The reviewer then manually extracted data from each study for the following physical qualities: strength, speed, power and change of direction. Where possible the mean, standard deviation, percent difference and effect size statistic were calculated. If the relevant information (sample size, standard deviation, change in means) was not available, then the authors' reported values were used. Effect size was calculated for each treatment to determine the magnitude of change in the outcome variable using the mean difference (Mdiff), pooled pre- (SD₁) and post-test (SD₂) standard deviation and pre- and post-test sample size pairs (*n*) (Lakens, 2013). A majority of studies meeting the inclusion criteria had a sample size of fewer than 20 participants; as such, Hedges' *g* correction was applied to Cohen's *d*, as it has been shown to correct for small sample bias (Lakens, 2013).

$$\text{Cohen's } d_{av} = \frac{Mdiff}{\frac{SD_1 + SD_2}{2}} \quad (1)$$

$$\text{Hedge's } g_{av} = \text{Cohen's } d_{av} \times \left(1 - \frac{3}{4(n) - 9}\right) \quad (2)$$

Values were interpreted as trivial $0.00 < \text{trivial} < 0.20$, $0.20 \leq \text{small} < 0.60$, $0.60 \leq \text{moderate} < 1.20$, $1.20 \leq \text{large} < 2.00$, $2.00 \leq \text{very large} < 4.00$ (Hopkins et al., 2009).

2.3. Results

2.3.1. Participant Characteristics

Data for participant and training intervention characteristics are reported as mean \pm standard deviation, unless otherwise stated. A total of 14 studies met the inclusion criteria and were included in the review, with a summary of the participant characteristics provided in Table 2. A total of 357

participants were recruited and included in the analysis. Of the 357 total participants, 203 were included in the experimental group, with the remaining 154 participants serving as controls; one study used a crossover design with participants serving as their own controls ($n = 20$). Background variables were provided in all studies except one (Mjøl̄snes et al., 2004). Participants took part in a range of team sports including basketball, soccer, handball, and rugby union. Elite junior or academy athletes were recruited in four studies (de Hoyo et al., 2015, 2016; Ishøi et al., 2018; Suarez-Arrones, 2018). Athletes from professional or Division I sport organisations were recruited in six studies (Askling et al., 2003; Iga et al., 2012; Krommes et al., 2017; Maroto-Izquierdo, García-López, & de Paz, 2017; Mjøl̄snes et al., 2004; Sabido et al., 2017). The remainder of studies recruited semi-professional or lower division athletes.

Table 2. Study characteristics for eccentric overload training interventions with male team sport athletes.

Study (Year)	Sample Size	Population	Age (Years)	Height (m)	Body Mass (kg)	Sport	Quality Assessment
Askling et al. (2003)	Exp = 15	Swedish Premier league	24.0 ± 2.6	1.82 ± 0.06	78.0 ± 5.0	Soccer	19
	Con = 15		26.0 ± 3.6	1.81 ± 0.07	77.0 ± 6.0		
Brughelli et al. (2010)	Exp = 13	Division 2 Spanish soccer	20.7 ± 1.6	1.80 ± 0.07	73.1 ± 6.0	Soccer	16
	Con = 11		21.5 ± 1.3	1.79 ± 0.07	72.5 ± 7.5		
Cook et al. (2013)	Exp = 5	Semiprofessional rugby union	19.4 ± 0.5	1.85 ± 0.03	93.8 ± 7.0	Rugby Union	16
	Exp = 5		19.8 ± 0.8	1.87 ± 0.05	96.6 ± 9.3		
	Exp = 5		19.6 ± 0.9	1.85 ± 0.04	95.8 ± 7.7		
	Exp = 5		19.8 ± 0.4	1.83 ± 0.05	92.8 ± 6.0		
de Hoyo et al. (2015)	Exp = 18	Division 1 Spanish academy soccer	18.0 ± 1.0	1.78 ± 0.03	70.9 ± 3.9	Soccer	16
	Con = 15		17.0 ± 1.0	1.78 ± 0.01	73.1 ± 2.6		
de Hoyo et al. (2016)	Exp = 17	Division 1 Spanish academy soccer	17.0 ± 1.0	1.78 ± 0.02	71.4 ± 3.9	Soccer	14
	Con = 14						
Iga et al. (2012)	Exp = 10	English Professional League	23.4 ± 3.3	1.77 ± 0.07	78.0 ± 8.2	Soccer	17
	Con = 8		22.3 ± 3.9	1.85 ± 0.09	78.0 ± 11.1		
Ishoi et al. (2018)	Exp = 11	Division 4 Danish academy soccer	19.1 ± 1.8	1.81 ± 0.07	76.2 ± 11.9	Soccer	17
	Con = 14		19.4 ± 2.1	1.81 ± 0.07	77.0 ± 8.7		
Krommes et al. (2017)	Exp = 9	Division 1 Danish professional soccer	23.0 ± 3.9	1.83 ± 0.05	73.1 ± 5.8	Soccer	16
	Con = 10		25.1 ± 4.9	1.81 ± 0.07	77.9 ± 9.9		
Maroto-Izquierdo et al. (2017)	Exp = 15	Division 1 professional handball	19.8 ± 1.0	1.86 ± 0.08	82.3 ± 3.3	Handball	17
	Con = 14		23.8 ± 1.6	1.84 ± 0.01	85.6 ± 3.7		

Mendiguchia et al. (2015)	Exp = 27	Semiprofessional Spanish soccer	22.7 ± 4.8	1.75 ± 0.06	71.6 ± 8.7	Soccer	18
	Con = 24		21.8 ± 2.5	1.77 ± 0.06	71.0 ± 7.7		
Mjølsnes et al. (2004)	Exp = 11	Division 1–4 Danish soccer				Soccer	14
	Exp = 9						
Sabido et al. (2017)	Exp = 11	Division 1 handball	23.9 ± 3.8	1.83 ± 0.07	79.5 ± 7.7	Handball	16
	Con = 10						
Sanchez-Sanchez et al. (2019)	Exp = 12	Regional	22.5 ± 2.2	1.76 ± 0.07	72.6 ± 9.1	Soccer/Basketball	16
	Con = 10						
Suarez-Arrones et al. (2018)	Exp = 14	Serie A Professional	17.5 ± 0.8	1.80 ± 0.06	70.6 ± 5.3	Soccer	12

2.3.2. Intervention Characteristics

Training interventions lasted from 3 to 10 weeks (8.1 ± 2.6), including 7 to 18 training sessions (13.3 ± 3.1), with the exception of Suarez-Arrones et al. (2018), whose intervention included 54 sessions over 27 weeks. Studies utilised a wide range of equipment including free weights typically found in performance settings, inertial flywheel devices or bodyweight-exercise based equipment. The prescribed training volume ranged from one to six sets of 5 to 12 repetitions. One study reported the number of sets (four) but not the number of repetitions (Brughelli et al., 2010). Five studies in total followed the Nordic hamstring exercise protocol (NORD) as described by Mjølsnes et al. (2004) which is a 10 week intervention progressively increasing volume from two to three sets of 5 to 12 repetitions utilising the NORD, performed concurrently with soccer specific training.

The prescription method of exercise intensity used in the experimental groups was quantified in only three studies. These authors prescribed intensity based on percentage of one repetition maximum (1RM) (Cook et al., 2013), percentage of bodyweight (Mendiguchia et al., 2015) or through a familiarisation protocol (Suarez-Arrones, 2018). The remaining studies verbally encouraged participants to produce a maximal effort either against a flywheel device of varying inertial resistance (Askling et al., 2003; de Hoyo et al., 2015, 2016; Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017; Sabido et al., 2017), or during the eccentric phase of bodyweight exercise (Brughelli et al., 2010; Ishøi et al., 2018; Krommes et al., 2017; Mjølsnes et al., 2004; Rey et al., 2017). Compliance to the training intervention was reported in all but three studies (Askling et al., 2003; Cook et al., 2013; Ishøi et al., 2018). Compliance values ranged from 70% to 100% ($94.5\% \pm 10.5\%$). All studies reporting concurrent sport practice in addition to the intervention reported no differences in sport-specific training volume between the experimental and control groups.

2.3.3. Outcome Measures

2.3.3.1. Strength

Strength outcomes were assessed in 9 of the 14 studies included in the literature review (Table 3). Five of the nine studies used an isokinetic dynamometer to perform the strength assessment. Training interventions utilised inertial flywheel devices (Askling et al., 2003; de Hoyo et al., 2015, 2016; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017; Sanchez-Sanchez et al., 2019; Suarez-Arrones, 2018), traditional isoinertial equipment (Cook et al., 2013; Mendiguchia et al., 2015) or exercises performed with bodyweight (Brughelli et al., 2010; Iga et al., 2012; Ishøi et al., 2018; Krommes et al., 2017; Mjøl̄snes et al., 2004). Mendiguchia et al. (2015) used both isoinertial and bodyweight exercises. Studies including the NORD reported effect sizes ranging from trivial (-0.17) (Brughelli et al., 2010) to moderate (0.60) (Mjøl̄snes et al., 2004). Effect sizes (0.81 to 1.06) were calculated for research involving inertial flywheel devices. Only Cook et al. (2013) reported outcome data for strength testing and training with isoinertial equipment. The authors found large (1.22 , bench press) to very large (2.16 , back squat) effects when eccentric training was compared to traditional training.

3.3.2. Speed

Nine of the fourteen studies reported outcomes measures of speed (Table 4): these measures included velocity (Mendiguchia et al., 2015), top speed (Mendiguchia et al., 2015) and time variables (Askling et al., 2003; Cook et al., 2013; de Hoyo et al., 2015; Ishøi et al., 2018; Krommes et al., 2017; Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017; Suarez-Arrones, 2018). For clarity, positive effect sizes represent a favourable change. Training interventions with flywheel devices reported effect sizes ranging from 0.19 (de Hoyo et al., 2015) to 0.98 (Maroto-Izquierdo, García-López, & de Paz, 2017). There were mixed results for NORD training interventions with some unfavourable (-0.07 to -0.60) and favourable (0.20 to 0.81) changes in speed outcomes. EO effects on short sprint (<10 m) times (0.19 to 0.81) (de Hoyo et al., 2015; Ishøi

et al., 2018; Krommes et al., 2017; Suarez-Arrones, 2018) were also compared to longer sprint times (>10 m) (-0.60 to 0.98) (Askling et al., 2003; de Hoyo et al., 2015; Krommes et al., 2017; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017).

3.3.3. Power

Explosive movement was measured using a variety of tests (counter-movement jump (CMJ), triple jump, leg press and throwing) in 7 of the 14 studies included in this review (Table 5). CMJ was assessed in six of the studies investigating power. Effect sizes for jump height (CMJ) ranged from small (0.27) to moderate (0.69). Cook et al. (2013) combined isoinertial eccentric training with overspeed exercises (1.22). Flywheel studies investigating lower-body power measures reported effect sizes of 0.29 to 1.63. Krommes et al. (2017) reported an effect size of 0.27 after a NORD intervention. One study examined upper-body power despite not including upper-body training (-0.13) (Sabido et al., 2017).

Table 3. Eccentric training intervention characteristics for strength outcomes.

Study (Year)	Weeks	Sessions	Sets × Reps	Equipment	Intensity	Prescription Method	Results
Askling et al. (2003)	10	16	4 × 8	Flywheel	60° s ⁻¹ or 1.5 s	“Max Effort”	EKFPT (28, 18.9%, <i>g</i> = 1.06); CKFPT (20, 15.3, <i>g</i> = 0.81)
Brughelli et al. (2010)	4	12	4–5 × ?	Bodyweight	n/a	“Max Effort”	CKFPT (-4, -2%, <i>g</i> = -0.17); CKEPT (6, 2.1%, <i>g</i> = 0.17)
Cook et al. (2013)	3	12	4 × 5	Isoinertial	80–120% 1RM	%1RM	Bench1RM (<i>g</i> = 1.22); Squat1RM (<i>g</i> = 0.9)
Iga et al. (2012)	4	9	2–3 × 5–8	Bodyweight	30° s ⁻¹ or 1 s	“Max Effort”	EKFPT (9 to 20, 7.4% to 20.2%, <i>g</i> = 0.19 to 0.54)
Ishoi et al. (2018)	10	12	2–3 × 5–12	Bodyweight	n/A	“Max Effort”	EKFPT (61.7, 19.2%, <i>g</i> = 0.94)
Maroto-Izquierdo et al. (2017)	6	15	4 × 7	Flywheel	Two 6.5 kg flywheels with moment inertia of 0.145 kg·m ²	“Max Effort”	LegPress1RM (31.6, 12.2%, <i>g</i> = 0.69)
Mendiguchia et al. (2015)	7	14	1–3 × 2–8	Isoinertial + Bodyweight	5–15 kg or 10–70% BW	Absolute Load + % Bodyweight	CKFPT (16.3 to 18.4, -12.1% to 13.1, <i>g</i> = 0.67 to 0.70); EKFPT (31.3 to 42.3, 13.2% to 17.2%, <i>g</i> = 0.68 to 0.96)
Mjølshes et al. (2004)	10	12	2–3 × 5–12	Bodyweight	n/a	“Max Effort”	EKFPT (27, 11.3%, <i>g</i> = 0.60)
Sabido et al. (2017)	7	7	2–4 × 8	Flywheel	Flywheel disc with inertia moment of 0.05 kg m ²	“Max Effort”	HalfSquat1RM (16.5, 14.2%, <i>g</i> = 1.67)

Notes. Results are reported as (change in mean, % difference, Hedges’ *g*). *Abbreviations.* EKFPT (Eccentric Knee Flexor Peak Torque), CKFPT (Concentric Knee Flexor Peak Torque), CKEPT (Concentric Knee Extensor Peak Torque), Bench1RM (Bench Press 1RM), Squat1RM (Back Squat 1RM), HalfSquat1RM (Half Squat 1RM), and LegPress1RM (Leg Press 1RM).

Table 4. Eccentric training intervention characteristics for speed outcomes.

Study (Year)	Weeks	Sessions	Sets × Reps	Equipment	ECC Load/Intensity	Prescription Method	Results
Askling et al. (2003)	10	16	4 × 8	Flywheel	60° s ⁻¹ or 1.5 s	“Max Effort”	F30 m (−0.08, −2.4%, <i>g</i> = 0.73)
Cook et al. (2013)	3	12	4 × 5	Isoinertial	80–120% 1RM	%1RM	Eccentric + Overspeed vs. Traditional 40 m (0.01, <i>g</i> = 1.06)
de Hoyo et al. (2015)	10	18	3–6 × 6	Flywheel	Concentric = optimal power output (per inertia = 0.11 kg/m ²)	“Max Effort”	10 m (−0.02, 1%, <i>g</i> = 0.18); F10 m (−0.04, 3.3%, <i>g</i> = 0.84); 20 m (−0.04, 1.5%, <i>g</i> = 0.30)
Ishøi et al. (2018)	10	12	2–3 × 5–12	Bodyweight	n/a	“Max Effort”	10 m (−0.04, 2.6%, <i>g</i> = 0.54)
Krommes et al. (2017)	10	12	2–3 × 5–12	Bodyweight	n/a n/a	“Max Effort”	5 m (−0.09, −10%, <i>g</i> = 0.81); 10 m (−0.10, −6%, <i>g</i> = 0.64); 30 m (0.10, 2.4%, <i>g</i> = −0.60)
Maroto-Izquierdo et al. (2017)	6	15	4 × 7	Flywheel	Two 6.5 kg flywheels with moment inertia of 0.145 kg·m ²	“Max Effort”	20 m (−0.40, −10.8%, <i>g</i> = 0.98)
Mendiguchia et al. (2015)	7	14	1–3 × 2–8	Isoinertial + Bodyweight	5–15 kg or 10–70% BW	Absolute Load + % Bodyweight	v5 m (0.20, 1.0%, <i>g</i> = 0.20); v20 m (−0.1, −0.4%, <i>g</i> = −0.08); TS (−0.1, −0.3%, <i>g</i> = −0.08)
Sabido et al. (2017)	7	7	2–4 × 8	Flywheel	Flywheel disc with inertia moment of 0.05 kg m ²	“Max Effort”	20 m (−0.08, −2.5%, <i>g</i> = 0.82)
Suarez-Arrones et al. (2018)	27	54	1–2 × 5–10	Inertial + Bodyweight	Inertia 0.05 kg/m ²	Highest power output between two loads during familiarization	10 m (<i>g</i> = 0.41); 30 m (<i>g</i> = 0.38); 40 m (<i>g</i> = 0.31)

Notes. Results are reported as (change in mean, % difference, Hedges’ *g*). *Abbreviations.* 5 m (5 m Sprint), 10 m (10 m Sprint), F10 m (Flying 10 m Sprint), 30 m (30 m Sprint) F30 m (Flying 30 m Sprint), v5 m (5 m velocity), v20 m (20 m velocity), and TS (Top Speed velocity)

Table 5. Eccentric training intervention characteristics for power outcomes.

Study (Year)	Weeks	Sessions	Sets × Reps	Equipment	ECC Load/Intensity	Prescription Method	Results
Cook et al. (2013)	3	12	4 × 5	Isoinertial	80–120% 1RM	%1RM	Eccentric + Overspeed CMJPP ($g = 1.22$)
de Hoyo et al. (2015)	10	18	3–6 × 6	Flywheel	Concentric = optimal power output (per inertia = 0.11 kg/m ²)	“Max Effort”	CMJ (2.6, 7.3%, $g = 0.60$)
Krommes et al. (2017)	10	12	2–3 × 5–12	Bodyweight	n/a	“Max Effort”	CMJ (1.15, 2.6%, $g = 0.27$)
Maroto-Izquierdo et al. (2017)	6	15	4 × 7	Flywheel	Two 6.5 kg flywheels with moment inertia of 0.145 kg·m ²	“Max Effort”	PWR90 (167.5, 21.5%, $g = 0.71$); PWR80 (165.6, 19.7%, $g = 0.73$); PWR70 (113.6, 12.4%, $g = 0.52$); PWR60 (91.5, 10.0%, $g = 0.41$); PWR50 (167.5, 21.5%, $g = 0.99$); CMJ (3.5, 9.8%, $g = 0.61$); SJ (3.3, 9.9%, $g = 0.54$)
Sabido et al. (2017)	7	7	2–4 × 8	Flywheel	Flywheel disc with inertia moment of 0.05 kg·m ²	“Max Effort”	CMJ (2.4, 6.0%, $g = 0.47$); TJ_R (0.19, 2.9%, $g = 0.29$); TJ_L (0.40, 6.2%, $g = 0.74$)
Sanchez-Sanchez et al. (2019)	5	10	2–3 × 6	Flywheel	Iso-inertial pulley (0.27 kg/ m ²) and flywheel (0.05 kg/m ²)	“Max Effort”	CMJ (2.6, 7.4%, $g = 0.46$)
Suarez-Arrones et al. (2018)	27	54	1–2 × 5–10	Inertial + Bodyweight	Inertia 0.05 kg·m ²	Highest power output between two loads during familiarization	HalfSquat30 ($g = 0.42$); HalfSquat40 ($g = 0.47$); RLHS30 ($g = 0.48$); LLHS30 ($g = 0.85$); RLHS40 ($g = 1.03$); LLHS40 ($g = 1.63$)

Notes. Results are reported as (change in mean, % difference, Hedges’ g). *Abbreviations.* CMJPP (Counter-movement Jump Peak Power), CMJ (Counter-movement Jump height), HalfSquat30 (Half Squat power at 30 kg), HalfSquat40 (Half Squat power at 40 kg), PWR90 to PWR 50 (Power at 90% to 50% 1RM Leg Press (W)), RLHS30 (Right Leg Half Squat power at 30 kg), LLHS30 (Left Leg Half Squat power at 30 kg), RLHS40 (Right Leg Half Squat power at 40 kg), LLHS40 (Left Leg Half Squat power at 40 kg), TJ_R (Triple Jump Right Leg), and TJ_L (Triple Jump Left Leg).

3.3.4. Change of Direction

Only three studies investigated the effects of eccentric training on change of direction performance (Table 6). The investigation by de Hoyo et al. (2016) used force plates to capture kinetic data in crossover and sidestep tasks. Contact time (0.48 to 1.43) and braking time (0.60 to 0.95) both displayed small to moderate effects. Effect size for peak braking force (0.72 to 0.84) and braking impulse (0.53 to 0.92) ranged from small to moderate. Two studies reported (Maroto-Izquierdo, García-López, & de Paz, 2017; Sanchez-Sanchez et al., 2019) moderate to large effect sizes (0.93 to 1.46) for changes in Illinois and T-test performance.

Table 6. Eccentric training intervention characteristics for change of direction outcomes.

Study (year)	Weeks	Sessions	Sets × Reps	Equipment	ECC Load/Intensity	Prescription Method	Results
							BT_crossover (0.01, 16.7%, $g = 0.60$);
							BT_sidestep (0.01, 16.7%, $g = 0.95$);
							CT_crossover (0.01, 7.1%, $g = 0.48$);
							CT_sidestep (0.03, 20.0%, $g = 1.43$);
de Hoyo et al. (2016)	10	18	3–6 × 6	Flywheel	Concentric = optimal power output (per inertia = 0.11 kg/m ²)	“Max Effort”	rB_IMP_crossover (0.16, 21.6%, $g = 0.92$);
							rB_IMP_sidestep (0.13, 13.5%, $g = 0.53$);
							rPB_crossover (7.4, 29.1%, $g = 0.72$);
							rPB_sidestep (9.0, 29.7%, $g = 0.84$)
Maroto-Izquierdo et al. (2017)	6	15	4 × 7	Flywheel	Two 6.5 kg flywheels with moment inertia of 0.145 kg·m ²	“Max Effort”	T-test (0.6, 6.5%, $g = 1.46$)
Sanchez-Sanchez et al. (2019)	5	10	2–3 × 6	Flywheel	Iso-inertial pulley (0.27 kg/ m ²) and flywheel (0.05 kg/m ²)	“Max Effort”	Illinois (1.0, 5.6%, $g = 0.93$)

Notes. Results are reported as (change in mean, % difference, Hedges' g). Abbreviations. **BT_crossover** (Braking Time in crossover cutting), **BT_sidestep** (Braking Time in sidestep cutting), **CT_crossover** (Contact Time in crossover cutting), **CT_sidestep** (Contact Time in sidestep cutting), **rB_IMP_crossover** (Relative Braking Impulse in crossover cutting), **rB_IMP_sidestep** (Relative Braking Impulse in sidestep cutting), **rPB_crossover** (Relative Peak Braking Force in crossover cutting), and **rPB_sidestep** (Relative Peak Braking Force in sidestep cutting).

2.4. Discussion

The goal of this systematic review was to identify and evaluate the existing literature surrounding EO training interventions and their effects on performance measures in trained team sport athletes. The current evidence is in support of the inclusion of eccentric training in training programs to improve performance measures of strength, speed, power and change of direction. However, inconsistencies exist within the literature with regard to methodologies and variables of interest that need careful consideration before the results can be extrapolated to other athletes or populations.

The quantification and prescription of EO intensity in well-trained athletes was only reported in four studies focused on performance outcomes (Askling et al., 2003; Cook et al., 2013; Iga et al., 2012; Mendiguchia et al., 2015). The loading parameters (i.e., load magnitude, repetitions, tempo) were unspecified in several training interventions (Brughelli et al., 2010; Ishøi et al., 2018; Krommes et al., 2017; Mjølunes et al., 2004), making it difficult to assess the connection between stimulus and adaptation (Toigo & Boutellier, 2006). Interestingly, Cook et al. (2013) were the only authors to prescribe supramaximal training loads (>100% 1RM), even though this method does not require specialised equipment beyond typical barbells and weight plates. The remaining two studies either estimated joint angular velocities (Askling et al., 2003) or used submaximal loads (Mendiguchia et al., 2015). Other prescription methods relied on instructing participants to perform one or more phases of the exercise with “maximal effort” (Brughelli et al., 2010; Ishøi et al., 2018; Mjølunes et al., 2004; Rey et al., 2017), but provided no further evidence for EO. Tous-Fajardo et al. (2006) observed that the magnitude of eccentric peak force with a flywheel device is largely dictated by the trainee, and that differences in EO exist between those with and without flywheel training experience. Thus, the

quantification of neuromuscular and mechanical output data in EO exercises may be necessary to determine the extent of training load and subsequent adaptation.

2.4.1. Strength

Maximum strength, as measured by a single maximal voluntary contraction, is influenced by both neurological and morphological factors that can be influenced through EO (Douglas et al., 2017b). Studies involving trained (Friedmann-Bette et al., 2010; Helland et al., 2017; Núñez et al., 2018; Vikne et al., 2006) or untrained participants (English et al., 2014; Farthing & Chilibeck, 2003) have demonstrated an increase in maximal strength after EO interventions, which may be due to greater neurological contributions and/or type-II muscle fibre hypertrophy. These adaptations are thought to be a result of the high levels of tension developed in the muscle fibres (Toigo & Boutellier, 2006), with relatively lower metabolic cost and levels of activation when compared to concentric contractions (Beaven et al., 2014). These activation patterns may be a result of the distinct molecular and neural characteristics of eccentric contractions (Douglas et al., 2017a), and could necessitate specific strategies in order to accurately assess and prescribe eccentric training (Meylan et al., 2008). A recent review by Douglas et al. (2017b) highlighted that motor unit recruitment and discharge rates are contributing factors to improvements in eccentric strength following eccentric or heavy resistance training.

The velocity of EO training appears to play an important role in determining subsequent strength adaptation following the intervention. For example, Roig et al. (2009) reviewed eccentric and concentric training studies and found that eccentric stimuli produced superior improvements in total strength. However, the effects were greater when the testing and training

velocities were matched. The authors concluded that performance outcomes were mode- and velocity-specific. In contrast to these findings, other investigations (Farthing & Chilibeck, 2003; Paddon-Jones et al., 2001) have found that high-velocity EO training ($180^{\circ}\cdot\text{s}^{-1}$) had a greater degree of transfer than slow velocity EO training ($30^{\circ}\cdot\text{s}^{-1}$) during isokinetic testing. Furthermore, one review (Buskard et al., 2018) challenged whether EO provided any additional benefit over traditional training, suggesting that specific populations such as athletes and the untrained may respond differently to EO as a training stimulus depending on baseline strength capabilities.

Studies in the current review reported effect sizes from -0.17 (Brughelli et al., 2010) to 1.67 (Sabido et al., 2017) when EO training methodologies were applied to athletes. Training interventions and assessments that were matched on mode of contraction reported effect sizes from 0.19 (Iga et al., 2012) to 1.67 (Sabido et al., 2017). Brughelli et al. (2008) conducted concentric isokinetic testing following a training intervention that emphasized eccentric contractions. The authors did not speculate whether mode specificity might have played a role in their findings. The only three studies (Cook et al., 2013; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017) to report on dynamic (eccentric and concentric) strength tests (1RM leg press, back squat, half squat) demonstrated moderate (0.69) to large (1.67) effects. Although some transfer effect has been noted between contraction modes (Isner-Horobeti et al., 2013), this phenomenon is inconsistent within the literature (Roig et al., 2009).

Three studies investigating NORD and strength outcomes found small to moderate improvements in trained athletes (Iga et al., 2012; Ishøi et al., 2018; Mjølshnes et al., 2004). The isokinetic assessments used by these authors matched the mode of contraction used in the training interventions. Ditroilo et al. (Ditroilo et al., 2013) found that the NORD is capable of

producing EMG levels greater than those reported in maximal eccentric isokinetic testing, which supports the NORD as an effective EO exercise.

The effect and time course of training duration and number of sessions on strength outcomes following EO training is unclear, as both shorter (3 weeks) and longer (10 weeks) interventions and smaller (7) (Sabido et al., 2017) and larger (16) (Askling et al., 2003) numbers of sessions resulted in improvements. More research is needed to understand the dose–response relationship between EO and strength in trained athletes. With the exception of Brughelli et al. (Brughelli et al., 2010), studies investigating strength-based outcomes in athletes appear to be in agreement with the literature that supports EO as a potent stimulus for neuromuscular strength adaptation (Douglas et al., 2017b).

2.4.2. Speed

The effect of EO training on measures of linear sprint ability are thought to involve numerous components (Alcaraz et al., 2018). Briefly, sprint performance consists of several phases, including acceleration and maximal speed, which have distinct kinetic and kinematic features (von Lieres und Wilkau et al., 2018). Acceleration is characterised by extensor action in the hip, knee and ankle, maximal rate of force development over minimal time (RFD), maximal relative strength and higher ground contact time. Maximum-velocity sprinting involves the hip and ankle extensors, RFD and relatively short ground contact time. These features are related to physical qualities such as mechanical stiffness and stretch-shortening cycle (SSC) performance (Brughelli & Cronin, 2008; Farley & González, 1996; Komi, 2000; López Mangini & Fábrega, 2016; Voigt et al., 1995). Studies investigating the contribution of mechanical (Malliaras et al., 2013) and neuromuscular (Friedmann-Bette et al., 2010; Liu et

al., 2013; Mike et al., 2017; Núñez et al., 2018; Papadopoulos et al., 2014) factors have demonstrated improvements as a result of eccentric training.

Several articles identified throughout the literature search were in agreement with the apparent positive effect of EO on sprint performance. Each of the nine studies included in the review reported trivial to moderate improvements in speed measures. Investigations involving short sprints (<10 m) showed trivial to moderate effect sizes. Krommes et al. (2017) reported moderate improvements in 5 m (0.81) and 10 m (0.64) sprint times, but moderately slower times in 30 m sprints (-0.60). Cook et al. (2013) reported that eccentric training alone did not improve 40 m sprint speed. Mendiguchia et al. (2015) described trivial results in 5 m velocity (0.20) and 50 m top speed (-0.07). Additionally, bilateral and unilateral EO training have been reported to increase power and change of direction ability without improving 10 m sprint times (Núñez et al., 2018). A recent review favoured the use of EO with a flywheel device over traditional resistance training for improving running speed (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017). However, as mentioned previously, controversy exists as to whether certain inertial devices are capable of producing EO (Gonzalo-Skok et al., 2017; Tous-Fajardo et al., 2006), as force production is in part determined by the experience of the trainee. As previously mentioned, acceleration and maximum-velocity sprinting are distinct physical abilities and may depend on separate performance qualities. Thus, identification and examination of the factors associated with the prescription of EO to enhance specific aspects of sprint performance are necessary.

Contraction velocity appears to be a contributing factor to subsequent adaptations in EO research (Douglas et al., 2017b; Isner-Horobeti et al., 2013; Roig et al., 2009), with high velocities resulting in greater magnitudes of neuromuscular adaptation. A review by Guilhem

et al. (2010) stated that isokinetic angular velocity in the literature ranges from $30^{\circ}\cdot\text{s}^{-1}$ to $210^{\circ}\cdot\text{s}^{-1}$. Askling et al. (2003) were the only authors in the current review to report the joint angular velocity ($60^{\circ}\cdot\text{s}^{-1}$) used in training interventions for speed outcomes, which resulted in a moderate effect (0.73) in trained athletes. Based on previous research investigating high- and low-velocity training (Oliveira et al., 2016b; Paddon-Jones et al., 2001), $60^{\circ}\cdot\text{s}^{-1}$ may represent a relatively low training velocity. Limited availability of EO literature examining trained populations makes it difficult to draw generalisations; however, it is speculated that distinct sprint qualities may be differentially affected by EO training parameters such as velocity.

2.4.3. Power

The storage and reutilisation of elastic potential energy during the eccentric phase of the SSC is thought to contribute to jump performance (Bridgeman et al., 2018; Cormie et al., 2010; Di Giminiani & Petricola, 2016; Komi, 2000; Laffaye & Wagner, 2013; McGuigan et al., 2006). In the current review, changes in lower-body power performance were measured primarily with jumping variations. These investigations (de Hoyo et al., 2015; Krommes et al., 2017; Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017; Sanchez-Sanchez et al., 2019) revealed small to moderate (0.27 to 0.61) improvements in CMJ performance, while the inclusion of overspeed training protocols resulted in large (1.22) improvements (Cook et al., 2013). One reason for the efficacy of EO training in improving power performance may be that relatively fewer motor units are recruited, resulting in more muscle tension, especially at higher velocities (Farthing & Chilibeck, 2003; Guilhem et al., 2010). The high levels of tension developed in the MTU may lead to adaptive responses in the elastic components of the muscle (Shepstone et al., 2005; Toigo & Boutellier, 2006).

However, investigations using EO have also reported no change in squat jump, counter-movement jump or rate of force development (Wirth et al., 2015). Additionally, eccentric duration and execution of the correct technique (Aboodarda et al., 2015; Mike et al., 2017) may actually decrease measures of velocity in a jump squat. Discrepancy in the effects of EO on power may be a result of individual differences (e.g., technique, anthropometric qualities, contractile and elastic capabilities), which have been shown to influence drop jump and CMJ performance (Bobbert et al., 1987). EO has also been shown to suppress performance qualities for extended periods of time, which could potentially interfere with results dependent on the timing of the post-testing regime (Brandenburg & Docherty, 2002; Leong et al., 2014). Thus, although there seems to be a favourable effect on the expression of power following EO, it is unclear whether the effect sizes related to power production in the literature review are affected by individual recovery profiles or individual differences.

2.4.4. Change of Direction

Despite recent evidence (Chaabene et al., 2018; Spiteri et al., 2014, 2015) on the relationship between eccentric strength and change of direction performance, only three studies in the present review examined any measure of agility. Kinetic data for a novel crossover and sidestep cutting task displayed moderate to large (0.48 to 1.43) changes in the eccentric phase of muscle action following an EO training intervention. Similar effect sizes (0.93 to 1.46) were reported for the Illinois and T-test times in trained athletes (Maroto-Izquierdo, García-López, & de Paz, 2017; Sanchez-Sanchez et al., 2019). Interestingly, neither study reported performing agility-specific training as part of the intervention. This lack of task-specific activities suggests that lower-body flywheel training may transfer to complex skills such as change of direction ability.

These findings are in agreement with existing literature that has reported improvements in change of direction ability following EO training interventions. Gonzalo-Skok et al. (2017) reported substantial improvements in measures of change of direction ability for two EO training programs. The authors reported that although bilateral and unilateral groups improved, differences existed between groups in power outputs and force-vector applications. These results support existing evidence (Núñez et al., 2018; Tous-Fajardo et al., 2016) for the positive but differential effects of EO on change of direction performance.

2.5. Conclusions

EO appears to be an effective training strategy for athletes and sports practitioners looking to improve measures of strength, speed, power and change of direction. The review highlights evidence suggesting EO can improve performance qualities even in experienced athletes. The exact neurological mechanisms and morphological adaptations underlying these changes have been the focus of a growing body of research. Due to a large degree of variation in the existing research, a dose-response relationship for a specific method and its intended adaptation has yet to be determined in trained team sport athletes. Future research should explore the quantification of eccentric ability, the prescription of eccentric training variables and the relationship between EO-induced adaptation and performance qualities.

CHAPTER 3:

Survey of eccentric-based strength and conditioning practices in sport

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2020). Survey of eccentric-based strength and conditioning practices in sport. *The Journal of Strength & Conditioning Research*, 34(10), 2769-2775.

Prelude: In conducting our literature review in the previous chapter the goal was to identify the evidence for eccentric-based training interventions in team sport athletes. ECC is well supported in scientific research and neuromuscular factors contributing to eccentric force production and subsequent adaptation have important benefits on physical performance. In the following chapter, we performed a survey to investigate the uptake of ECC research in applied settings. The intent was to inform both researchers and practitioners on ECC practices being implemented in the field and to identify gaps that may serve to further the body of research and influence practice.

3.1 Introduction

Resistance training using various loads and velocities can result in altered hormonal, structural and neuromuscular characteristics vital for athletic performance (American College of Sports Medicine, 2009). Eccentric-based training (ECC), which emphasizes the active lengthening of the muscle-tendon unit (MTU), has been proposed as an effective method of improving muscular strength, lean mass, and explosive ability and in some cases may be superior to traditional and concentric-only training (Douglas et al., 2017b; Roig et al., 2009; Vogt & Hoppeler, 2014). The manipulation of eccentric parameters may lead to adaptive responses in neuromuscular activation, type II muscle fiber hypertrophy, and the attenuation of muscle soreness (Douglas et al., 2017a) that could be of value to strength and conditioning practitioners.

Several studies have reported the relatively large force generating capacity and subsequent concentric force enhancement that characterizes eccentric contractions (English et al., 2014; Hollander et al., 2007; Lindstedt et al., 2001; Malliaras et al., 2013). However, the interactions between training variables (i.e. volume, loading, tempo), and physical performance in a practical setting warrant further research. These factors likely have implications in the prescription and adaptation to eccentric exercise throughout the training process.

Despite these positive reports, Buskard et al. (2018) questioned the justification of supramaximal ECC for all populations in a recent meta-analysis given their findings yielded similar benefits when compared to traditional training for weaker participants. Mike et al. (2017) demonstrated strength improvements with submaximal eccentric loads, but found longer eccentric durations actually decreased squat jump peak velocity. These findings suggest that the prescription process and the inclusion of other ECC methods (i.e. tempo) may have differential effects on strength and power outcomes. For practitioners, these factors will likely

play a role in the decision-making process of when and how to implement ECC in the annual training plan.

The efficacy of ECC as a training strategy for improving neuromuscular performance is well documented (Isner-Horobeti et al., 2013; Suchomel et al., 2019b; Wagle et al., 2017). Numerous investigations have reported positive physiological and performance outcomes following ECC in both untrained and athletic populations (Bogdanis et al., 2018; Coratella et al., 2015; de Hoyo et al., 2016; Ishøi et al., 2018; Krommes et al., 2017; Stasinaki et al., 2019). However, the extent to which this body of research influences practice remains to be seen. Therefore, the purpose of this study is to investigate common practices for ECC program design and implementation with athletes in actual training environments.

3.2 Methods

Experimental Approach to the Problem

The survey consisted of 44 total questions and was divided into four sections (Coach Demographic, Perceptions of Eccentric Training, Athlete Demographic, and Program Design). For clarity, eccentric exercise was defined as “an exercise where the downward portion of a movement is emphasized through tempo, load, velocity, etc.”. The ‘Coach and Athlete Demographic’ sections were comprised of mostly closed-ended, multiple-choice questions. The ‘Perceptions of Eccentric Training’ section was designed to gain a greater understanding of what sources coaches use to learn about ECC as well as how coaches subjectively gauge the efficacy of ECC when compared to traditional training. The ‘Program Design’ section included closed- and open-ended components to allow participants to describe their approach to developing ECC programs.

Participants

Strength and conditioning practitioners were surveyed regarding eccentric exercise prescription and program development (see Text, Supplemental Digital Content 1, which contains the survey). Inclusion criteria required that potential respondents were actively involved in the planning and implementation of training programs for athletes. Participants were identified through existing coaching networks and were sent an electronic link to anonymously complete the survey. Those participants who completed the survey were asked to forward the link to appropriate contacts.

Procedures

A cross-sectional, web-based survey (Qualtrics, Provo, UT, USA) was used to collect responses. The study design and survey instrument were approved by the University of Waikato Human Research Ethics Committee: (HREC(Health)2018#60). A pilot version of the survey was sent to a small group of coaches ($n = 6$) before being sent out to the target population. Originally, 224 participants were contacted, which led to 117 total responses. Of the total responses, 19 were excluded from the analysis; one respondent declined to participate in the survey, while 18 surveys were left blank. The remaining 98 surveys met the inclusion criteria and were included in the final analysis.

Statistical Analyses

Survey data were collated in an Excel spreadsheet (Microsoft Corporation, Redmond, WA, USA) via the Qualtrics export function. Answers were reported as absolute values or as a percentage of the total responses. Strength and conditioning practitioners may have been

responsible for working with multiple teams or athletes concurrently, therefore the total responses for a single question may have exceeded the number of surveys included in the analysis. Responses to open-ended questions and comments were sorted into categories for a frequency count by the primary author and then discussed with the research team before a consensus was reached.

3.3 Results

Demographic data from the 98 respondents and their athletes are presented in Table 7 and 8. Athletics or track and field (13.0%), rugby union (12.2%), football (9.0%) and basketball (8.3%) were the most common sports worked with of the 278 total answers, including respondents working with multiple teams. Other responses listed netball (2.5%) and hockey or field hockey (2.5%) most frequently. Respondents working at the professional (34%) or elite/non-professional (20%) level made up approximately 54% of the total sample. Demographic data for the athletes are listed in Table 9.

Table 7. Demographic data for ECC survey respondents

Demographics	Number of responses	% of respondents
Age group		
18 to 24 years old	1	1%
25 to 34 years old	53	55%
35 to 44 years old	29	30%
45 to 54 years old	9	9%
55 to 64 years old	4	4%
Sex		
Female	12	12%
Male	86	88%
Education		
Associate degree	2	2%
Bachelor degree	28	29%
Doctorate degree	10	10%
Master degree	55	57%
Some college credit	1	1%
Certification*		
ASCA	30	26%
CSCCA	10	9%
NSCA	45	39%
UKSCA	7	6%
Other	24	21%

Table 8. Demographic data for ECC survey respondents (continued).

Demographics	Number of responses	% of respondents
Location		
United States of America	30	31%
New Zealand	24	24%
Australia	10	10%
United Kingdom	8	8%
Malaysia	6	6%
Canada	5	5%
Switzerland	3	3%
China	2	2%
Ireland	2	2%
Sweden	2	2%
Argentina	1	1%
Brazil	1	1%
Hong Kong (S.A.R.)	1	1%
India	1	1%
Italy	1	1%
Samoa	1	1%
Experience		
< 2 years	4	4%
3 to 5 years	21	22%
6 to 8 years	16	17%
9 to 11 years	20	21%
12 to 14 years	9	9%
15 to 17 years	8	8%
18 to 20 years	4	4%
> 20 years	14	15%

Notes. * Respondents may hold more than one certification resulting in a different number of total responses. ASCA – Australian Strength and Conditioning Association; CSCCA – Collegiate Strength and Conditioning Coaches Association; NSCA –National Strength and Conditioning Association; UKSCA – United Kingdom Strength and Conditioning Association.

Table 9. Athlete demographics

Demographics	Number of responses	% of respondents
Age group*		
< 17 years	17	8%
17 to 20 years	52	26%
21 to 25 years	64	32%
26 to 30 years	42	21%
31 to 35 years	20	10%
> 35 years	8	4%
Sex*		
Female	30	28%
Male	50	46%
Mixed	28	26%
Training experience*		
< 6 months	22	9%
6 months to 1 year	30	12%
1 to 2 years	53	22%
3 to 5 years	59	24%
6 to 8 years	42	17%
9 to 11 years	23	10%
> 11 years	13	5%

Notes. * Coaches working with one or more teams reported data for each of their groups resulting in different total numbers of responses.

Perceptions of Eccentric Training

In order to gain a greater understanding of how ECC is prescribed, participants were asked about their sources for training information. Responses indicated that academic journals were the most popular source of information for ECC (22%) along with professional colleagues/other programs (21%), conference (17%), book (15%), website (15%), workshop (9%) and other (4%). Approximately 4% of respondents did not use ECC for the following reasons: “confidence and proven success utilizing other methods”, “lack of knowledge, experience in successfully implementing this method of resistance training”, and “potential

short term impact on performance”. When asked if respondents had prescribed ECC with their athletes in the last 24 months, 96% responded “yes”.

Program Design

The majority of respondents preferred to implement ECC outside of the competition season: either in the pre-season (32%) or off-season (30%). Seventeen percent of respondents preferred ECC in the early competition phase. Very few utilized ECC in the late competition phase (8%), post-season (5%), or playoffs (4%).

Respondents were asked to rank their reasons for implementing ECC. General (32%) and sports-specific performance (32%) combined for 64% of the number one reason to include ECC. Injury prevention (24%) and injury rehabilitation (8%) taken together accounted for 32% of respondents’ primary reason to include ECC. Respondents listed injury prevention (40.6%), general sports performance (25.0%), injury rehabilitation (17%), and specific sports performance (15.6%) as the second reason to include ECC in their programming. The proportions of specific physical abilities targeted with ECC are displayed in Figure 5. Twenty-five percent of participants reported performing fitness / energy system development / conditioning concurrently with ECC. When asked if respondents actively avoided targeting a specific athletic ability or form of training concurrently with ECC, 37% responded “no”; 34% avoided various high-intensity training activities (high neural output, maximum strength, speed); and 14% reported avoiding training that could cause additional DOMS.

PERCENTAGE OF PHYSICAL ABILITIES TARGETED BY ECC METHODS

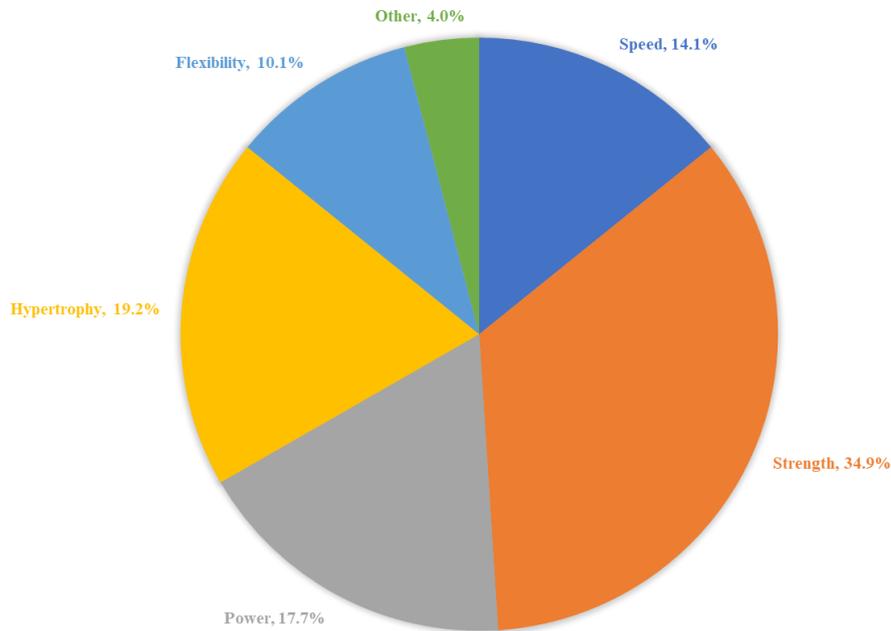


Figure 5. Proportion of specific physical abilities targeted by practitioners using ECC methods in athletes.

Fifty-eight percent of respondents said they did not use any form of athlete monitoring to quantify ECC load or fatigue. Additionally, 75% reported not using any eccentric-specific testing to assess physical performance. The back squat (54 responses), rear foot elevated squat / Bulgarian (37 responses), bench press (35 responses), and pull up (34 responses) were the most common exercises where ECC was applied. The back squat was ranked as the most important exercise for ECC prescription by 64% of respondents followed by rear foot elevated squats (13%), Nordics (11%), and pull ups (9%).

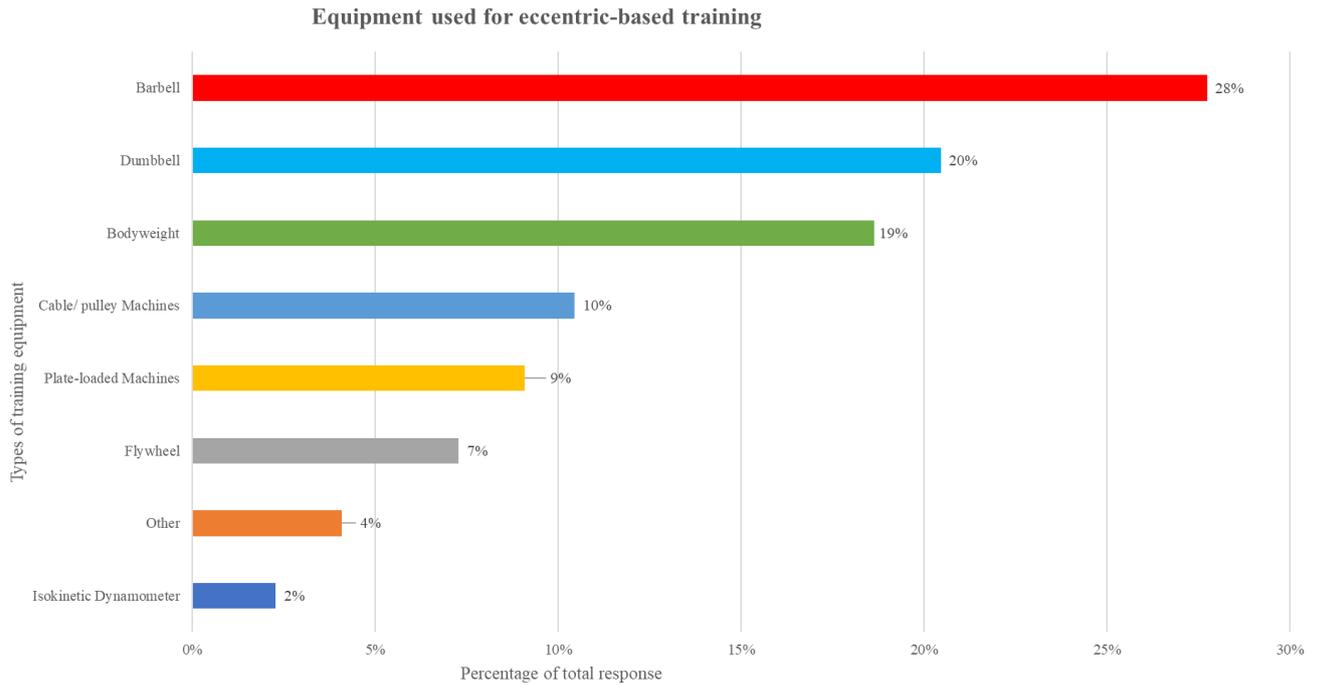


Figure 6. Equipment used by strength and conditioning practitioners in ECC methods with athletes.

The equipment used for ECC and the most common methods for modifying the eccentric phase of the aforementioned exercises are displayed in Figure 6 and Figure 7 respectively. Of those methods, respondents commented using velocities of “[less than] 0.35 m/s”, and “0.10 m/s” while comments related to tempo ranged from 3 to 6 second durations during the eccentric phase.

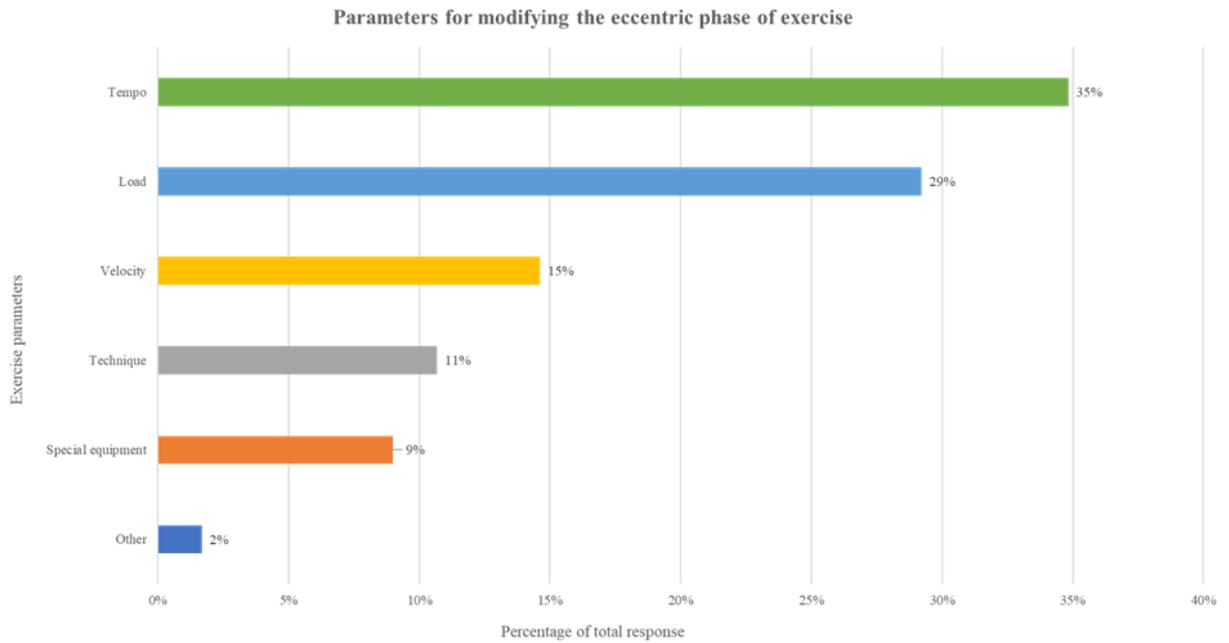


Figure 7. Responses to how practitioners modify ECC exercise parameters with athletes.

Forty-seven percent of participants reported sequencing eccentric-based exercises as the primary exercise (the main exercise of a session). Participants reported training volume primarily within 3 to 5 sets of 3 to 6 repetitions with 1 to 4 minutes of rest (Table 10). Furthermore, participants reported prescribing 2 days (38%), and 3 days (36%) of recovery as the most frequent time between training sessions of the same movement pattern or body part. Participants prescribed ECC for the same movement pattern or body part 2 days per week (56%), 1 day per week (29.2%), and 3 days per week (10%). The most common method to quantify the intensity of ECC was through % of one repetition maximum (34%) followed by rate of perceived exertion (20%), and velocity (16%).

Table 10. ECC programming variables used with athletes.

Variable	Number of responses	% of responses
Program duration (weeks)		
< 1	2	3%
1 to 3	29	41%
4 to 6	28	39%
7 to 9	4	6%
10 to 12	2	3%
> 12	6	8%
Sets		
< 3	12	8%
3	49	32%
4	43	28%
5	25	17%
6	12	8%
> 6	10	7%
Repetitions		
< 3	24	11%
3	33	15%
4	40	18%
5	42	19%
6	39	17%
7	11	5%
8	18	8%
> 8	10	4%
Rest (minutes)		
< 1	0	0%
1 to 2	33	46%
3 to 4	30	42%
5 to 6	3	4%
> 6	1	1%
Other	4	6%

3.4 Discussion

Survey responses indicated that practitioners use ECC to improve a range of athletic abilities which is supported by research investigating strength, speed, explosive ability and change of direction (McNeill et al., 2019). Strength was the most common response, which is perhaps unsurprising given the evidence regarding the capacity for eccentric maximal strength (Hollander et al., 2007; Hortobágyi & Katch, 1990). A variety of ECC methods, such as tempo, inertial devices, and the use of accentuated loads have been shown to improve measures of strength (Suchomel et al., 2019b) which is at least partially supported by the findings of this study, although the extent to which inertial devices are used in practice is unclear. ECC has been shown to improve strength more than concentric training alone (Roig et al., 2009), however, the efficacy of specific ECC methods on strength performance may vary based on population and training experience (Buskard et al., 2018). The review by Buskard *et al.* suggests that supramaximal loading, while effective, may be more appropriately reserved for individuals with greater strength and training experience. Two respondents in the current survey commented that “I don't [prescribe] heavy eccentrics with athletes with a low training age. However I do modify tempos to accentuate the eccentric portion...” and “When used with a low training age, the weight is a lighter weight and the eccentric is used more as a positional tool” suggesting that training age may influence ECC prescription. The athletes trained by respondents of this survey varied widely in terms of experience (Table 9) with nearly 21% of athletes having one year or less and approximately 32% of athletes having greater than five years of training experience. The use of tempo as an ECC method may have a relatively low potential for training stimulus while accentuated and supramaximal eccentric loading may be comparatively more advanced (Suchomel et al., 2019a). Indeed, the respondents in the current survey reported using loads from 105% to 140% concentric 1RM. This disparity of methods

may be reflected in our data as both tempo and load were reported as the most common ways to modify the eccentric phase of exercise.

In addition to strength, practitioners also reported using ECC to improve hypertrophy, power, and speed. Although each of these qualities may require specific programming strategies, ECC may enhance common elements of physical performance including neuromuscular and morphological factors (Douglas et al., 2017b). Respondents indicated goals specific to physical abilities such as hypertrophy: “high level motor unit & fibre recruitment”, and “mechanical strain” for hypertrophy. Responses for power included “type II fibre overshoot”, “Improved fiber recruitment”, and “Increasing the strength base...”. Those respondents who reported using ECC for speed responded “Overload posterior chain and load Tendons” and “Adding sarcomeres in series...”. These answers suggest that practitioners are using overlapping adaptive responses to support different physical abilities. However, the dose-response relationship and optimization of particular ECC methods for distinct physiological and performance outcomes warrants further investigation.

The nature of ECC may present challenges for practitioners with regards to exercise selection in athlete populations. The prescription of heavy loading may warrant the use of spotters and specialized equipment to ensure a safe training environment (Meylan et al., 2008). Isokinetic dynamometers, for training purposes, may help to resolve these issues, but may be resource prohibitive for many real training environments (Meylan et al., 2008). Encouragingly, Coratella et al. (Coratella et al., 2015) suggested that unilateral ECC may be as effective as isokinetic means when performed with dynamic constant external resistance exercises. Survey responses specified the use of traditional exercises (back squat, rear foot elevated split squat, bench press, pull up) and equipment (barbell, dumbbell, bodyweight) for the implementation of ECC

highlighting the need for practical programming strategies. Simple bodyweight exercises such as the Nordic hamstring exercise (Iga et al., 2012; Ishøi et al., 2018; Krommes et al., 2017) and Copenhagen adductor exercise (Ishøi et al., 2016) have been shown to result in improved sprinting, jumping and eccentric strength. Future research should continue exploring the relationship between programming strategies and adaptive outcomes of practical ECC exercises.

Seventeen respondents reported avoiding the concurrent programming of high-intensity activities during ECC blocks. Of note is a body of research that examines the relationship between muscle damage and fatigue on proprioception in the affected limb (Proske, 2019). Evidence has shown changes in perception of limb position and force production following ECC (C. Brockett et al., 1997) suggesting that muscle damage may play a role in proprioception. Similar effects on position sense were noted after matched eccentric and concentric training highlighting fatigue as a contributor. Taken together, the effects of ECC during periods of intense or sport-specific training may affect the overall goal for the training phase, although the long-term adverse effects of ECC on performance and injury mechanisms are still unclear (Proske, 2019). Subsequently, concerns regarding DOMS may be one reason that nearly two-thirds of practitioners in the current survey preferred to prescribe ECC outside of the competitive season. However, this practice warrants further scrutiny as regular exposure has been suggested as an important factor in the protective benefits from ECC exercises like Nordics (Goode et al., 2015). Additionally, the occurrence of DOMS is known to be mitigated after repeated exposure to ECC (Chen et al., 2019; Lavender & Nosaka, 2008) supporting consistent, repeated exposures and systematic progression in training volume. Practitioners should consider these factors when deciding to integrate ECC into their yearly training plans.

Dynamic resistance training is commonly prescribed as a percentage of a maximal repetition or on the basis of movement velocity which is well supported and is generally believed to induce intensity- and volume-specific adaptations (American College of Sports Medicine, 2009). A similar approach to ECC is difficult for practitioners to implement as qualities like maximal eccentric strength have proven challenging to measure (Meylan et al., 2008). Several protocols have been proposed to assess eccentric qualities such as strength (Hollander et al., 2007), change of direction (de Hoyo et al., 2016; Nimphius et al., 2016), and explosive ability (Bogdanis et al., 2018; Cormie et al., 2010; Laffaye & Wagner, 2013). Eccentric testing may aid practitioners in the prescription of ECC, but do not appear to be widely adopted based on the findings of this survey, given that just over three-quarters of respondents reported not using any eccentric-specific testing. These findings are surprising given the evidence supporting the contribution of eccentric phase characteristics to dynamic performance (Cormie et al., 2010; Laffaye & Wagner, 2013). Participants using eccentric monitoring for fatigue reported practices such as “RPE”, “Questionnaires”, and “athlete feedback”. As athlete monitoring is an established practice in sport, engaging in eccentric-specific monitoring practices may be especially pertinent at early phases of ECC prescription. A greater understanding of how monitored eccentric contraction qualities contribute to sports performance and injury prevention may help define testing and monitoring protocols that could aid in the prescription of ECC interventions

The effects of eccentric tempo and velocity during training has been investigated as a method for improving performance (Bogdanis et al., 2018; Mike et al., 2017; Oliveira et al., 2016b; Stasinaki et al., 2019). Following longitudinal exposure, fast ECC may result in greater gains in strength, torque, and muscle cross-sectional area than slow ECC (Farthing & Chilibeck, 2003; Paddon-Jones et al., 2001; Shepstone et al., 2005). Paddon-Jones et al. (2001), suggested that

fast ECC may also elicit more generalizable adaptations leading to improvements in torque production over a wider range of testing velocities. More recently, Zachariah et al. (2019) reported that fast eccentric squat training (eccentric duration 0.7 to 1.1 seconds) resulted in significant changes in strength and explosive ability using 50% to 70% 1RM, although these participants were untrained. Interestingly, Sharifnezhad et al. (2014) found that fast lengthening velocities led to an increase in fascicle length, which would likely contribute to increased force production and contraction velocity (Vogt & Hoppeler, 2014). Conversely, Douglas et al. (2018) found that fast ECC impaired sprint performance, although the time course of recovery and adaptation following the intervention may have interfered with results. Participants in the current survey reported using eccentric contraction durations from 3 to 6 seconds and relatively slow velocities. It is important to note that, unlike traditional dynamic training where eccentric and concentric contractions are coupled, the typical response (e.g. supercompensation) from ECC in an athletic context remains relatively unknown. It is apparent that the specific velocity during ECC may play an important role in enhancing physical performance.

Responses indicated that academic journals were the single most common source of ECC information; however, 78% of information used to guide ECC prescription tended to be more anecdotal in nature. Three respondents indicated other media as a source of training information, specifically highlighting books such as “Triphasic Training” (Dietz & Peterson, 2012). Although these sources provide valuable observations from experienced practitioners there is scope for a greater degree of evidence-based ECC prescription.

The authors recognize the complex task of designing training programs in competitive sport with the understanding that athlete health, wellness, individual characteristics, organizational

resources, time constraints, and sport-specific training (among other factors) play a role in the process. A survey tool that captures all of the nuances of ECC is unlikely and as such there may be specific elements of ECC that were not evident in the process. Although an electronic survey allows for the economical collection of data across the globe, the authors acknowledge the constraints of this platform as a limitation in the current investigation. Future ECC survey research could further differentiate the application of ECC training across sports, training ages and sex.

3.5 Practical Applications

This survey sought to gather information regarding ECC prescription from coaches working with trained athletes. The findings of this survey indicate that designing resistance training programs based on the unique properties of eccentric contractions is apparent among strength and conditioning practitioners across a wide range of sports and athletes. The popularity of ECC in practice may reflect anecdotal experience as well as empirical evidence, but more research is needed to understand the long-term implications of ECC and the effect on different aspects of physical performance.

The authors suggest that ECC is a diverse exercise regime from which distinct training methods may be derived. Practitioners wanting to implement ECC might first consider how the eccentric phase contributes to performance and injury prevention within their athletic populations. Once a particular strategy or method has been identified, the internal response (e.g., muscle damage, soreness, acute loss of force production) should be considered within the context of the periodization scheme and overall training plan. Accordingly, athlete monitoring and wellness

tracking may be useful in determining the time course of recovery and adaptation, especially in the early phase of ECC.

SECTION 3

Development and Application of an Eccentric Force-Velocity Profile

CHAPTER 4:

Eccentric Force-Velocity Characteristics during a Novel Squat Protocol in Trained Rugby Union Athletes – Pilot

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Eccentric Force-Velocity Characteristics during a Novel Squat Protocol in Trained Rugby Union Athletes—Pilot Study. *Journal of Functional Morphology and Kinesiology*, 6(2), 32.

Prelude: Eccentric strength characteristics have been shown to be important factors in both research and practice for the improvement and understanding of physical performance. Many eccentric tests have been performed with specialised equipment or with supramaximal loading. The purpose of this study was to investigate within- and between- session reliability of an incremental, submaximal eccentric back squat protocol.

4.1 Introduction

Eccentric-based training (ECC) has been shown to be an effective strategy for improving physical performance in athletic populations when compared to traditional or concentric-only programs (Douglas et al., 2017b; McNeill et al., 2019; Roig et al., 2009). The relationship between eccentric phase characteristics and dynamic performance has been previously explored (Laffaye & Wagner, 2013; Spiteri et al., 2015) and may explain favourable changes in strength, jumping, and sprinting ability following eccentric-based training interventions. Indeed, the stretch-shortening cycle is a well-documented phenomenon in which elastic potential energy stored during the eccentric phase is reutilised to augment the subsequent concentric action (Komi, 2000). Currently, there is a lack of submaximal eccentric assessments for strength and power development and existing research appears to commonly use concentric strength as a proxy for eccentric-specific exercise prescription (Mike et al., 2017; Shibata et al., 2018; Stasinaki et al., 2019; Zacharia et al., 2019). The discrepancy between maximal concentric and eccentric strength has been reported as approximately 20% to 60% depending on the testing procedures (Hollander et al., 2007; Hortobagyi & Katch, 1990). Thus, the investigation of a prescription tool for the purpose of eccentric program design is warranted.

The efficacy of ECC methods to improve performance is likely of interest to strength and conditioning practitioners, but there appears to be a lack of standardisation around the practical assessment of eccentric-specific characteristics. Meylan et al. (2008) reviewed different protocols for assessing eccentric strength and reported a lack of available reliability statistics and questioned the practicality of existing options. Recently, Bogdanis et al. (2018) investigated a submaximal, eccentric-only protocol with university students but only reported relative reliability for the within-session values. Other researchers (Hollander et al., 2007; Spiteri et al., 2015) have utilised a three-second eccentric squat to determine maximal eccentric

strength in athletes that was largely dependent on subjective determination of the failure threshold. Douglas et al. (2020) addressed this by adding an objective velocity standard to their testing protocol. However, the nature of a maximal eccentric test typically relies on extremely heavy loading and forces applied to the musculo-skeleton system, which may limit the applicability in sports as a result of potential muscle damage, soreness, decreased sport performance and recovery time (Nicol et al., 2006).

A recent review has reported on the concentric force-velocity relationship in single fibre, and in vivo investigations suggesting a hyperbolic shape, while the inclusion of the eccentric phase produces a sigmoidal curve around zero velocity (Alcazar et al., 2019). This effect is mirrored in earlier research that suggests the existence of a plateau in force production beyond a certain limit, potentially as a result of neural inhibition, which may diminish with training (Aagaard et al., 2000). The monitoring of force-velocity characteristics during incremental multi-joint assessment has allowed for the accurate estimation of maximum strength in dynamic movement (Picerno et al., 2016). At present there are limited eccentric-specific testing options available to practitioners, therefore, an incremental, submaximal protocol may provide valuable insight into the characteristics of an individual's eccentric force-velocity profile.

The aim of this pilot study was to investigate between- and within-session reliability for novel force-velocity data during the eccentric phase of a barbell back squat with participants having the intent of maximizing downward velocity. We hypothesised that following two familiarisation sessions, the results of this experimental protocol with trained athletes would meet commonly applied standards of reliability. In order to make these findings applicable to a practical sport environment, trained athletes were recruited to perform the barbell back squat under standardised incremental loading conditions.

4.2 Methods

Participants

Twenty-four semi-professional, male rugby-union athletes were recruited to participate in this study. Age (20.8 ± 2.0 y), height (185.6 ± 6.6 cm), and body mass (100.4 ± 13.7 kg) were recorded prior to the initial testing session. Participants were asked to refrain from strenuous activity at least 24 h prior to testing and to maintain their normal diet on testing days. Inclusion criteria were males 18 years or older, two years of resistance training experience, participation in provincial-level rugby union or higher, and free from any significant musculoskeletal injury or illness occurring within the last month. All participants gave their written consent to participate after being informed through written and oral description of the research project and all relevant information. This research project was approved by the Human Research Ethics Committee of the University of Waikato on 24-10-2018 (HREC[Health]2018#60).

Study Design

Participants completed all familiarisation and testing sessions in their normal training environment at approximately the same time as their normal training sessions to minimise the effects of diurnal variation (between 5 am and 8 am). Further, participants were asked to maintain their normal nutritional practices prior to each testing session. A test–retest reliability design was used with a smaller subset of participants ($n = 13$; age = 21.2 ± 2.2 y; height = 184.9 ± 8.0 cm; body mass = 102.2 ± 15.5 kg) completing a second testing session. The drop out in the second trial was due to scheduling conflicts ($n = 6$) or not showing up to scheduled testing sessions ($n = 5$). At least seven days separated each testing session to allow for recovery from delayed-onset muscle soreness (Nicol et al., 2006). Kinetic and kinematic data were captured for each repetition performed during the eccentric squat assessment. Specifically, eccentric peak force (EPF), eccentric peak velocity (EPV), eccentric mean force (EMF), eccentric mean

velocity (EMV), eccentric mean rate of force development (RFD), range of motion (RoM), and duration of the eccentric phase (duration) were analysed during the first and second testing sessions. The initiation of the eccentric phase was defined as the point of minimum force recorded during the downward phase of movement which was identified manually by the primary investigator (Hansen et al., 2011). The end of the eccentric phase was determined by the software and was considered to be the lowest point of vertical displacement (Figure 8).

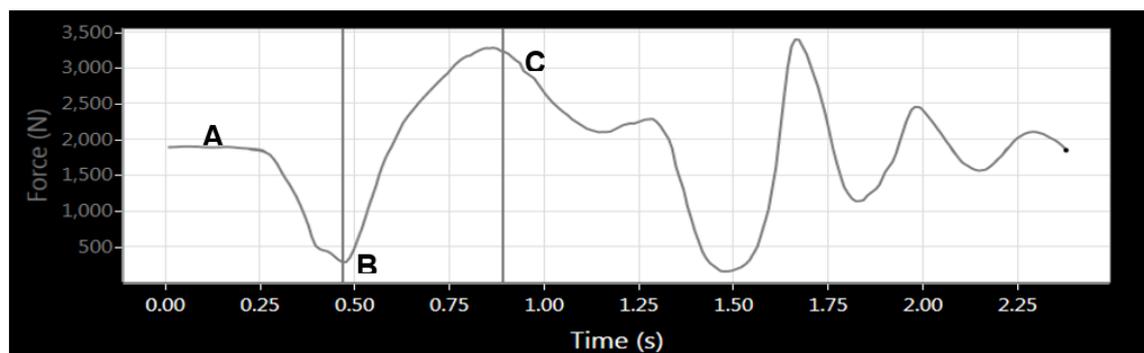


Figure 8. Example of a force trace during an incremental eccentric back squat with a trained rugby union athlete. **A** represents the standing position with the barbell held across the trapezius muscles. The vertical line at **B** is the point of minimum force and is considered the beginning of the eccentric phase. **C** coincides with the point of lowest displacement and the end of the eccentric phase.

Experimental Procedures

Prior to the initial testing, participants reported to the training facility to complete two familiarisation sessions separated by 24 h. A dynamic, bodyweight warm-up routine was performed consisting of five minutes of stationary biking at a self-selected pace followed by: good mornings, single leg squats (Bulgarian squat), core stability (dead bugs), shoulder internal/external rotation, and hip internal/external rotation for two sets of ten repetitions each (side) and 90–120 s rest between sets. This warm-up procedure was performed before each familiarisation and testing session. Participants were asked to back squat to a self-selected depth approximating 90° at the knee using three standardised loads (wooden dowel/~300 g, 60 kg, and 80 kg) for ten, five, and five repetitions, respectively, with 90–120 s rest between sets.

The participants received verbal instructions to perform the first repetition in a “slow and controlled” manner with a “two seconds down, two seconds up” tempo and then progressively increase the eccentric and concentric velocity such that the last repetition was performed at maximal velocity. A digital timer was provided to assist with the tempo of the initial repetitions and the rest period between sets.

Following the dynamic warm-up, each participant completed the novel eccentric force-velocity assessment using six different absolute loads in the barbell back squat (20, 40, 60, 80, 100, and 120 kg). The manner of testing was consistent in both trials, with loads proceeding in ascending order. Participants unable to complete three repetitions at a given load were excused from that load (120 kg; Trial 1, $n = 5$; Trial 2, $n = 2$). Technique was standardised with feet placed shoulder width apart and toes turned slightly out. A barbell was placed across the trapezius with hands placed comfortably on the barbell. Participants were asked to descend until they reached 90° of flexion at the knee. Each attempt was performed on two force plates (PASCO Scientific Inc., Roseville, CA, USA) with a linear position transducer (Celesco Transducer Products, Chatsworth, CA, USA) attached to the barbell just inside the collar, positioned laterally to the participant’s centre of mass. Custom-made software (Weightroom, HPSNZ, Auckland, New Zealand) down sampled the signal to 100 Hz and 250 Hz for ground reaction forces and linear displacement, respectively. The same equipment was used by the same operator in all testing sessions. Previous research has shown this frequency provides reliable ground reaction force data during athletic testing (Hori et al., 2009).

Participants were asked to perform three dynamic repetitions at each load while attempting to maximise velocity in the eccentric and concentric phases. Each participant was asked to remain motionless between repetitions and was given approximately three to five minutes rest between

sets (Thompson, W. R. et al., 2010). Loud music was played during each testing session over the gym speaker system, and verbal encouragement was given during each attempt. The movement cues for the assessment were standardised as “fast down, fast up”, “move as quickly as possible”, and “squat to your normal depth. Further, participants were asked to keep their feet in contact with the ground throughout the trial to minimise movement variation. A certified strength and conditioning specialist oversaw all familiarisation and testing sessions to ensure participants understood the procedures.

2.4. Statistical Analyses

Data were initially log-transformed for reliability analysis to reduce bias from non-uniformity of error and are presented as mean \pm SD or 90% confidence limits. Intraclass correlation coefficient (ICC), coefficient of variation (CV), and the change in mean were calculated for EPF, EPV, EMF, EMV, and RFD using customised Excel spreadsheets (Hopkins, 2015). Two-way mixed effects ICCs (3,1) were interpreted accordingly: <0.4 poor, 0.4 to 0.75 fair, 0.75 to 0.9 good, and >0.9 excellent (Fleiss, 1999; Rosner, 2016). Between-session analysis was comprised of mean values for each trial. Within-session analysis was conducted on the three repetitions completed for each load in Trial 1.

Trials and repetitions were assessed for systematic error (i.e., learning effects) using repeated measures analysis of variance (Rstudio, version 1.2.5033 with R version 3.6.2). Generalised eta squared (η^2_G) effect sizes for repeated measures were interpreted as <0.02 as trivial, 0.02 to 0.13 as small, 0.13 to 0.26 as medium, and >0.26 as large (Bakeman, 2005). A Bonferroni-Holm post hoc test was performed if significant differences were found. The alpha level for significance was set at $p \leq 0.05$. If the assumption of sphericity was violated, the adjusted p -values were reported. If systematic error was present the repetition or trial was either excluded or the measurement schedule was modified (Weir, 2005).

4.3 Results

Within-session, one-way repeated measures ANOVA revealed a significant main effect for repetitions in each variable tested ($p < 0.001$ for all variables; EMF, $\eta^2 G = 0.015$; EMV, $\eta^2 G = 0.179$; EPF, $\eta^2 G = 0.030$ EPV, $\eta^2 G = 0.175$; Mean RFD, $\eta^2 G = 0.048$; Duration, $\eta^2 G = 0.032$; RoM, $\eta^2 G = 0.125$). Post hoc comparisons revealed that repetition A was significantly different from B and C across all variables ($p < 0.001$). No significant differences were detected between B and C with the exception of eccentric duration ($p = 0.04$). Reliability analysis shows consistently larger changes in the mean and lower absolute reliability (CV) for each variable when repetition A is included (Table 11). Specifically, range of motion and the duration of the eccentric phase tended to have higher absolute reliability when repetition A was excluded. These measures may suggest the presence of systematic error (i.e., learning effect, protective strategies) between repetitions and thus repetition A was excluded from the test–retest analysis (Hopkins et al., 2001).

Table 11. Reliability and change scores for within-session repetition comparison in an eccentric back squat test.

	CV (%)	Change in Mean (%)
EPV		
AB	5.8 (5.3 to 6.5)	12.2 (11.0 to 13.5)
AC	7.0 (6.3 to 7.8)	11.8 (10.3 to 13.3)
BC	5.7 (5.2 to 6.3)	-0.4 (-1.5 to 0.7)
EPF		
AB	3.7 (3.3 to 4.1)	6.0 (5.2 to 6.7)
AC	4.5 (4.1 to 5.0)	5.8 (4.9 to 6.7)
BC	3.2 (2.9 to 3.6)	-0.2 (-0.8 to 0.5)
EMV		
AB	6.1 (5.5 to 6.8)	12.7 (11.4 to 14.0)
AC	7.6 (6.9 to 8.4)	11.9 (10.2 to 13.5)
BC	6.1 (5.5 to 6.8)	-0.7 (-1.9 to 0.4)
EMF		
AB	4.8 (4.3 to 5.3)	3.2 (2.3 to 4.2)
AC	4.6 (4.2 to 5.1)	2.7 (1.8 to 3.6)
BC	4.0 (3.6 to 4.5)	-0.5 (-1.3 to 0.3)
RFD		
AB	13.7 (12.4 to 15.4)	15.4 (12.5 to 18.4)
AC	15.6 (14.1 to 17.5)	12.7 (9.5 to 16.0)
BC	13.6 (12.3 to 15.2)	-2.3 (-4.7 to 0.2)
RoM		
AB	4.9 (4.3 to 5.8)	7.6 (6.1 to 9.1)
AC	6.6 (5.7 to 7.7)	8.1 (6.1 to 10.2)

BC	2.0 (1.7 to 2.3)	1.7 (1.1 to 2.3)
Duration		
AB	6.5 (5.9 to 7.3)	-5.3 (-6.5 to -4.1)
AC	7.4 (6.7 to 8.2)	-4.3 (-5.6 to -2.9)
BC	6.8 (6.2 to 7.6)	2.4 (1.1 to 3.8)

Notes: CV and change in mean values were calculated with log-transformed data. Values are presented with 90% confidence limits. Sample size for 120 kg, $n = 19$; for all other loads $n = 24$. Abbreviations: ABC = first, second, and third repetition of the test, respectively; EMF = eccentric mean force; EMV = eccentric mean velocity; RFD = eccentric mean rate of force development; EPF = eccentric peak force; EPV = eccentric peak velocity; RoM = eccentric range of motion; Duration = time duration of eccentric phase.

No significant differences were found in the between-session ANOVA except for EPF ($p = 0.049$, $\eta^2 G = 0.006$) suggesting that participants were adequately familiarised with the testing procedure (EMF, $p = 0.46$, $\eta^2 G = 0.005$; EMV, $p = 0.71$, $\eta^2 G = 0.001$; EPV, $p = 0.77$, $\eta^2 G = 0.001$; Mean RFD, $p = 0.89$, $\eta^2 G < 0.001$; Duration, $p = 0.33$, $\eta^2 G = 0.006$; RoM, $p = 0.90$, $\eta^2 G < 0.001$). The p -value for EPF was found to be less than the alpha level for significance, but the effect size was trivial therefore the results for EPF were interpreted as having acceptable between-session reliability. Relative (ICC) and absolute (CV) measures of reliability differed across the variables tested (Table 12). EMF, EMV, and EPV resulted in poor to good relative reliability depending on the load while absolute reliability ranged from 2.4% to 15.5%. EPF demonstrated good relative reliability (≥ 0.82) and an absolute reliability of $\leq 7.3\%$ for each load. A Bland–Altman plot for differences between trials is shown in Figure 9. Mean rate of force development tended to show the lowest levels of both relative and absolute reliability when 90% confidence limits were included.

Table 12. Between-session reliability for eccentric force-time-displacement variables obtained with different loads in the back squat.

	Trial 1 ± SD	Trial 2 ± SD	% Change in Mean (90% CL)	% CV (90% CL)	ICC (90% CL)
EPF					
20	2683 ± 426	2662 ± 537	-1.4 (-4.3 to 1.5)	4.3 (3.3 to 6.7)	0.95 (0.88 to 0.98) *
40	2818 ± 420	2808 ± 436	-0.5 (-3.3 to 2.3)	4.1 (3.1 to 6.3)	0.94 (0.84 to 0.98) *
60	2996 ± 503	2852 ± 462	-4.8 (-7.8 to -1.7)	4.7 (3.6 to 7.3)	0.93 (0.83 to 0.97) *
80	3006 ± 421	2911 ± 493	-3.5 (-6.5 to -0.5)	4.5 (3.3 to 6.8)	0.93 (0.82 to 0.97) *
100	2994 ± 392	2925 ± 460	-2.6 (-5.3 to 0.2)	4.1 (3.1 to 6.3)	0.93 (0.82 to 0.97) *
120	2941 ± 385	2898 ± 459	-1.7 (-4.1 to 0.7)	3.2 (2.4 to 5.2)	0.96 (0.88 to 0.99) *
EPV					
20	2.04 ± 0.25	2.11 ± 0.26	3.8 (-0.4 to 8.2)	6.1 (4.6 to 9.4)	0.81 (0.56 to 0.92)
40	1.94 ± 0.21	1.98 ± 0.22	2.0 (-1.9 to 5.9)	5.6 (4.2 to 8.6)	0.79 (0.52 to 0.92)
60	1.81 ± 0.19	1.79 ± 0.19	-1.2 (-3.9 to 1.6)	4.0 (3.0 to 6.1)	0.88 (0.71 to 0.95)
80	1.59 ± 0.20	1.61 ± 0.18	1.5 (-3.0 to 6.1)	6.6 (4.9 to 10.1)	0.74 (0.42 to 0.89)
100	1.40 ± 0.18	1.41 ± 0.16	0.9 (-2.7 to 4.7)	5.4 (4.1 to 8.3)	0.84 (0.61 to 0.94)
120	1.24 ± 0.22	1.25 ± 0.22	0.9 (-5.9 to 8.2)	9.5 (6.9 to 15.5)	0.80 (0.49 to 0.93)
EMF					
20	1453 ± 213	1452 ± 267	-0.5 (-4.2 to 3.3)	5.5 (4.1 to 8.5)	0.91 (0.78 to 0.97) *
40	1611 ± 158	1573 ± 232	-2.9 (-7.9 to 2.3)	7.8 (5.9 to 12.1)	0.65 (0.28 to 0.85)
60	1835 ± 176	1807 ± 208	-1.7 (-5.4 to 2.2)	5.7 (4.3 to 8.7)	0.77 (0.48 to 0.91)
80	2015 ± 167	1949 ± 188	-3.4 (-6.6 to 0.0)	5.0 (3.7 to 7.6)	0.74 (0.43 to 0.90)
100	2187 ± 175	2121 ± 197	-3.2 (-6.3 to 0.1)	4.8 (3.6 to 7.3)	0.75 (0.44 to 0.90)
120	2273 ± 126	2229 ± 180	-2.1 (-4.9 to 0.7)	3.8 (2.8 to 6.1)	0.77 (0.43 to 0.91)
EMV					
20	1.43 ± 0.15	1.48 ± 0.18	3.3 (-0.5 to 7.3)	5.5 (4.1 to 8.4)	0.80 (0.55 to 0.92)
40	1.33 ± 0.11	1.35 ± 0.14	1.1 (-2.7 to 5.0)	5.7 (4.2 to 8.7)	0.73 (0.41 to 0.89)
60	1.23 ± 0.14	1.21 ± 0.14	-1.4 (-4.0 to 1.3)	3.9 (2.9 to 6.0)	0.91 (0.76 to 0.96) *
80	1.08 ± 0.13	1.07 ± 0.13	-0.1 (-3.8 to 3.7)	5.6 (4.2 to 8.5)	0.83 (0.60 to 0.93)
100	0.92 ± 0.14	0.92 ± 0.13	-0.3 (-4.6 to 4.1)	6.5 (4.9 to 10.0)	0.82 (0.59 to 0.93)
120	0.79 ± 0.17	0.78 ± 0.18	-1.9 (-7.5 to 4.1)	7.9 (5.8 to 13.0)	0.92 (0.77 to 0.97) *
RFD					
20	6631 ± 1682	7144 ± 2309	6.1 (-1.3 to 14.0)	10.9 (8.1 to 16.9)	0.90 (0.75 to 0.96)
40	6266 ± 1286	6425 ± 1427	2.4 (-4.9 to 10.3)	11.2 (8.3 to 17.4)	0.81 (0.56 to 0.92)
60	6053 ± 1494	5781 ± 1370	-4.3 (-9.8 to 1.5)	8.9 (6.6 to 13.8)	0.90 (0.76 to 0.96) *
80	5101 ± 1296	4979 ± 1306	-2.8 (-11.8 to 7.2)	15.0 (11.1 to 23.6)	0.74 (0.42 to 0.89)
100	4120 ± 1114	4125 ± 1084	0.6 (-12.8 to 16.0)	22.7 (16.7 to 36.3)	0.50 (0.05 to 0.78)
120	3388 ± 1180	3353 ± 1364	-2.1 (-16.3 to 14.5)	22.5 (16.2 to 38.1)	0.81 (0.51 to 0.93)

Notes: Mean values are presented as raw data, while coefficient of variation (CV) and intraclass correlation coefficient (ICC) values were calculated with log-transformed data. Values are presented with ± standard deviation (SD) or 90% confidence limits (90% CL). Asterisk (*) denotes an ICC above 0.75 (based on confidence limits). Sample size for 120 kg, $n = 11$; for all other loads $n = 13$. Abbreviations: ABC = first, second, and third repetition of the test, respectively; EMF = eccentric mean force; EMV = eccentric mean velocity; RFD = eccentric mean rate of force development; EPF = eccentric peak force; EPV = eccentric peak velocity.

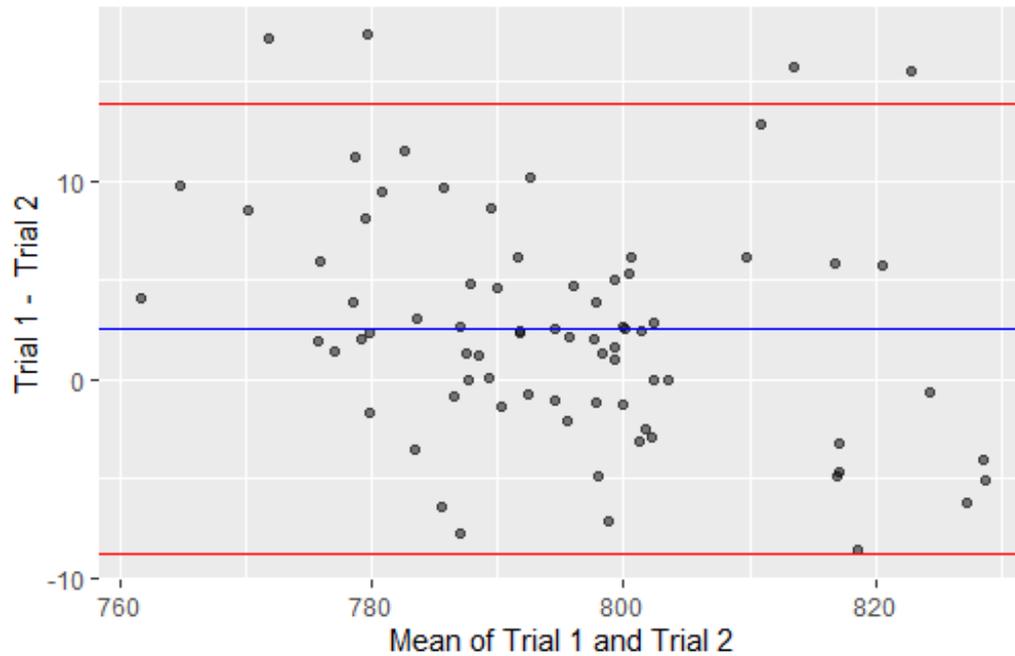


Figure 9. Bland–Altman analysis for between trial differences for eccentric back squat force-velocity assessment in trained athletes. Data shown is for log-transformed eccentric peak force across all loads tested.

4.4 Discussion

To our knowledge, this is the first study to examine the reliability of aspects of the eccentric phase across different loading conditions performed with the intent to maximise velocity in trained athletes. This investigation utilised a well-accustomed exercise in the participants’ normal training environment. The findings of the current study suggest that analysis of EPF has good reliability across loading conditions. EPV, EMV, and EMF have CV values under the commonly applied threshold of 10%; however, we acknowledge that this value constitutes an arbitrary cut-off point (Atkinson & Nevill, 1998). Based on the specific model of ICC (3,1) in this study, practitioners should be cautious when inferring results to other populations and testing conditions.

The results of this investigation were in agreement with our hypothesis that force and velocity results from an eccentric back squat assessment are reliable following familiarisation of the

testing protocols. Hansen et al. (2011) investigated different methods of quantifying force-time variables, noting that peak values may be a more reliable measure as these are not dependent on beginning and end points. The mean values found in this investigation are in agreement with Hansen as they tended to have lower reliability, especially in mean rate of force development. Pérez-Castilla et al. (2019) also reported smaller CV values during the eccentric phase of mean velocity and mean power during a loaded counter-movement jump. The relative reliability of EPF in our study appears to be similar to eccentric peak force values found by Frohm et al. (2005) in their investigation of a supramaximal protocol.

Within-session variability was found to be significantly greater during the first repetition, and as a result, was removed when conducting test–retest analysis. As noted in Table 11, the change in mean after the first repetition is consistently positive in force and velocity variables. One explanation for this might be that participants were using the initial repetition as “practice” or “warm up” which may explain the subsequent improvements in performance. Hopkins et al. (2001) noticed that error values were consistently larger between the first two trials but smaller in subsequent trials for studies investigating power. Future testing and study designs should accommodate for this variability between initial and subsequent trials.

The results of the current study demonstrate novel findings with regard to the eccentric characteristics of trained athletes in a familiar exercise. The relationship with load was found to differ between the variables of interest used in the investigation (Table 12). EPF tended to demonstrate a non-linear trend as barbell load increased while EMF increased concomitantly with load. This discrepancy in ground reaction forces (GRF) may have implications in training program design when the goal is to expose athletes to higher barbell loads or greater magnitudes of GRF. In a recent study (Douglas et al., 2018) investigating ECC with academy

rugby athletes, the authors found small differences between fast and slow ECC groups both with and without the inclusion of accentuated loading. The eccentric loads used in that study ranged from 74% to 110% of concentric 1RM. By comparison, our study noted a plateau in peak force after 60 kg which may have been notably less than the loads used in their investigation. Therefore, although the loading schemes, and likely mean forces, differed between experimental groups, the groups may have been exposed to similar peak forces. We postulate that the novel findings from our study may help facilitate training load selection in future studies that elicit distinct GRF between experimental groups. Practitioners wanting to implement ECC should consider programming variables such as load, velocity, GRF and their effect on the resultant adaptation to the specific demands imposed by these methods.

4.4.1 Limitations

The authors acknowledge that maximal strength was not tested and used to prescribe individualised testing loads. Maximal strength likely varied between individuals in the current study and thus each absolute load represented a different percentage of an individual's ability. The extent to which relative strength levels played a role in the reliability of different measures is unclear. However, EPF reliability was found to be consistent across each of the loads tested. The barbell loads in this investigation were exploratory and represented a wide spectrum of potential force-velocity outcomes, although it is noted that these loads exceeded the strength capabilities of some individuals accounting for the drop out at 120 kg. The manner in which testing proceeded, in an ascending order, was chosen by the authors to allow for data collection in a practical environment. Sufficient rest was provided to minimise any fatigue effect, with rest periods aligning with guidelines for maximal concentric strength testing (Thompson, W. R. et al., 2010). Additionally, sampling frequency may have played a role in the results from this investigation. While 100 Hz has been shown to meet minimum standards of reliability,

Hori et al. (2009) found that reductions in precision were noted below a 200 Hz threshold. Future studies examining reliability in eccentric variables should consider using testing instruments with higher sampling frequencies.

4.5 Conclusions

The aim of this investigation was to determine the reliability of force and velocity values during the eccentric phase of a novel back squat test in trained athletes. Based on these findings, eccentric peak force has the highest absolute and relative reliability across all loads tested. The authors postulate the dynamic contractions used in this study may have a stronger relationship to the specific demands of rugby union than traditional physical testing. This protocol provides strength and conditioning professionals with a novel tool for understanding eccentric-specific changes following targeted training interventions. Practitioners wanting to implement ECC based on the relationships observed in this study may adjust loading strategies (heavier or lighter loads) to maximise the desired programming outcomes (GRF, EPV, etc.) Although the generalisation of these findings is limited to the current sample, practitioners may implement this test to determine reliability with their own athletes. Caution is advised when interpreting rate of force development measures as these have shown greater measurement error than those derived from peak values. The contribution of these variables to physical performance as well as the sensitivity to change following longitudinal training interventions warrants further research.

CHAPTER 5:

Eccentric Force-Velocity-Load Relationship in Trained Rugby Union Athletes

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Eccentric Force-Velocity-Load Relationship in Trained Rugby Union Athletes. *The Journal of Strength & Conditioning Research*

Prelude: The results of our pilot study show that a novel submaximal eccentric back squat test is reliable in trained athletes. Thus, we sought to investigate the force-velocity relationship further as the framework for prescribing eccentric-based training. The “force-velocity curve” is traditionally thought to resemble a hyperbolic shape; however, there is less evidence regarding this relationship during eccentric muscle action, especially in applied settings. The purpose of this study was to investigate the force-velocity-load relationship in an incremental eccentric back squat test.

5.1 Introduction

Eccentric muscle actions have been studied extensively in relation to sports due to the unique physiology involved and the implications on both performance and resistance training in athletic populations (Douglas et al., 2017a, 2017b; Hollander et al., 2007; Hortobágyi & Katch, 1990). In locomotion, the eccentric phase is thought to absorb kinetic energy within the muscle-tendon unit and enhance subsequent movements like jumping and sprinting (Lindstedt et al., 2001). Considerable interest has been placed on manipulating the eccentric phase of resistance training to promote adaptations beyond that of concentric-limited or traditional exercise prescription (Isner-Horobeti et al., 2013; Roig et al., 2009). This phenomenon has applications in sports performance where practitioners seek to maximize force producing capabilities of their athletes.

The application of eccentric-based training (ECC) in athletic populations has both practical (McNeill et al., 2020; Suchomel et al., 2019a, 2019b) and theoretical support (Douglas et al., 2017a) as a strategy for improving measures of strength and explosive ability. Current research suggests that training with fast eccentric muscle actions may lead to an increase in muscle fascicle length potentially through the addition of sarcomeres in the muscle fibre (Sharifnezhad et al., 2014; Stasinaki et al., 2019; Zacharia et al., 2019). These adaptations may lead to an increase in contraction velocity and force production (Vogt & Hoppeler, 2014) and have been postulated to play a role in sport performance via the stretch-shortening cycle (Cowell et al., 2012). The guidelines for the prescription of different ECC methods in practice have received attention in scientific literature (Suchomel et al., 2019b). However, the parameters for prescribing fast or slow ECC from a kinetic and kinematic perspective vary widely as studies have reported angular velocities ranging from $240^{\circ}\cdot\text{s}^{-1}$ (Sharifnezhad et al., 2014) to $30^{\circ}\cdot\text{s}^{-1}$ (Iga et al., 2012). The application of these velocities to traditional, iso-inertial exercises is

unclear as there is relatively less evidence regarding the interaction between force and velocity during eccentric contractions (Alcazar et al., 2019).

The force-velocity relationship in muscle fiber is traditionally thought to take on a hyperbolic shape, known as the “force-velocity curve”, with concentric force production decreasing as velocity increases in a non-linear fashion (Alcazar et al., 2019). Studies investigating the eccentric force-velocity relationship in isokinetic or single-fiber testing have demonstrated a steep increase in force at low velocities, with a non-linear plateauing effect as velocity increases (Edman, 1988; Komi, 1973). However, a review by Meylan et al. (2008) suggests that the forces and velocities recorded in isokinetic tests may not be representative of the demands placed on athletes in the context of their sport. Eccentric-based training utilizing isotonic and isokinetic means may differ in their imposed mechanical load, altering the subsequent adaptation (Guilhem et al., 2013), although both modalities may result in significant improvements to strength and muscle architecture (Coratella et al., 2015). Further, a review by Wagle et al. (2017) highlights additional loading during eccentric training may contribute to superior improvements in strength, suggesting that training methods designed on the basis of concentric muscle action may not optimize the stress applied throughout an eccentric resistance exercise.

There are relatively few reliable measures of eccentric performance available to sport practitioners for exercises commonly used for ECC, outside of maximal eccentric strength (Bridgeman et al., 2016; Hollander et al., 2007). Thus, the systematic prescription of individualized ECC may be improved through the investigation of eccentric-phase kinetic and kinematic variables. We hypothesized that eccentric force variables would generally increase with load and decrease with velocity. The purpose of this cross-sectional study is to investigate

the force-velocity-load relationship in an incremental eccentric back squat testing protocol in trained athletes.

5.2 Methods

Experimental Approach to the Problem

All testing and familiarization sessions were completed in the regular training environment during the normal training times with participants wearing athletic attire. Participants were asked to maintain their normal dietary routines 24 hours before all familiarization and testing sessions. The testing order was standardized as Day 1: anthropometric (height, weight, skinfold), 1-repetition-maximum back squat (1RM); Day 2: eccentric back squat testing with each testing session separated by 72 hours to allow for recovery. The same general warm-up routine was performed consisting of five minutes stationary biking at a self-selected pace followed by a series of dynamic movements including: good mornings, single leg squats (Bulgarian squat), core stability (dead bugs), shoulder internal/ external rotation, and hip internal/ external rotation for two sets of ten repetitions each (side) with 90-120 s rest between sets. This warm-up procedure was performed before each familiarization and testing session.

Participants

Thirty-seven male rugby union athletes agreed to participate in this study (Table 13). Inclusion criteria were: males 18 years or older; at least two years of resistance training experience; participation in provincial-level rugby union or higher; and free from any significant musculoskeletal injury or illness occurring within the last month. Participants were asked to refrain from strenuous activity in the 24 hours prior to testing. All participants were informed of the purpose, benefits, and risks of the study through written and oral description and gave their written consent to participate prior to engaging in any activity. This research project was

approved by the Human Research Ethics Committee of the University of Waikato in October of 2018 (HREC[Health]2018#60).

Table 13. Descriptive characteristics of participants.

Variable	Mean (\pm SD)
Age (y)	21.5 (2.5)
Height (cm)	184.9 (7.44)
Body Mass (kg)	101.0 (11.5)
Squat (kg)	166.7 (18.9)

Notes. y = years, cm = centimeters, kg = kilograms

Procedures

Ground reaction force and displacement-time data were captured using two force plates (PASCO Scientific, CA, USA) and a linear position transducer (Celesco, CA, USA). Data were down sampled to 100 Hz and analyzed using custom-made software (Weightroom, HPSNZ, Auckland, New Zealand). The same equipment was used by the same operator in all testing sessions to reduce inter-operator variability. Force values were scaled to body mass ($\text{N}\cdot\text{kg}^{-1}$). Loud music and verbal encouragement were allowed for all familiarization and testing sessions. A certified strength and conditioning specialist supervised all familiarization and testing sessions to ensure participants adhered to the testing procedures.

Eccentric Force-Velocity Test: Two familiarisation sessions were performed before the eccentric test took place. After the same general warm up routine described previously, participants were asked to back squat at three different loads (wooden dowel/ 300 grams, 60 kg, and 80 kg) for ten, five and five repetitions, respectively. The participants received verbal instructions to perform the first repetition in a "slow and controlled" manner with a "two second down, two seconds up tempo" and then progressively increase the eccentric and concentric velocity such that the last repetition was performed at maximal velocity. For the final repetition,

participants were instructed to move “down fast, up fast” and “squat to your normal depth”. A digital timer was provided to assist with the tempo of the initial repetitions.

The eccentric force-velocity assessment was performed using six absolute loads (20, 40, 60, 80, 100, and 120 kg). The exercise technique was similar to that used in the 1RM back squat. Three repetitions were performed at each load with the best attempts recorded for analysis. If a participant was unable to complete all three repetitions they were excused from that load. Participants were asked to maximize velocity in both the eccentric and concentric phases while remaining motionless between repetitions and a three-minute rest period was allowed between sets (Thompson, W. R. et al., 2010). Further, participants were asked to keep their feet in contact with the ground throughout the trial in an attempt to minimize movement variation. The initiation of the eccentric phase was defined as the point of minimum force recorded during the downward phase of movement which was identified manually by the primary investigator (Hansen et al., 2011). The end of the eccentric phase was determined by the software and was considered to be the lowest point of vertical displacement.

Maximal Strength Back Squat: Maximal strength for each individual was tested in order to scale the absolute loads in the eccentric test. Technique in the barbell back squat was standardized as feet placed shoulder width apart and toes turned slightly out. A barbell was placed across the trapezius with hands placed comfortably on the barbell. Three specific warm-up sets were allowed consisting of six to eight, three to five, and one to three repetitions at 60, 75, and 90% of the historical 1RM with a three-minute period between sets and maximal attempts (Thompson, W. R. et al., 2010). Load was increased until participants could no longer complete a repetition with correct technique (e.g. approximately 90° knee flexion). Spotters were used during all maximal strength assessments. An attempt was not considered valid if the

spotters came in contact with the participant or the bar during the movement. Participants had up to four attempts to lift the maximum load possible for a single repetition.

Statistical Analyses

Separate linear mixed models were used to assess the fixed effect of barbell load on relative eccentric peak force (REPF), relative eccentric mean force (REMF), eccentric peak velocity (EPV) and eccentric mean velocity (EMV), while intercepts were allowed to vary by individual as a random effect. The model intercept was represented as the lightest barbell load in the testing sequence, 20 kg. Therefore, coefficients for other barbell loads in the models represents the difference between those loads and the model intercept (Table 14). Regression assumptions were assessed visually via fitted vs. residual plots, QQ plots, and histograms of model residuals. Analyses were conducted in R Studio (version 4.0.5) using the lme4 package. An intraclass correlation coefficient (ICC) was derived from model random intercepts using between-subject variance divided by total error variance (Lorah, 2018). Analysis of ICC values shows the proportion of variance in the dependent variable (eccentric characteristics) explained by the grouping variable (individual athletes) and were interpreted accordingly; small (0.1 to 0.3), moderate (0.3 to 0.5), large (0.5 to 0.7), very large (0.7 to 0.9) and nearly perfect (0.9 to 1.0) (Hopkins et al., 2009). The best result from each load in the eccentric back squat test was recorded. The statistical significance level was set at $p \leq 0.05$.

5.3 Results

Force-velocity-load relationship

The reliability of eccentric phase variables in the back squat has been examined in our lab (McNeill et al., 2021) and by others (Bogdanis et al., 2018). (Table 14). Findings from the linear

Table 14. Estimated coefficients of fixed and random effects from linear mixed model analyses on the effects of barbell load on eccentric kinetics and kinematics.

Fixed Effects	REPF		EPV		REMF		EMV	
	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE
20 kg (Intercept)	27.6 (26.5 to 28.7) *	0.64	2.27 (2.21 to 2.33) *	0.03	15.1 (14.6 to 15.5) *	0.25	1.58 (1.54 to 1.63) *	0.03
40 kg	1.96 (1.40 to 2.53) *	0.35	-0.09 (-0.13 to -0.05) *	0.02	1.95 (1.57 to 2.32) *	0.23	-0.10 (-0.13 to -0.07) *	0.02
60 kg	2.69 (2.12 to 3.25) *	0.35	-0.30 (-0.34 to 0.27) *	0.02	3.54 (3.17 to 3.92) *	0.23	-0.27 (-0.30 to -0.23) *	0.02
80 kg	2.94 (2.37 to 3.50) *	0.35	-0.51 (-0.55 to -0.48) *	0.02	4.94 (4.56 to 5.32) *	0.23	-0.41 (-0.44 to -0.38) *	0.02
100 kg	2.92 (2.36 to 3.49) *	0.35	-0.70 (-0.74 to -0.66) *	0.02	6.56 (6.19 to 6.94) *	0.23	-0.57 (-0.60 to -0.54) *	0.02
120 kg	2.20 (1.64 to 2.76) *	0.35	-0.91 (-0.95 to -0.87) *	0.02	7.83 (7.45 to 8.21) *	0.23	-0.73 (-0.76 to -0.70) *	0.02
Random Effects	ICC (90%CI)	Std Dev. (90% C.I.)	ICC (90%CI)	Std Dev. (90% C.I.)	ICC (90%CI)	Std Dev. (90% C.I.)	ICC (90%CI)	Std Dev. (90% C.I.)
Athlete	0.85 (0.83 to 0.88)	3.64 (2.98 to 4.42)	0.74 (0.70 to 0.79)	0.17 (0.14 to 0.21)	0.55 (0.49 to 0.62)	1.12 (0.89 to 1.38)	0.72 (0.67 to 0.76)	0.13 (0.11 to 0.16)
Residual		1.49 (1.35 to 1.60)		0.10 (0.09 to 0.11)		1.00 (0.91 to 1.08)		0.08 (0.07 to 0.09)

Notes. REPF = relative eccentric peak force, EPV = eccentric peak velocity, REMF = relative eccentric mean force, EMV = eccentric mean velocity. * significant at 0.05

mixed model analysis including estimated coefficients, standard errors, 90% confidence intervals, and ICC values are listed in Table 14. There was a significant effect of load ($p < 0.05$) in the analysis of REPF, EPV, REMF, and EMV. Coefficients show an initial increase and then plateau in REPF relative to the intercept across the loads used in the investigation. EPV, REMF, and EMV the estimated coefficients tended to show a linear trend for each level of load. Random effects for individual athletes resulted in a 13.2% (REPF), 7.49% (EPV), 7.41% (REMF), and 8.23% (EMV) variation in the fixed effect intercept.

Figure 10 depicts the force-velocity-load relationship between REPF, REMF, EPV, and EMV. With the exception of REPF, it appears that as eccentric velocity increases force production decreases along with concomitant decreases in load. A non-linear relationship was observed

between REPF and additional barbell load as different loading conditions appear to result in similar levels of peak force despite changes in velocity.

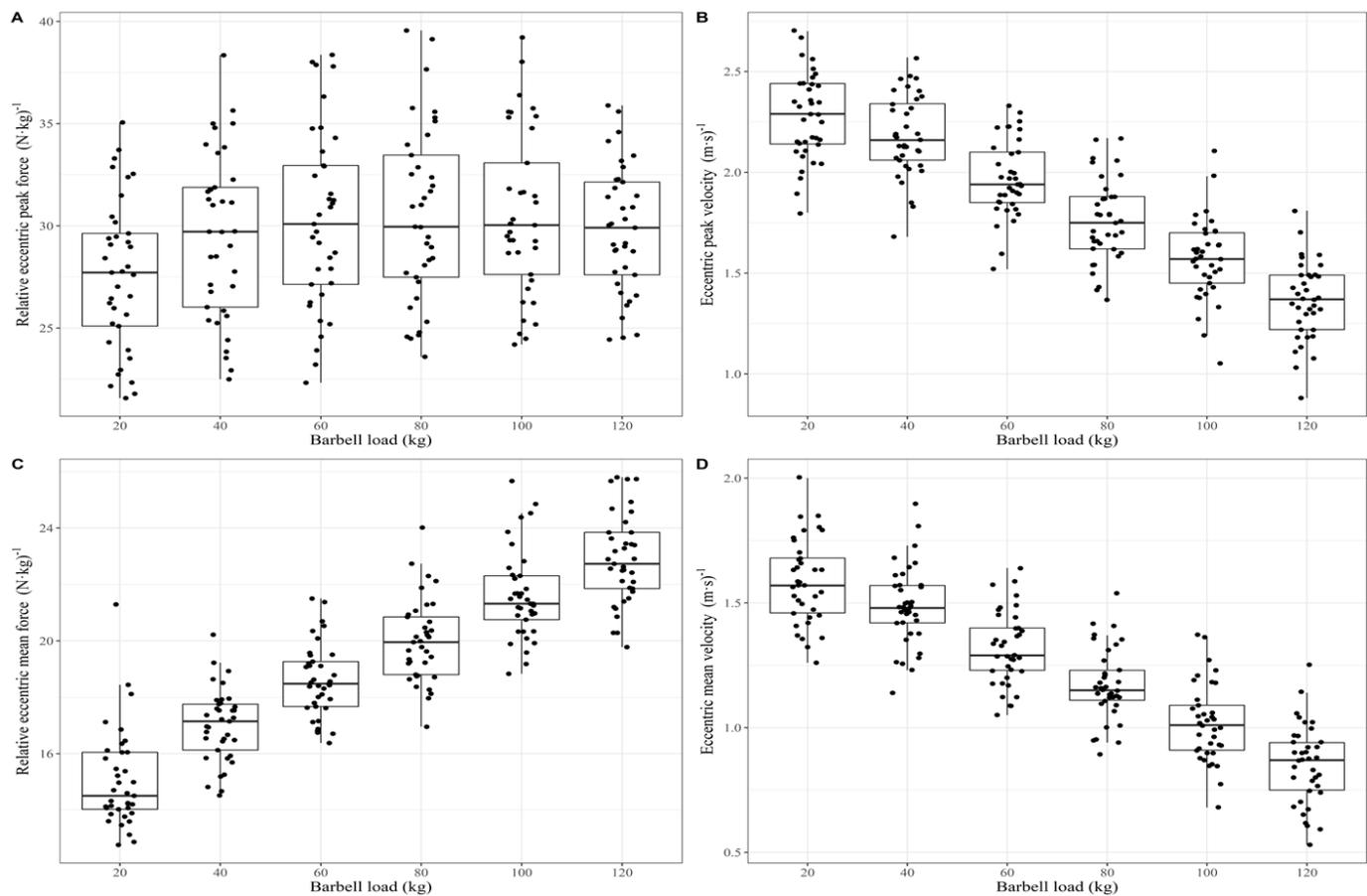


Figure 10. Relative eccentric peak force (A), eccentric peak velocity (B), relative eccentric mean force (C), and eccentric mean velocity (D) and their relationship with barbell load in an eccentric back squat test. N = force in newtons, kg = kilograms, $N \cdot kg^{-1}$ = force per kg of body mass, $m \cdot s^{-1}$ = meters per second.

Variance between random intercepts was also apparent due to differences in individual characteristics. ICC values reveal the proportion of variance in the dependent variables explained by individual characteristics to be very large (REPF, EPV), moderate to large (REMF), and large to very large (EMV).

Figure 11 displays the individual variance via random intercepts relative to the overall intercept of the linear mixed model. Based on these random intercepts, ICC values reveal the proportion of variance in the dependent variables explained by individual characteristics after accounting for changes in barbell load. The magnitude of these values in REPF and EPV were very large, follow by large to very large in EMV, and moderate to large in REMF.

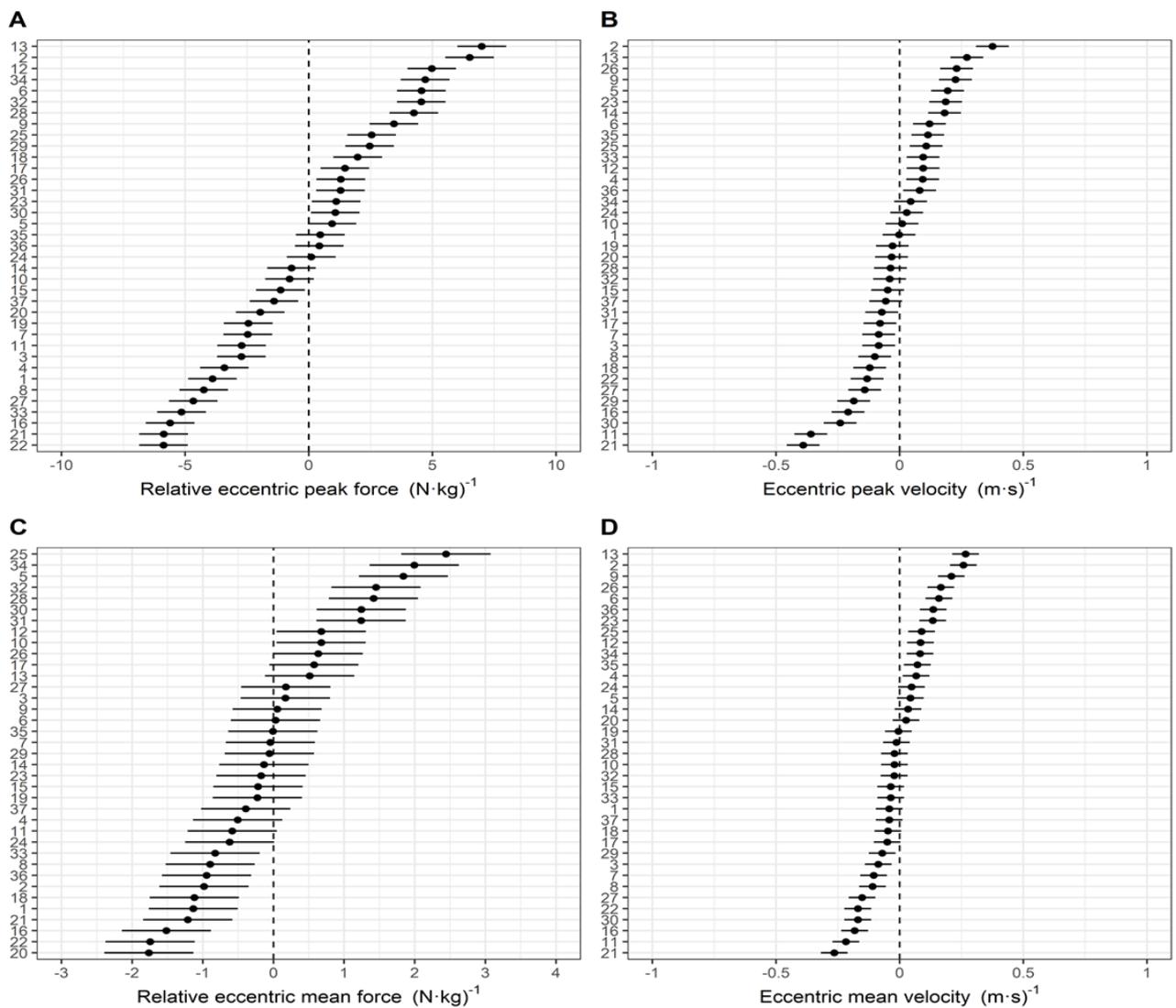


Figure 11. Individual (random) intercepts and 90% confidence intervals from linear mixed model analysis. Relative eccentric peak force (A), eccentric peak velocity (B), relative eccentric mean force (C), and eccentric mean velocity (D) and their relationship with barbell load in an eccentric back squat test. N = force in newtons, kg = kilograms, $\text{N}\cdot\text{kg}^{-1}$ = force per kg of body mass, $\text{m}\cdot\text{s}^{-1}$ = meters per second.

5.4 Discussion

Force-velocity-load relationship

The relationships found in our analysis of EPV, EMV, and REMF tend to agree with our hypothesis and depict a linear relationship that deviates from the commonly observed hyperbola in force-velocity research (Edman, 1988). Although a linear force-velocity relationship has been observed in multi-joint movements (Bobbert, 2012), the inclusion of experimental conditions at the extreme of force and velocity production may cause this relationship to become hyperbolic (Alcazar et al., 2019). As our study was designed to investigate submaximal loads, this may have influenced the trends seen in the data. These findings are consistent with a pilot study performed in our lab with a similar rugby population (McNeill et al., 2021). Existing research has shown that cross-bridging time, neural activation, and mechanical properties are contributing factors to the well-established force-velocity relationship seen in vivo with humans (Alcazar et al., 2019). Additionally, the findings of this study highlight that the specific variable and its parameters may influence the practical interpretations of the force-velocity relationship (i.e., linear, non-linear, hyperbolic). Specifically, when performed with maximal intent these measures of velocity (EPV, EMV) and force (REMF) tend to decrease and increase, respectively, with additional load under iso-inertial conditions. From a practical perspective, these findings may inform the prescription and individualisation of ECC in the back squat for athletes.

The analysis of REPF yielded a non-linear relationship with load when accounting for individual differences. Notably, increasing loads failed to create substantial changes in REPF in rugby union athletes during a familiar exercise. The lower limbs are often described as a spring-mass model which absorbs the momentum and subsequent braking impulse generated during eccentric actions which is then utilized during the concentric phase (Lindstedt et al.,

2002; Morin et al., 2006). A novel aspect of the protocol used in this study was the dynamic nature of the exercise requiring participants to complete both the eccentric and concentric actions. Bogdanis et al. (2018) conducted a fast half-squat protocol in resistance-trained university students while measuring ground reaction forces, wherein only the eccentric phase was performed. In agreement with our findings, REPF did not increase beyond a certain threshold. Similarly, Komi (1973) found that the eccentric force production rose sharply and then levelled off at higher velocities. Our findings suggest that eccentric force changes differentially with a trend towards peak force levelling off as load increases and velocity decreases. A review by Aagaard (2018) highlighted several neural inhibitory mechanisms that limit eccentric force production as a protective mechanism against muscle damage. These mechanisms are thought to have a plateauing effect on maximal strength in untrained individuals. The effect may be reduced or removed following electrical stimulation or exposure to heavy resistance training (Aagaard et al., 2000). The participants in the current study were strength-trained individuals, so the additional loading may have created the kinetic potential for peak forces beyond the capacity of the muscle-tendon to produce force eccentrically, possibly activating an inhibitory response. Although the physiological mechanisms are beyond the scope of this article, the failure to create additional peak force despite additional loading may be partially explained by neural inhibition in the lower limbs. The novel findings of this study suggest lighter loads can be prescribed to maximise eccentric peak force in trained athletes.

Limitations

The decision to include both the eccentric and concentric phase in the current protocol was intended to capture the ability of the muscle-tendon complex to create a braking impulse and change downward momentum during the stretch-shortening cycle. As a result, our findings and

interpretations may be limited in regards to existing eccentric-only research; however, we believe this dynamic action with a minimal amortization phase may have more practical application in the training of team sport and specifically rugby athletes. The participants chosen for this study were male, rugby union athletes, and therefore caution should be exercised when generalizing these findings to other sport- or sex-specific populations.

The barbell loads in this investigation were absolute and chosen to represent a wide range of potential force-velocity outcomes at submaximal levels. The manner in which testing proceeded, in an ascending order, was chosen by the authors to allow for data collection in a practical environment. To control for these potential limitations, individual differences were included in our statistical model and rest periods were aligned to guidelines for maximal concentric strength testing to minimize the effects of fatigue (Thompson, W. R. et al., 2010). Sampling frequency from force plates at 100 Hz has been shown to meet minimum standards of reliability, although Hori et al. (2009) found that reductions in precision were noted below a 200 Hz threshold. Future studies should consider the potential impacts of both order effects in load selection and testing instruments with higher sampling frequencies.

5.5 Conclusions

Our study contributes to the existing body of force-velocity research through the addition of a multi-joint investigation focusing on the eccentric phase of dynamic action in trained athletes. These findings suggest that eccentric force and velocity parameters differ in their relationships depending on the specific variables being investigated and under what loading conditions they are being examined.

At a practical level, the implementation of the research may rely on the specific priorities of the strength and conditioning practitioners. If the goal is to expose athletes to greater degrees of peak force during the eccentric phase, then the prescription of relatively light loads might be an effective method of prescribing fast ECC in the back squat. Indeed, heavier loads may result in diminishing magnitudes of peak ground reaction forces. In a broader sense, the authors feel that more research is necessary to further understand the implications of prescribing training programs for athletes on the basis of particular kinetic and kinematic variables and the effect of this approach on subsequent adaptation and performance outcomes.

Future research may investigate how these eccentric-phase characteristics change over time, the relationship with changes in physical performance, and the trainability of the different components of eccentric force production following targeted ECC interventions.

CHAPTER 6:

Performance changes following fast- and controlled-tempo eccentric-based training in rugby union athletes

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Performance changes following fast- and controlled- tempo eccentric-based training in rugby union athletes. *The Journal of Strength & Conditioning Research*

Prelude: Findings from our investigation of the eccentric force-velocity-load relationship showed that eccentric peak force plateaus at low relative loads and high velocities. Fast eccentric-based training has been suggested as an effective method for improving measures of strength, speed, and explosive ability when compared to slow ECC. The purpose of this study was to compare the effects of fast-tempo and controlled-tempo ECC using a traditional exercise (barbell back squat) on strength, speed, and jumping ability in trained athletes.

6.1 Introduction

Participation in professional rugby union generally involves explosive, collision-based competitions and trainings which demand a range of physical qualities such as strength, speed, and acceleration (Campbell et al., 2018; Quarrie et al., 2013). Resistance training programs designed to target and enhance these specific qualities may then improve physical performance. As an alternative method to traditional or concentric-based training (CONC), Eccentric-based training (ECC) may further improve the physical performance of trained athletes (McNeill et al., 2019). Eccentric muscle action is thought to have unique mechanical properties in comparison to concentric muscle action (Douglas et al., 2017a). Additionally, 20 to 60% differences have been observed between eccentric and concentric strength (Hollander et al., 2007), suggesting the two measures may represent distinct physical qualities. Eccentric-specific characteristics such as force production have been associated with strength, power, and jump performance in resistance trained men (Bridgeman et al., 2018), and may help determine dynamic performance (Cormie et al., 2010; Laffaye & Wagner, 2013). Eccentric strength may also contribute to stiffness regulation and rate of force development (Douglas et al., 2020), and is a quality that is commonly targeted by strength and conditioning practitioners on the basis of improving sports performance (McNeill et al., 2020). The implementation of different ECC methodologies with team sport athletes remains relatively unexplored.

In a series of reviews by Suchomel and others (2019a, 2019b) a number of potential ECC methods were proposed for practical application with athletic populations. One of these strategies, the manipulation of temporal parameters, may be especially useful for improving athletic performance. Existing literature supports the use of heavy load and/ or fast contraction velocity for the improvement of muscle function and athletic characteristics (Douglas et al., 2017b). In practice, much of the proposed methodology for high-force/ high-velocity eccentric

training is performed with specialised equipment or under iso-kinetic conditions (Douglas et al., 2018; Farthing & Chilibeck, 2003; Liu et al., 2013). Eccentric flywheel training may represent a type of high-velocity/ low-load eccentric training when familiarised participants are able to delay the braking impulse appropriately (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017). Small to large improvements in strength, speed, and power have been observed in professional athletes following 6 to 7 weeks of this type of training (Maroto-Izquierdo, García-López, & de Paz, 2017; Sabido et al., 2017). Emerging research has shown that traditional iso-inertial exercise (i.e., the barbell back squat) is capable of producing high-force/ high-velocity eccentric conditions under relatively light load when performed with maximal intent (Study 4).

The effects of fast eccentric training on performance in trained athletes are not well understood. Douglas et al. (2018) observed small improvements in sprint time in trained rugby union athletes following slow accentuated eccentric training, but found that fast accentuated eccentric training may have impaired sprint performance. The authors of that study noted the time course of adaptation may have played a role in the observed effects of the eccentric training program. Mike et al. (2017) compared the effects of different eccentric tempos with the same load on performance, noting that strength, power and vertical jump performance largely improved to a similar extent in all conditions. One proposed mechanism for the efficacy of ECC is the addition of sarcomeres in series within the muscle fibre, with longer fascicle lengths believed to increase muscle fibre shortening velocity (Toigo & Boutellier, 2006). Changes in fascicle length following longitudinal exposure to ECC may differ depending on the exposure to high-velocity or high-load eccentric contractions (Sharifnezhad et al., 2014). Therefore, highly trained athletes with several years of resistance training and participation in their respective sports may have developed different eccentric force and velocity capacities. Research

investigating force-velocity profiling (Samozino et al., 2012) suggests there is an optimal balance in mechanical factors that determine power output for an individual. Resistance training programs designed on the basis of the individual force-velocity profile have been shown to optimise this balance and improve physical performance to a greater degree than traditional program design (Jiménez-Reyes et al., 2019; Simpson et al., 2021). The effects of individual ECC force-velocity characteristics and their responsiveness to ECC methods remain unexplored.

The purpose of this study was to compare the effects of two different ECC method, fast-tempo (FAST) and controlled-tempo (CTRL) on physical performance in trained, semi-professional rugby union athletes. The duration of the training program was 6 weeks, inclusive of a 1-week taper phase. Eccentric force-velocity profile data was collected to further understand how the individual capacity to utilise eccentric work may affect their response to ECC. Due to the specificity of the movements involving a rapid stretch-shortening cycle, we hypothesized the two groups would differ most in their improvements of tests including a rapid stretch-shortening cycle.

6.2 Methods

Experimental Approach to the Problem

Participants were assigned an ID number, ranked, and then matched according to baseline dynamic back-squat strength (1RM), and playing position. Participants were then randomly assigned via coin flip to a resistance training program with either a fast- (FAST) or controlled-tempo (CTRL) squat. The training programs were administered with professional athletes during the early off-season with all sessions being performed in their normal training facility. The programs involved four resistance training sessions per week, inclusive of plyometric, and

dynamic muscle contractions, and were identical with the exception of the eccentric back squat exercise, which was performed once per week. Training volume and intensity were prescribed in a stepwise linear manner for a duration of 6 weeks inclusive of a taper week. The FAST group was asked to perform the eccentric phase of the squat with maximal intent to move quickly. The CTRL group performed the eccentric phase of the squat with a 3-second duration according to an electronic metronome placed in front of them in order to limit individual movement variation. Volume load (total repetition x % of 1 repetition maximum) was calculated to minimize differences in the number and intensity of muscle contractions across the training phase. The total prescribed volume load was 5,990 units for the FAST group (week 1 = 720; week 2 = 1,170; week 3 = 1,400; week 4 = 1,500; week 5 = 1,200; deload = 720). The total prescribed volume for the CTRL group was 6,495 units (week 1 = 675; week 2 = 1,050; week 3 = 1,320; week 4 = 1,500; week 5 = 1,365; deload = 585). The rationale for differences in the training program was made according to research suggesting that a threshold in peak ground reaction force may exist for fast eccentric work beyond 70% of concentric 1RM (Bogdanis et al., 2018), as well as research in our lab showing a linear drop off in peak velocity with added barbell load (McNeill et al., 2021).

Participants

Twenty-seven participants were recruited from a semi-professional rugby union team. Inclusion criteria were: males 18 years or older; at least two years of resistance training experience; participation in provincial-level rugby union or higher; and free from any significant musculoskeletal injury or illness occurring within the last month. Only athletes who completed 90% of training sessions were included in the final analysis. All participants were informed of the purpose, benefits, and risks of the study through written and oral description and gave their written consent to participate prior to engaging in any activity. This research

project was approved by the Human Research Ethics Committee of the University of Waikato in October of 2018 (HREC[Health]2018#60).

Testing Procedures

All testing was completed in the regular training environment during the normal training times with participants wearing athletic attire. Participants were asked to refrain from strenuous activity and maintain their normal dietary routines 24 hours before all familiarisation and testing sessions. All participants were recruited from the same provincial rugby union team and were involved in equivalent weekly schedules and twice weekly tactical trainings. An overview of the study design can be found in Figure 12. The testing order was standardized as Day 1: anthropometric (height, weight, skinfold), 1-repetition-maximum back squat (1RM); Day 2: explosive (counter-movement jump, drop jump), eccentric back squat testing; Day 3: speed (10 m, 20 m) with each testing session separated by 48 hours to allow for recovery. Prior to familiarization and testing sessions, a general warm-up routine was performed consisting of five minutes stationary biking at a self-selected pace followed by a series of dynamic movements including: good mornings, single leg squats (Bulgarian squat), core stability (dead bugs), shoulder internal/ external rotation, and hip internal/ external rotation for two sets of ten repetitions each (side) with 90-120 seconds rest between sets.

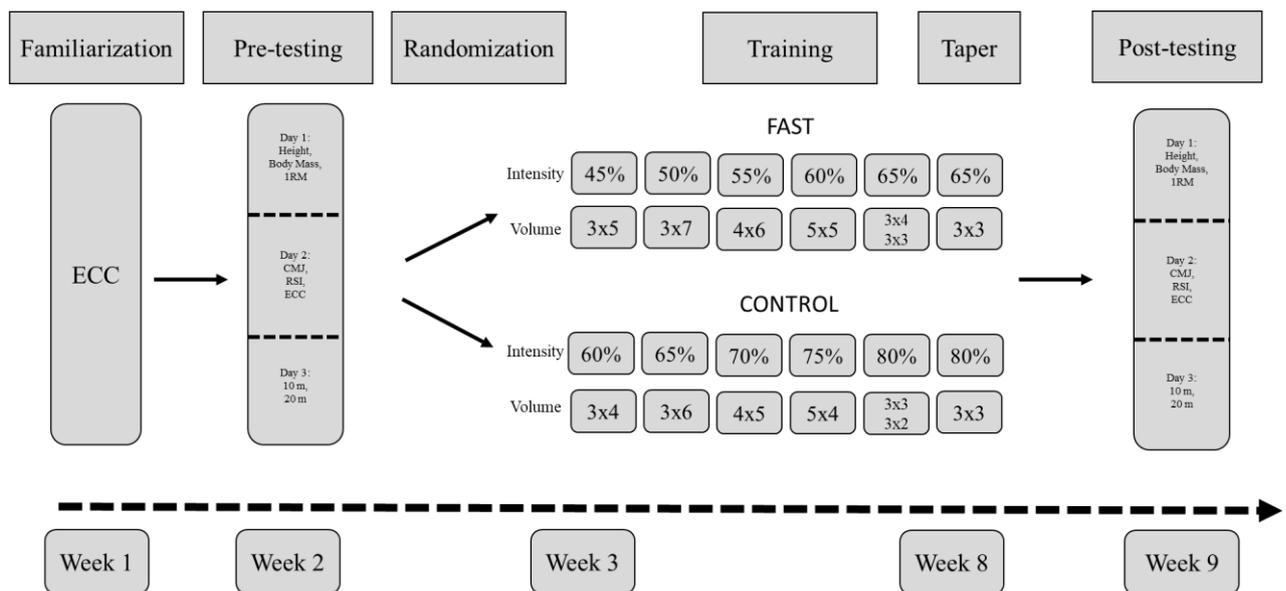


Figure 12. Pre- and post-randomized parallel group study design of two eccentric-based resistance training programs. 1RM = 1 repetition-maximum test in the barbell back squat, CMJ = counter-movement jump height, RSI = reactive strength index (flight time/ contact time), ECC = eccentric force-velocity profiling, 10 m/ 20 m = sprint test. FAST = fast eccentric back squat program, CONTROL = 3-second controlled tempo eccentric. Intensity = prescription for the eccentric squat exercise based on 1RM. Volume = sets x repetitions of the eccentric squat exercise. All other aspects of the training program were identical. Changes in volume seen in the 5th week of the Training phase were manipulated to manage the difference in volume load between the two groups.

Ground reaction force and time-displacement data were captured during the CMJ, RSI, and Eccentric Force-Velocity Profile assessment using two force plates (PASCO Scientific, CA, USA) and a linear position transducer (Celesco, CA, USA). Data were down sampled to 100 Hz and analysed using custom-made software (Weightroom, HPSNZ, Auckland, New Zealand). Sprint times were captured using dual-beam timing gates (Swift, QLD, Australia). The same equipment was used by the same operator in all testing sessions to reduce inter-operator variability. Loud music and verbal encouragement were allowed for all familiarisation and testing sessions. A certified strength and conditioning specialist supervised all familiarisation and testing sessions to ensure participants adhered to the testing procedures.

Maximal Strength Back Squat: Technique in the barbell back squat was standardised as feet placed shoulder width apart and toes turned slightly out. A barbell was placed across the trapezius with hands placed comfortably on the barbell. Three specific warm-up sets were allowed consisting of six to eight, three to five, and one to three repetitions at 60, 75, and 90%, respectively, of the historical 1RM with a three-minute period between sets and maximal attempts [26]. Load was increased until participants could no longer complete a repetition with correct technique (e.g., approximately 90° knee flexion). Spotters were used during all maximal strength assessments. An attempt was not considered valid if the spotters came in contact with the participant or the bar during the movement. Participants had up to four attempts to lift the maximum load possible for a single repetition. The best attempt was recorded and scaled to body mass.

Explosive Ability: Participants were asked to complete two assessments of explosive jumping ability; the drop jump and counter-movement jump. The drop jump test was performed from a 30 cm wooden box placed 10 cm behind two force plates. The technique of the drop jump test was standardised as feet placed shoulder width apart and hands held on hips. The participants' feet were aligned with the front of the box and they were instructed to hop off the box with both feet, land simultaneously with both feet and produce a rapid, maximal jump effort. Participants were instructed to "maximise height with minimal contact time" [27]. Reactive strength index (RSI) was calculated as flight time divided by contact time, based on data from drop jump testing [25]. The counter movement jump was performed while standing on two force plates. Participants were asked to drop down to a self-selected depth and then produce a rapid, maximal jump effort with hands kept on the hips. Participants were instructed to "jump as high as you can". The best result of up to three attempts for both jumps was recorded and 60 seconds rest between attempts was allowed.

Eccentric Force-Velocity Profile: The eccentric force-velocity assessment was performed using six absolute loads (20 kg, 40 kg, 60 kg, 80 kg, 100 kg, 120 kg). The exercise technique was similar to that used in the 1RM back squat, the familiarisation and testing procedures have been discussed elsewhere (McNeill et al., 2021). Participants stood on two force plates, with a linear position transducer attached to the barbell, lateral to the centre of mass. Three repetitions were performed at each load; if a participant was unable to complete all three repetitions they were excused from that load. Participants were asked to maximise velocity in both the eccentric and concentric phases while remaining motionless between repetitions and a three-minute rest period was allowed between sets [26]. Participants were asked to keep their feet in contact with the ground throughout the trial in an attempt to minimise movement variation. Relative eccentric peak force (REPF), relative eccentric mean force (REMF), eccentric peak velocity (EPV), and eccentric mean velocity (EMV) were recorded retrospectively from the software. The best attempts were kept for analysis, and force values were scaled to body mass.

Speed: Sprints were performed over a 20 m distance with 10 m (0-10 m), and 20 m splits. Splits of ≤ 10 m and > 10 m were chosen to distinguish acceleration ability and maximal speed ability [28]. Each sprint was performed from a staggered stance with the front foot 0.5 m behind the starting line. The testing was performed indoors on an artificial turf surface with athletic footwear. Each participant was allowed three maximal attempts with three minutes rest in between each trial, the best times were recorded for analysis.

Statistical analysis

All data are reported as mean \pm SD unless otherwise noted. Separate linear mixed models were constructed to examine the effect of the training program on each of the performance variables.

Trial (Pre, Post), Group (FAST, CTRL), and their interaction were assessed as fixed effects with the individual athletes specified as the random effect (random intercept). Interclass correlation coefficients were calculated from the random effects of the mixed model using between-athlete variance divided by total variance (Lorah, 2018). The ICC values from mixed models are thought to represent the proportion of variance explained by the random effect and were interpreted accordingly; small (0.1 to 0.3), moderate (0.3 to 0.5), large (0.5 to 0.7), very large (0.7 to 0.9) and nearly perfect (0.9 to 1.0) (Hopkins et al., 2009; Lorah, 2018). Model residuals were assessed visually using fitted vs. residual plots, QQ plots, and histograms and approximated normality. Effect sizes (Hedges' $g \pm 90\%$ confidence intervals) were calculated by expressing the difference in change scores between groups divided by the pooled standard deviation (Lakens, 2013). If the 90% CL overlapped small positive and negative values the effect was deemed unclear (Batterham & Hopkins, 2006). Threshold values for Hedges' g statistics were < 0.20 (trivial), > 0.20 (small), > 0.60 (moderate), > 1.2 (large) and > 2.0 (very large) (Hopkins et al., 2009). Statistical analyses were conducted using the lme4 (version 1.1-26), lmerTest (version 3.1-3), and effsize (version 0.8.1) package in R Studio (version 4.0.5) and statistical significance was set at $p \leq 0.05$.

6.3 Results

Participant dropout occurred for several reasons: leaving the team ($n = 2$; 1 CTRL, 1 FAST), contact injury during rugby training ($n = 4$; 2 CTRL, 2 FAST), called into representative team ($n = 3$; 1 CTRL, 2 FAST), testing schedule conflicts ($n = 5$; 1 CTRL, 4 FAST). Descriptive characteristics of the FAST and CTRL groups of the remaining participants in this study can be seen in Table 15. After accounting for attrition, a moderate and significant difference was found between groups at baseline for RSI ($g = 1.04, p = 0.02$). All other variables: Squat, ($g =$

0.24, $p = 0.31$) CMJ, ($g = 0.51$, $p = 0.13$) 10 m, ($g = < 0.001$, $p = 0.45$) 20 m, ($g = 0.12$, $p = 0.38$) revealed small to trivial, non-significant differences between groups at baseline. A separate analysis revealed trivial, non-significant differences in the prescribed volume load ($g = 0.11$, $p = 0.43$) between groups.

Table 15. Baseline data for fast-eccentric (FAST) and controlled-tempo (CTRL) group.

	n =	FAST	n =	CTRL
Age (y)	9	22.2 (± 2.7)	11	21.7 (± 2.5)
Body Mass (kg)	9	97.8 (± 8.6)	11	98.9 (± 10.7)
Height (cm)	9	182.3 (± 6.6)	11	185.9 (± 9.9)
Skinfold (mm)	9	82.1 (± 13.9)	10	88.5 (± 27.8)

Notes. y = years, kg = kilograms, cm = centimetres, mm = millimetres, n = sample size for respective studies.

Due to participant dropout only a small final sample size was collected for the eccentric force-velocity profile (4 to 9 in the FAST and CTRL group, respectively). Therefore, no statistical analysis was performed on this test, and these variables were removed from the mixed model analysis. Baseline eccentric profile data and the raw data collected from the study are included as supplemental material for future studies.

Statistical analysis via linear mixed modelling (Table 16) revealed group x trial interaction effects were not significant for any of the performance variables included in the analysis, thus only main effects were interpreted. A significant main effect for trial in the squat ($p = 0.02$) and CMJ ($p = 0.04$) were observed indicating an increase in performance from pre- to post-test. Trial effects for RSI ($p = 0.07$), 10 m sprint ($p = 0.91$), and 20 m sprint ($p=0.74$) were not significant. As mentioned previously, a significant effect for group was observed in RSI. No other significant effects for group or trial were observed for any performance variable following the 6-week ECC program. Inter-individual responses to the different training

programs across pre- and post-testing are presented in Figure 13. ICC values indicate the proportion of variance explained by individual athlete random intercepts in the squat (96%, nearly perfect), CMJ (77%, very large), RSI (83%, very large), 10 m sprint (93%, nearly perfect), 20 m sprint (93%, nearly perfect).

Pre- and post-test performance results for both groups are presented in Table 17 with percent change, within- and between-group effect size differences, and the respective sample size included in the final analysis (n) for each test. Within-group effect sizes for FAST ranged from trivial to moderate in the Squat, and trivial to moderate in the CMJ. RSI, 10 m sprint time, and 20 m sprint time all resulted in trivial to small improvements. In the CTRL group trivial to small effect size differences were observed in both the Squat and RSI. CMJ showed trivial to moderate changes. Analysis of 10 m sprint time and 20 m sprint time revealed trivial changes. The between-group differences for Squat, CMJ, RSI, and 10 m sprint time were unclear. Differences in 20 m sprint time were moderate ranging from trivial to large.

Table 16. Linear mixed model analysis of responses to eccentric-based training programs in rugby union athletes.

Fixed Effects	Squat (1RM/body mass)		CMJ (cm)		RSI (ft/ct)		10 m sprint (s)		20 m sprint (s)	
	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE	Est. (90% C.I.)	SE
Intercept	1.60 (1.51 to 1.70)	0.06	37.9 (35.4 to 40.3)	1.5	2.44 (2.23 to 2.64)	0.13	1.75 (1.70 to 1.79)	0.03	3.03 (2.96 to 3.10)	0.04
Trial*Group	0.01 (-0.04 to 0.05)	0.03	-1.1 (-3.9 to 1.7)	1.7	-0.05 (-0.25 to 0.15)	0.13	-0.01 (-0.04 to 0.01)	0.02	-0.04 (-0.08 to 0.01)	0.03
Trial										
Pre										
Post	0.05 ‡ (0.02 to 0.08)	0.02	2.6 ‡ (0.75 to 4.5)	1.1	0.16 (0.02 to 0.29)	0.08	-0.001 (-0.02 to 0.02)	0.01	0.01 (-0.02 to 0.03)	0.02
Group										
Controlled										
Fast	0.14 (0.01 to 0.27)	0.08	3.2 (-0.4 to 6.9)	2.3	0.47 ‡ (0.16 to 0.79)	0.19	-0.001 (-0.06 to 0.06)	0.04	-0.02 (-0.12 to 0.09)	0.06
Random Effects	<i>ICC (90%CI)</i>	<i>Std Dev. (90% C.I.)</i>	<i>ICC (90%CI)</i>	<i>Std Dev. (90% C.I.)</i>	<i>ICC (90%CI)</i>	<i>Std Dev. (90% C.I.)</i>	<i>ICC (90%CI)</i>	<i>Std Dev. (90% C.I.)</i>	<i>ICC (90%CI)</i>	<i>Std Dev. (90% C.I.)</i>
Athlete	0.96 (0.95 to 0.96)	0.20 (0.16 to 0.25)	0.77 (0.75 to 0.77)	4.95 (3.52 to 6.38)	0.827 (0.825 to 0.828)	0.44 (0.32 to 0.55)	0.928 (0.926 to 0.931)	0.09 (0.07 to 0.11)	0.93 (0.932 to 0.937)	0.15 (0.12 to 0.19)
Residual		0.04 (0.03 to 0.06)		2.73 (2.02 to 3.49)		0.20 (0.15 to 0.25)		0.03 (0.02 to 0.03)		0.04 (0.03 to 0.05)

Notes. 1RM = one repetition maximum back squat, cm = centimetre, RSI = flight time/ contact time, s = seconds. Pre and Controlled were specified as the respective reference groups in the model. ‡ significant at $p < 0.05$

Table 17. Between- and within-group changes in performance for fast- and controlled-tempo groups following an eccentric training program.

	Fast-Tempo					Controlled-Tempo					Between-group effect size (g) differences (90% CL)
	n =	Pre-test (± SD)	Post-test (± SD)	% Δ	g (90% CL)	n =	Pre-test (± SD)	Post-test (± SD)	% Δ	g (90% CL)	
Squat (kg)	8	1.69 (± 0.13)	1.74 (± 0.14)	3.0	0.36 (0.14 to 0.58) *	11	1.61 (± 0.23)	1.65 (± 0.24)	2.8	0.18 (0.04 to 0.32) *	0.16 (-0.62 to 0.93)
CMJ (cm)	9	40.4 (± 3.6)	42.1 (± 5.4)	4.1	0.30 (-0.12 to 0.72) *	11	38.1 (± 5.1)	40.6 (± 5.2)	6.7	0.45 (0.09 to 0.81) *	-0.22 (-0.97 to 0.53)
RSI (ft/ct)	9	2.96 (± 0.4)	3.06 (± 0.5)	3.4	0.18 (-0.14 to 0.50)	11	2.45 (± 0.6)	2.61 (± 0.5)	6.3	0.26 (0.02 to 0.51) *	-0.18 (-0.93 to 0.57)
10 m (sec)	8	1.74 (± 0.1)	1.72 (± 0.1)	0.9	-0.21 (-0.43 to 0.02) *	12	1.74 (± 0.1)	1.74 (± 0.1)	0.0	0.01 (-0.19 to 0.18)	-0.38 (-1.15 to 0.38)
20 m (sec)	8	3.00 (± 0.1)	2.97 (± 0.1)	1.1	-0.29 (-0.53 to -0.06) *	12	3.02 (± 0.2)	3.03 (± 0.2)	0.2	0.03 (-0.14 to 0.21)	-0.68 (-1.45 to 0.10) **

Notes. Mean and standard deviation values are presented for pre- and post-test values with 90% confidence intervals provided for effect size differences. Samples size (n =), percent change (Δ; initial value – final value/ initial value), and Hedges' g (± 90% confidence interval) for each test is reported for both within group and between group changes. 1RM/ kg = 1 repetition maximum/ body mass in kilograms, CMJ = countermovement jump height in centimetres, RSI = reactive strength index (flight time/ contact time), 10 m and 20 m sprint times in seconds. Threshold values for Hedges' g statistics were < 0.20 (trivial), > 0.20 (*, small), > 0.60 (**, moderate), > 1.2 (***, large) and > 2.0 (****, very large).

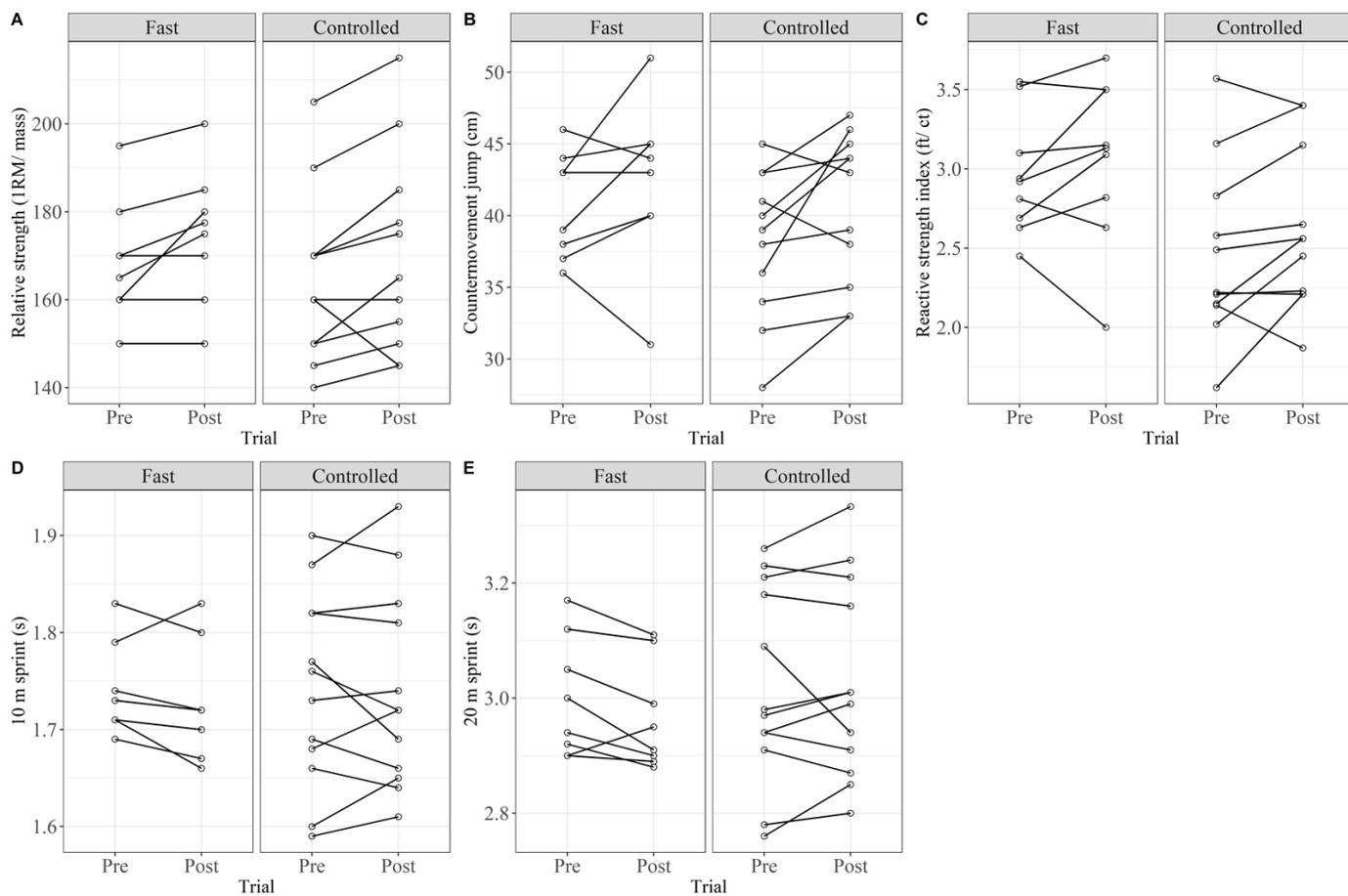


Figure 13. Inter-individual responses to different eccentric-based training programs (fast and controlled tempo) across (A) relative strength, (B) countermovement jump, (C) reactive strength index, (D) 10 m sprint time, and (E) 20 m sprint time. 1RM = 1 repetition maximum strength in the back squat, mass = body mass, cm = centimetre, ft/ ct = flight time divided by contact time, s = seconds

6.4 Discussion

Our study attempted to assess the effects of a 6-week fast ECC training program on physical performance in rugby union athletes. This is a novel implementation of fast ECC using a traditional iso-inertial exercise that directly compares the effects of a more common controlled-tempo approach in trained athletes. The main findings of this study show that individual characteristics in response to ECC may affect the outcomes of the training program regardless of the eccentric tempo. Further, results from fast ECC may be hard to distinguish from those

resulting from a slow ECC. Contrary to our hypothesis, results did not appear to vary on the basis of the involvement of the stretch-shortening cycle. In general, the between-group effect size differences were unclear with the exception of the 20 m sprint time, that favoured fast ECC training.

These findings indicate that fast ECC may improve late-phase acceleration ability to a slightly greater extent than controlled-tempo ECC. Muscle-tendon unit stiffness has been shown to increase following extremely heavy controlled-tempo ECC, but not with submaximal loads (Malliaras et al., 2013). Additionally, improved sprinting ability has been associated with greater stiffness regulation in the lower limb; however supramaximal eccentric training may not transfer to sprinting ability (Cook et al., 2013). The training loads chosen in the FAST group of our study may have created the kinetic and kinematic potential to expose the athletes to greater peak forces than those experienced in the slow group, potentially contributing towards a shift in lower limb stiffness. Coupled with existing evidence for the addition of sarcomeres in series following similar methodology (Bogdanis et al., 2018; Sharifnezhad et al., 2014) fast ECC may provide a sufficient stimulus for improvements in sprint ability in trained athletes. Stiffness regulation has been shown to be task dependent (Douglas et al., 2020), and the improvements in sprinting performance noted in our study may be constrained by the lack of sprint-specific training. Conversely, Douglas et al. (2018) found that fast accentuated eccentric loading may have compromised sprint performance in trained rugby athletes. Although their crossover design differed from that in our study, comparable between- and within group differences were observed.

Both groups improved to a similar extent in the 1RM back squat despite differences in the intensity (%1RM) of the training program. The size principle suggests that motor units are recruited sequentially based on size (Henneman et al., 1965) and that larger, type II motors

units are recruited under high force demands like weightlifting (Suchomel et al., 2018). Our findings challenge the commonly recommended concentric-based training loads of greater than 80 to 85% 1RM for the development of maximal strength in trained individuals and athletes (American College of Sports Medicine, 2009). Contraction velocity may affect motor unit recruitment, potentially lowering the threshold for the activation of type II muscle fibres. Additionally, fast eccentric training has been shown to concurrently increase fascicle length and maximal strength with loads no greater than 70% 1RM. These neuromuscular factors, as a result of exposure to fast ECC, may partially explain the similarities observed between the two groups in our study albeit by differing mechanisms. Despite the relatively light loads used in the fast ECC group, participants were able to maintain their maximal strength with trivial to moderate improvements. Both groups were exposed to similar volume loads, suggesting that ECC methods may alter adaptation to a similar degree regardless of the training intensity prescribed.

The athletes that participated in this study were adult males currently competing at a provincial-level or above in rugby union with a resistance training history of at least 2 years. These factors along with randomisation in the study design are intended to designate this as a relatively homogenous group for the purposes of scientific control. Our intention was to investigate the effects of individual differences by including individuals as random effects in our statistical model. After accounting for the trial, group, and interaction effects, individual characteristics still accounted for 73 to 96% of variance across the physical performance measures used in our study. Recently, a body of research has suggested that for similar levels of power output an individualised balance of force and velocity exists, and that training on the basis of this profile may optimise and improve ballistic performance (Jiménez-Reyes et al., 2019; Samozino et al., 2012). Haugen et al. (2019) found that participation in sport has been associated with sport

specific force-velocity profiles with sprint mechanical variables being much larger in sports that involve sprinting; however, even within a single sport, individual force-velocity characteristics still varied widely. The competition, training, and positional demands of rugby union have likely resulted in the longitudinal exposure to differing levels of high-velocity and/or high-force eccentric contractions notwithstanding those included in the current investigation. These factors may partially explain the individual differences observed in our study. Unfortunately, due to the participant dropout in our study the effects of individual ECC force-velocity capacities on the response to ECC training remains unclear.

In a study by Brughelli et al. (2008), a 10-item scale was proposed to measure the quality of strength and conditioning research interventions. In relation to that scale, this investigation scored highly for several reasons with regard to research design, methodology, and the applied nature of the intervention. In particular, the opportunity to use a control group, test for similarity at baseline, and then randomise trained professional athletes were strengths of this study relative to other ECC interventions with team sport athletes (McNeill et al., 2019). Arguably, the practical usefulness of our eccentric force-velocity profile is limited to teams with access to force plates and LPT technologies.

Limitations

The prescribed fast ECC training program was dependent on the maximal intent of the athlete to rapidly descend to approximately 90° of knee flexion. Although each training session was specifically monitored by at least one certified strength and conditioning professional, the actual eccentric training velocity across the 6-week program was not directly measured. Due to constraints within the team, a 4-day per week resistance training program was compulsory, and thus changes directly resulting from the ECC component may have been affected by the

total amount of resistance training despite being matched for exercise, sets, reps, intensity and frequency. As discussed previously, the time course for performance adaptation in response to ECC training in trained athletes is not well understood. A one-week taper was included in our study design to accommodate recovery and limit the effects of cumulative fatigue. Unfortunately, due to the constraints of the rugby union schedule a longer, or individualized taper period was not possible during the current investigation; thus, it is possible that persistent neuromuscular fatigue may have affected the results in the current study.

6.5 Conclusions

Based on these findings, the implementation of fast and slow ECC using traditional iso-inertial exercise appears to be justified as a method for improving strength and explosive ability owing to the trivial to small improvements seen within the groups. The strength and conditioning practitioner may wish to apply either method based on their periodisation scheme (i.e., block periodisation) and targeted outcome (i.e., acceleration) knowing that strength levels may be maintained or improved. Despite the small magnitude of change observed in the current investigation, this training program involved one specific ECC session per week. These results seem to suggest that the addition of one ECC exercise into a resistance training program may contribute to improvements in physical performance in trained athletes. Future investigations should examine the dose-response relationship with fast ECC using traditional exercise and whether additional weekly ECC training is warranted for further improvement. Although, we were unable to conclude how to optimise ECC at the individual level, an individualised approach to programming ECC appears to be warranted in the current population.

CHAPTER 7:
General Discussion

7.1 Summary

The purpose of this thesis was to investigate eccentric-based training in athlete populations with the intention of improving physical performance. Specifically, these investigations focused on rugby union athletes and measures of strength, speed, and explosive ability commonly employed to monitor changes in performance. The literature review and survey were conducted with a broader lens including competitive team sports with practitioners defining their own methodology for the assessment, prescription, and implementation of eccentric based training. The subsequent studies were a mix of cross-sectional and longitudinal investigations designed to collect information on the eccentric force-velocity-load relationship to be used as a prescriptive framework for a training study. The longitudinal training study then compared the effects two ECC programs on physical performance while controlling for individual responses.

7.1.1 Section 1: Practical and Applied Research Foundations for Eccentric-based Training

The goals of the systematic literature review and survey were to identify and evaluate the existing theoretical support and practical application of ECC interventions and their effects on physical performance measures in trained athletes. In conducting both a literature review and survey of practitioners, we sought to capture as much information as possible regarding the state of ECC knowledge. We acknowledge that while a link exists between research and practice, we wanted to assess the alignment between the theory and application. The current evidence is in support of ECC to improve performance measures of strength, speed, power, and change of direction. These findings appear to be reflected in the uptake of eccentric research by practitioners working with athletes in the field. Inconsistencies exist, however, within the literature and real-world application with regard to prescription, methodology, and individualisation that need to be considered.

The relationship between a training stimulus and the subsequent adaptation is important for the prescription and periodisation of physical qualities. Guidelines have been established for the use of percentages of a concentric-based maximal repetition in traditional dynamic exercise, and the response to these modalities are generally well-understood (American College of Sports Medicine, 2009). Eccentric-based training presents unique challenges for training prescription as the measurement of eccentric-specific qualities may be difficult, especially in practical environments (Meylan et al., 2008). There are numerous protocols that have been proposed to assess eccentric qualities such as strength (Hollander et al., 2007), change of direction (de Hoyo et al., 2016; Nimphius et al., 2016), and explosive ability (Bogdanis et al., 2018; Cormie et al., 2010; Laffaye & Wagner, 2013). Eccentric testing may aid practitioners in the prescription of ECC given the evidence supporting the contribution of eccentric phase characteristics to dynamic performance (Cormie et al., 2010; Laffaye & Wagner, 2013). Several training interventions included in the literature review (Brughelli et al., 2010; Ishøi et al., 2018; Krommes et al., 2017; Mjøl̄snes et al., 2004) did not specify their prescription methodology making it difficult to reproduce their results. The quantification and prescription of ECC intensity in team sport athletes was reported using velocity, concentric-based loads, or “maximal effort” (Askling et al., 2003; Brughelli et al., 2010; Cook et al., 2013; Iga et al., 2012; Ishøi et al., 2018; Mendiguchia et al., 2015; Mjøl̄snes et al., 2004; Rey et al., 2017), but provided no further guidance for exercise execution.

The lack of a prescriptive framework in ECC literature is problematic as the actual kinetic and kinematic outputs experienced throughout the muscle tissue of the individual are unclear. As an example, Tous-Fajardo et al. (2006) demonstrated that the training status of the participant likely dictates the magnitude of eccentric peak force experienced with inertial flywheel

equipment. Thus, in order to determine the subsequent adaptation from ECC it may be necessary to quantify the neuromuscular and mechanical outputs from different ECC methods. A greater understanding of how eccentric characteristics contribute to sports performance may help define testing and monitoring protocols that could aid in the prescription of ECC interventions

The effect of eccentric velocity during training has been investigated as a method for improving strength, and explosive ability (Bogdanis et al., 2018; Oliveira et al., 2016b; Stasinaki et al., 2019). A review by Guilhem et al. (2010) stated that isokinetic angular velocity in the literature ranges from $30^{\circ}\cdot\text{s}^{-1}$ to $210^{\circ}\cdot\text{s}^{-1}$. In our literature review, Askling et al. (2003) were the only authors to report the joint angular velocity ($60^{\circ}\cdot\text{s}^{-1}$) used in the training intervention, which resulted in a moderate effect (0.73) in trained athletes on measures of speed. Recently, Zachariah et al. (2019) reported that fast eccentric squat training (eccentric duration 0.7 to 1.1 seconds) resulted in significant changes in strength and explosive ability using 50% to 70% 1RM. This tempo would likely result in a contraction velocity much higher than the 3 to 6 second durations reported in our survey. Sharifnezhad et al. (2014) found that fast lengthening velocities led to an increase in fascicle length, which would likely contribute to increased force production and contraction velocity (Vogt & Hoppeler, 2014). Conversely, Douglas et al. (2018) found that fast ECC impaired sprint performance, although the time course of recovery and adaptation at the individual level may have influenced the observed effects.

Maximal strength was a commonly targeted physical quality by practitioners using ECC in our survey. Tempo and percentage of maximal strength were the most common methods of prescribing ECC in the survey which aligns with existing methods of ECC in research (Suchomel et al., 2019b). Participants in the survey reported using loads ranging from

submaximal to 140% of concentric 1RM. Submaximal loading may have a relatively low potential for training stimulus, while accentuated and supramaximal eccentric loading may be limited to athletes that are comparatively more advanced (Suchomel et al., 2019a). Research supporting the use of supramaximal loads suggests that individuals with greater baseline strength and training experience may benefit to a greater extent than those with lower baseline strength levels (Buskard et al., 2018). The athletes trained by the surveyed respondents varied widely in terms of training experience with 21% having 1 year or less of supervised resistance training and 32% having more than 5 years training experience. The effects of individual characteristics at baseline on the efficacy of ECC on physical performance may warrant future investigation.

Sprint performance and explosive ability may be positively affected by ECC methods, although these results may be specific to the loading parameters and individuals in the study. Trivial to moderate improvements were observed in our literature review in measures of sprint ability, although acceleration and top speed may be determined by different contributions of stiffness, mechanical efficiency, and rate of force development (Brughelli & Cronin, 2008; Farley & González, 1996; Komi, 2000; López Mangini & Fábrega, 2016; Voigt et al., 1995). Identifying the factors associated with the prescription of ECC may be necessary to enhance specific aspects of sprint performance. Interventions involving sprinting performance that were identified in the literature review revealed trivial to moderate improvements in short sprints (<10 m) (Krommes et al., 2017; Mendiguchia et al., 2015), but trivial to moderate *unfavourable* decrements in sprinting performance in 30 to 50 m distances (Cook et al., 2013; Krommes et al., 2017; Mendiguchia et al., 2015). The eccentric portions of these training programs were performed at velocities which may be substantially slower than the maximal joint angular velocities reported elsewhere (Aagaard, 2018). The authors note that what constitutes fast and

slow eccentric contractions may be specific to the context of the training program. Joint angular velocity during a fast eccentric squat will likely be different than velocities observed during a sprinting program. Additionally, bilateral and unilateral ECC training have been reported to improve power and change of direction ability without improving 10 m sprint times (Núñez et al., 2018). A recent review favoured the use of a flywheel device over traditional resistance training for improving running speed (Maroto-Izquierdo, García-López, Fernandez-Gonzalo, et al., 2017); however, as mentioned previously, controversy exists as to whether certain inertial devices truly overload the eccentric phase, and therefore constitute ECC (Gonzalo-Skok et al., 2017; Tous-Fajardo et al., 2006).

In terms of explosive ability, investigations using ECC have also reported no change in squat jump, counter-movement jump, or rate of force development (Wirth et al., 2015). Additionally, eccentric duration and execution of the correct technique may actually decrease measures of velocity in a jump squat (Aboodarda et al., 2015; Mike et al., 2017). These discrepancies may be a result of individual differences (e.g., technique, anthropometric qualities, contractile, and elastic capabilities), which have been shown to influence drop jump and CMJ performance (Bobbert et al., 1987). Eccentric-based training has also been shown to suppress performance qualities for extended periods of time, which could potentially interfere with results dependent on the timing of the post-testing regime (Brandenburg & Docherty, 2002; Leong et al., 2014). Although ECC appears to improve the expression of sprint ability and explosive ability following longitudinal training, it is unclear as to what extent the effects observed in the literature review are affected by individual characteristics.

7.1.2 Section 2: Development and Application of an Eccentric Force-Velocity Profile

Throughout the process of conducting the literature review and survey, several key factors were identified with regards to ECC and physical performance in team sport athletes. Namely, that

the prescription of eccentric contraction velocity may play a key role in adaptation, and that designing ECC to account for individual factors may optimise the targeted outcomes. Therefore, in Section 2 a novel eccentric-based assessment was developed in order to better understand individual eccentric characteristics. This protocol was based on the concept of the force-velocity relationship, and would allow practitioners to prescribe ECC relative to the capacity of the athlete. A reliability study was conducted before implementing the test with a wider group of rugby union athletes. A longitudinal training study was then conducted to investigate the effects of two ECC programs on physical performance.

The aim of Chapter 4 was to determine the reliability of force and velocity values during the eccentric phase of a novel back squat test in trained rugby union athletes via a pilot study. Absolute barbell loads of 20, 40, 60, 80, 100, and 120 kg were lifted with the intent to maximise eccentric velocity. Ground reaction force and velocity measures were captured via two force plates and a linear position transducer. Interclass correlation coefficients ($ICC \geq 0.82$) and coefficients of variation ($CV < 7.3\%$) were highest in eccentric peak force across all loads tested. In general, peak values were more reliable than mean values suggesting they may be more sensitive to detecting real change following a training intervention. Eccentric rate of force development revealed the lowest absolute and relative reliability values, and thus may not be appropriate for monitoring eccentric specific adaptation in this protocol. As part of the assessment, three attempts were allowed at each load; however, analysis of a systematic trial effect showed that the initial attempt may be significantly lower than subsequent efforts. Therefore, further implementation of this testing procedure should account for the differences in attempts. This novel assessment allows for the investigation of submaximal eccentric loads, and may reduce the need to use supramaximal or extremely heavy procedures, thus minimising injury risk. One novel aspect of this investigation is the use of dynamic contractions, both eccentric and concentric, which may have a stronger relationship to the specific demands of

team sport athletes than one mode of muscle action in isolation. In general, the main findings of Chapter 4 were that eccentric force and velocity characteristics at submaximal loads meet commonly accepted standards of reliability in physical performance.

The intention of Chapter 5 was to build on the reliability of the pilot study to further examine the force-velocity-load relationship during the eccentric phase of a multi-joint, dynamic exercise, the barbell back squat. The same protocol described in Chapter 4 was employed with a larger squad of rugby union athletes prior to the off-season phase of the annual calendar. Ground reaction forces and velocity were captured in the same manner with the best attempt recorded for analysis. The findings of this study suggest that the overall relationship between eccentric force and velocity may differ depending on the specific variables being investigated, and the loading conditions under which they are being examined. The linear relationship commonly seen in concentric research, with decreasing force and increasing velocity values, was also observed in our analysis of mean eccentric force and velocity. Conversely, the peak eccentric force and velocity relationship was more parabolic in nature, resembling the relationship seen in isokinetic research of isolated muscle. Although, the design of this study was not mechanistic in nature, the peak force values observed at relatively light loads may reflect the maximal capacity of the muscle tissue throughout the lower body to absorb eccentric force. Practitioners may implement the findings of this research by improving their ability to prescribe ECC methods for a given outcome. Importantly, exposing athletes to greater magnitudes of peak force may be accomplished at relatively light loads for the individual athlete, with greater loads resulting in diminishing peak force values.

Chapter 6 utilised the assessment protocol from Chapters 4 and 5 in order to investigate how changes in eccentric force and velocity may affect physical performance following an eccentric training intervention. Based on findings from the literature review and survey, the

implementation of fast- and controlled-tempo ECC was investigated using parallel groups of randomly assigned, semi-professional rugby union athletes. The use of a traditional iso-inertial exercise was intended to make these findings applicable without the use of specialised equipment. Results following the 6-week intervention revealed that between-group differences are largely unclear with the exception of 20 m sprint times (Hedges' g effect size = 0.68) revealing a moderate difference favouring the fast eccentric group. This is in agreement with existing literature on the effects of slow- or controlled-tempo eccentric training on maximal sprinting velocity (Cook et al., 2013; Krommes et al., 2017). Importantly, this investigation was conducted within a professional training environment and, although the controlled-tempo group does not represent a true experimental control, these findings may be more generalisable to this population of athletes. Additionally, although between-group differences were largely trivial, differences were observed for within-group comparisons. Thus, fast- and controlled-tempo ECC appears to be justified as a method for improving strength and explosive ability owing to the trivial to small improvements seen within the groups.

Depending on the specific training phase and the need to adjust load according to the desired outcomes, fast- or controlled-tempo ECC may fit the need of the strength and conditioning practitioner. Unfortunately, the eccentric force and velocity protocol that was developed in earlier chapters was unable to be used for statistical analysis due to participant dropout that occurred for several reasons. Changes in eccentric force and velocity characteristics following the training intervention would have been analysed with changes in performance for a potential causal relationship. Scheduling conflicts and contact injuries occurring during tactical rugby sessions accounted for a majority of participant attrition. This data may have provided insight into the individual characteristics of the participants, with the goal of creating an objective basis for the individualisation of ECC methods. Applied research in a professional sporting

environment is subject to these risks, and although these factors were considered during the recruitment phase of our study, drop out occurred primarily in the fast-tempo group.

7.2 Practical Implications

The overall goal of this thesis was to provide strength and conditioning practitioners with a systematic framework for the individual prescription of ECC for improving physical performance. Based on the findings of this thesis there are several practical implications which may assist with the prescription and implementation of ECC:

- Based on our survey findings, training experience may be a sound basis for the individualisation of ECC. It is recommended that slow eccentric tempo training be used with novice athletes while supramaximal methods can be used with more experienced individuals.
- We recommend that ECC be used to improve maximal strength during the pre-season or off-season phases of competition.
- The back squat was the most commonly used exercise in the implementation of ECC, and the vast majority of practitioners utilised equipment commonly found in most commercial gyms (i.e., barbells, dumbbells, weight plates). This finding highlights the need for methods that use non-specialised equipment
- Based on the findings within this thesis, we recommend measuring peak eccentric values as they are the more reliable and thus likely to be more sensitive to real changes in physical performance in our eccentric assessment.
- Eccentric rate of force development has been found to be a contributor to ballistic performance in other research, although in our test it was the least reliable eccentric variable and may not be appropriate for routine monitoring of physical performance.

- In addition to peak values, we recommend testing mean eccentric force and velocity, respectively, as they tend to show linear decreases and increases, respectively, with added load. This relationship may aid in the prescription of ECC with loads not directly used in our study.
- Maximal peak eccentric force may occur at relatively light loads (< 80 kg ,or 40 to 60% 1RM) depending on the individual, allowing practitioners to prescribe relatively light eccentric loads when targeting high force adaptations.
- Physical performance may change to a similar extent following longitudinal exposure to different ECC methods despite differences in prescribed load.
- Within group differences may justify the inclusion of submaximal fast- and controlled-tempo ECC in a training program, despite the small magnitudes of change that were observed, according to the needs of the strength and conditioning practitioner.
- Individual characteristics may account for large proportions of the variance noted in physical performance following 6-weeks of ECC. Thus, we recommend an individualised, rather than one size fits all, approach to both the selection of ECC methodology and the loading parameters chosen for the training program.

7.3 Limitations

Eccentric muscle contractions and their respective characteristics are commonly implemented in rehabilitation, injury prevention, and performance across a range of physical qualities. The identification and calculation of the effect for eccentric methodology is challenging due to the widespread use of eccentric interventions that are not adequately quantified. This thesis was designed from the outset to specifically investigate eccentric performance training in male rugby union athletes which necessitated constraints on the scope of the literature review that we conducted. After much deliberation, we also decided that the nature of team sport and long-term participation in the sport-specific training would likely involve eccentric actions from

sprinting, jumping, and change of direction. This exposure may affect the response to ECC interventions compared to the training history of individual sport athletes. As a result, studies involving individual sports, untrained participants, and female athletes were excluded, possibly biasing our results. Further, the findings of this literature review are based on a limited number of available training studies. Although this small number of studies informs the need to conduct further investigations, the sample size also limits our ability to infer the effects of ECC interventions relative to training status or strength beyond those included in the studies themselves.

The training of athletic populations around the globe is complex process crossing cultural, financial, individual, and organizational boundaries and thus a single electronic survey may not adequately capture the nuances of a high-performance strength and conditioning program. Further, the survey was also only employed in the English language and may have been unavailable to practitioners who speak different languages. Therefore, sampling bias may have affected our ability infer the results of our survey to the practice of ECC in the larger community of practitioners.

Maximal strength was not tested during the pilot eccentric force-and velocity protocol, and therefore strength differences between individuals may have influenced the results. The manner in which testing proceeded, in an ascending order, was chosen by the authors to allow for data collection in a practical environment. Order effect was not controlled for through randomisation of the testing order. Additionally, sampling frequency may have played a role in the results from Chapters 4, 5, and 6. Although force plates sampling at 100 Hz have been shown to meet minimum standards of reliability, Hori et al. (2009) found that reductions in precision were noted below a 200 Hz threshold.

Generalisations of our findings in the eccentric force and velocity assessment to existing eccentric-only or isokinetic research may be limited. The decision to include both the eccentric and concentric phase in the current protocol was intended to capture the ability of the muscle-tendon complex and reflect the demands that may occur in team sports. This dynamic action with a minimal amortization phase may have more practical application in the training of team sport and specifically rugby athletes. The participants chosen for this study were male, rugby union athletes, and therefore caution should be exercised when generalizing these findings to other sport- or sex-specific populations.

Our applied study of ECC was completed within the actual training environment of professional rugby union athletes, and as such the risk of participant dropout due to factors beyond the control of the researchers was a limitation of this study. The ability to collect data within this context was a strength of the thesis and added to the ecological validity of our findings. However, this degree of practical application was a trade-off with the ability to more thoroughly standardise the testing environment and can be considered a limitation of the applied studies in this thesis. Individual differences have been shown to play a role in the response to ECC and were included in our statistical model, although due to participant dropout analysis of the causal nature of these factors was not possible. The fast-tempo ECC training program was dependent on the maximal intent of the athlete to rapidly descend to approximately 90° of knee flexion. At least one certified strength and conditioning professional monitored each session for adherence to the program, although the actual eccentric training velocity across the 6-week program was not available for analysis. Due to constraints within the team, a 4-day per week resistance training program was compulsory, and thus changes directly resulting from the ECC component may have been affected by the total amount of

resistance training despite being matched for exercise, sets, reps, intensity, and frequency. As discussed previously, the time course for performance adaptation in response to ECC training in trained athletes is not well understood. A one-week taper was included in our study design to accommodate recovery and limit the effects of cumulative fatigue. Unfortunately, due to the constraints of the rugby union schedule a longer, or individualized taper period was not possible during the current investigation; thus, it is possible that persistent neuromuscular fatigue may have affected the results in the current study.

7.4 Conclusion

This thesis, and the scientific evidence within, supports the use of eccentric-based training for improving physical performance and recommends the individualisation of this approach for specific outcomes. Eccentric muscle action, due to the unique characteristics occurring at the molecular level, has broad reaching implications in the training of team sport athletes who are required to absorb and utilise eccentric force. As a general strategy, designing eccentric resistance training programs to improve physical performance is well supported in research performed with team sport athletes. This existing body of research has potentially influenced practice, as a majority of strength and conditioning practitioners may implement these strategies with their athletes. Rather than one specific method of resistance training, eccentric-based training may represent a wide range of different parameters that may be utilised to improve different aspects physical performance.

This thesis expands the eccentric-based training literature through the development and application of an eccentric specific assessment. This test was designed to be submaximal in nature while informing practitioners on the capacity of the individual in regards to the eccentric force-velocity relationship. Overall, the assessment was found to be reliable with novel implications relevant to the prescription of eccentric training. A potential learning effect was

observed following the initial repetition of our protocol despite multiple familiarisation sessions. The practical application of this observation is that multiple repetitions in this protocol are recommended, and that practitioners may consider using the mean of these trials. Thus, two different eccentric resistance training programs were developed and implemented with trained athletes to determine how longitudinal exposure to eccentric training would affect individual eccentric-specific characteristics, and measures of physical performance. The main findings of our training intervention are in agreement with existing literature that eccentric-based training appears to be capable of improving physical performance in trained individuals. Differences between eccentric contraction velocities were unclear as physical performance changed to a similar extent in both groups; however, 20 m sprint times favoured the fast-eccentric group. These findings contradict Douglas et al. (2018) who found that fast accentuated eccentric loading may impair sprint performance, but are in agreement with other investigations (Cook et al., 2013; Krommes et al., 2017) that found slow eccentric training may not benefit top speed sprinting ability. Due to challenges associated with research in applied settings, the individualisation of eccentric training on the basis of our novel assessment remains unclear; however, the extent of individual eccentric characteristics supports the notion that an individualised approach is warranted to optimise physical performance.

Directions for future research are included within the individual chapters relevant to the specific research question. In general, future studies should consider the findings of our eccentric force-velocity assessment and the association between these characteristics and measures of performance. Existing research consistently supports the contribution of the eccentric phase to dynamic and ballistic performance; however, it is unclear to what extent eccentric characteristics underpin physical performance relative to other existing performance variables. As noted throughout the thesis, individual characteristics likely play a role in the

response to eccentric exercise. The extent to which these characteristics are modifiable remains to be seen, and will likely be the subject of future investigations.

References

- Aagaard, P. (2018). Spinal and supraspinal control of motor function during maximal eccentric muscle contraction: Effects of resistance training. *Journal of Sport and Health Science*, 7(3), 282–293. <https://doi.org/10.1016/j.jshs.2018.06.003>
- Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, S. P., Halkjær-Kristensen, J., & Dyhre-Poulsen, P. (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *Journal of Applied Physiology*, 89(6), 2249–2257. <https://doi.org/10.1152/jappl.2000.89.6.2249>
- Abbott, B. C., Bigland, B., & Ritchie, J. M. (1952). The physiological cost of negative work. *The Journal of Physiology*, 117(3), 380–390. <https://doi.org/10.1113/jphysiol.1952.sp004755>
- Aboodarda, S. J., Page, P. A., & Behm, D. G. (2015). Eccentric and concentric jumping performance during augmented jumps with elastic resistance: A meta-analysis. *International Journal of Sports Physical Therapy*, 10(6), 839.
- Alcaraz, P. E., Carlos-Vivas, J., Oponjuru, B. O., & Martínez-Rodríguez, A. (2018). The effectiveness of resisted sled training (RST) for sprint performance: A systematic review and meta-analysis. *Sports Medicine*. <https://doi.org/10.1007/s40279-018-0947-8>
- Alcazar, J., Csapo, R., Ara, I., & Alegre, L. M. (2019). On the shape of the force-velocity relationship in skeletal muscles: The linear, the hyperbolic, and the double-hyperbolic. *Frontiers in Physiology*, 10, 769. <https://doi.org/10.3389/fphys.2019.00769>
- American College of Sports Medicine. (2009). American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise*, 41(3), 687–708. <https://doi.org/10.1249/MSS.0b013e3181915670>
- Askling, C., Karlsson, J., & Thorstensson, A. (2003). Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scandinavian Journal of Medicine and Science in Sports*, 13(4), 244–250. <https://doi.org/10.1034/j.1600-0838.2003.00312.x>
- Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (Reliability) in variables relevant to sports medicine: *Sports Medicine*, 26(4), 217–238. <https://doi.org/10.2165/00007256-199826040-00002>
- Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, 37(3), 379–384. <https://doi.org/10.3758/BF03192707>
- Batterham, A. M., & Hopkins, W. G. (2006). Making Meaningful Inferences About Magnitudes. *International Journal of Sports Physiology and Performance*, 1(1), 50–57. <https://doi.org/10.1123/ijsp.1.1.50>
- Beaven, C. M., Willis, S. J., Cook, C. J., & Holmberg, H.-C. (2014). Physiological Comparison of Concentric and Eccentric Arm Cycling in Males and Females. *PLoS ONE*, 9(11), e112079. <https://doi.org/10.1371/journal.pone.0112079>
- Bobbert, M. F. (2012). Why is the force-velocity relationship in leg press tasks quasi-linear rather than hyperbolic? *Journal of Applied Physiology*, 112(12), 1975–1983. <https://doi.org/10.1152/jappphysiol.00787.2011>
- Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sports and Exercise*, 19(4), 332–338. <https://doi.org/10.1249/00005768-198708000-00003>
- Bogdanis, G. C., Tsoukos, A., Brown, L. E., Selima, E., Veligekas, P., Spengos, K., & Terzis, G. (2018). Muscle fiber and performance changes after fast eccentric complex training.

- Medicine & Science in Sports & Exercise*, 50(4), 729–738.
<https://doi.org/10.1249/MSS.0000000000001507>
- Brandenburg, J. P., & Docherty, D. (2002). The effects of accentuated eccentric loading on strength, muscle hypertrophy, and neural adaptations in trained individuals. *Journal of Strength and Conditioning Research*, 16(1), 25–32. <https://doi.org/10.1519/00124278-200202000-00005>
- Bridgeman, L. A., McGuigan, M. R., Gill, N. D., & Dulson, D. K. (2016). Test-retest reliability of a novel isokinetic squat device with strength-trained athletes. *Journal of Strength and Conditioning Research*, 30(11), 3261–3265. <https://doi.org/10.1519/JSC.0000000000001410>
- Bridgeman, L. A., McGuigan, M. R., Gill, N. D., & Dulson, D. K. (2018). Relationships between concentric and eccentric strength and countermovement jump performance in resistance trained men: *Journal of Strength and Conditioning Research*, 32(1), 255–260. <https://doi.org/10.1519/JSC.0000000000001539>
- Brockett, C. L., Morgan, D. L., & Proske, U. (2001). Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine and Science in Sports and Exercise*, 33(5), 783–790. <https://doi.org/10.1097/00005768-200105000-00017>
- Brockett, C., Warren, N., Gregory, J. E., Morgan, D. L., & Proske, U. (1997). A comparison of the effects of concentric versus eccentric exercise on force and position sense at the human elbow joint. *Brain Research*, 771(2), 251–258.
- Brughelli, M., & Cronin, J. (2008). Influence of running velocity on vertical, leg and joint stiffness: Modelling and recommendations for future research. *Sports Medicine*, 38(8), 647–657. <https://doi.org/10.2165/00007256-200838080-00003>
- Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). Understanding change of direction ability in sport. *Sports Medicine*, 38(12), 1045–1063. <https://doi.org/10.2165/00007256-200838120-00007>
- Brughelli, M., Mendiguchia, J., Nosaka, K., Idoate, F., Arcos, A. L., & Cronin, J. (2010). Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Physical Therapy in Sport*, 11(2), 50–55. <https://doi.org/10.1016/j.ptsp.2009.12.002>
- Buskard, A. N. L., Gregg, H. R., & Ahn, S. (2018). Supramaximal eccentrics versus traditional loading in improving lower-body 1RM: A meta-analysis. *Research Quarterly for Exercise and Sport*, 89(3), 340–346. <https://doi.org/10.1080/02701367.2018.1472365>
- Campbell, P. G., Peake, J. M., & Minett, G. M. (2018). The specificity of rugby union training sessions in preparation for match demands. *International Journal of Sports Physiology and Performance*, 13(4), 496–503. <https://doi.org/10.1123/ijsp.2017-0082>
- Chaabene, H., Prieske, O., Negra, Y., & Granacher, U. (2018). Change of direction speed: Toward a strength training approach with accentuated eccentric muscle actions. *Sports Medicine*, 48(8), 1773–1779. <https://doi.org/10.1007/s40279-018-0907-3>
- Chen, T. C., Yang, T., Huang, M., Wang, H., Tseng, K., Chen, H., & Nosaka, K. (2019). Damage and the repeated bout effect of arm, leg, and trunk muscles induced by eccentric resistance exercises. *Scandinavian Journal of Medicine & Science in Sports*, 29(5), 725–735. <https://doi.org/10.1111/sms.13388>
- Cook, C. J., Beaven, C. M., & Kilduff, L. P. (2013). Three weeks of eccentric training combined with overspeed exercises enhances power and running speed performance gains in trained athletes. *Journal of Strength and Conditioning Research*, 27(5), 1280–1286. <https://doi.org/10.1519/JSC.0b013e3182679278>
- Coratella, G., Milanese, C., & Schena, F. (2015). Unilateral eccentric resistance training: A direct comparison between isokinetic and dynamic constant external resistance

- modalities. *European Journal of Sport Science*, 15(8), 720–726. <https://doi.org/10.1080/17461391.2015.1060264>
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and Science in Sports and Exercise*, 42(9), 1731–1744. <https://doi.org/10.1249/MSS.0b013e3181d392e8>
- Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 1 – biological basis of maximal power production. *Sports Medicine*, 41(1), 17–38. <https://doi.org/10.2165/11537690-000000000-00000>
- Cowell, J. F., Cronin, J., & Brughelli, M. (2012). Eccentric muscle actions and how the strength and conditioning specialist might use them for a variety of purposes. *Strength & Conditioning Journal*, 34(3), 33–48. <https://doi.org/10.1519/SSC.0b013e318253f578>
- de Hoyo, M., Pozzo, M., Sañudo, B., Carrasco, L., Gonzalo-Skok, O., Domínguez-Cobo, S., & Morán-Camacho, E. (2015). Effects of a 10-Week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *International Journal of Sports Physiology and Performance*, 10(1), 46–52. <https://doi.org/10.1123/ijssp.2013-0547>
- de Hoyo, M., Sañudo, B., Carrasco, L., Mateo-Cortes, J., Domínguez-Cobo, S., Fernandes, O., Del Ojo, J. J., & Gonzalo-Skok, O. (2016). Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. *Journal of Sports Sciences*, 34(14), 1380–1387. <https://doi.org/10.1080/02640414.2016.1157624>
- Di Giminiani, R., & Petricola, S. (2016). The power output-drop height relationship to determine the optimal dropping intensity and to monitor the training intervention: *Journal of Strength and Conditioning Research*, 30(1), 117–125. <https://doi.org/10.1519/JSC.0000000000001076>
- Dietz, C., & Peterson, B. (2012). *Triphasic training: A systematic approach to elite speed and explosive strength performance*. Bye Dietz Sport Enterprise.
- Ditroilo, M., De Vito, G., & Delahunt, E. (2013). Kinematic and electromyographic analysis of the Nordic hamstring exercise. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, 23(5), 1111–1118. <https://doi.org/10.1016/j.jelekin.2013.05.008>
- Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017a). Eccentric exercise: Physiological characteristics and acute responses. *Sports Medicine*, 47(4), 663–675. <https://doi.org/10.1007/s40279-016-0624-8>
- Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2017b). Chronic adaptations to eccentric training: A systematic review. *Sports Medicine*, 47(5), 917–941. <https://doi.org/10.1007/s40279-016-0628-4>
- Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2018). Effects of accentuated eccentric loading on muscle properties, strength, power, and speed in resistance-trained rugby players. *Journal of Strength and Conditioning Research*, 32(10), 2750–2761. <https://doi.org/10.1519/JSC.0000000000002772>
- Douglas, J., Pearson, S., Ross, A., & McGuigan, M. (2020). Reactive and eccentric strength contribute to stiffness regulation during maximum velocity sprinting in team sport athletes and highly trained sprinters. *Journal of Sports Sciences*, 38(1), 29–37. <https://doi.org/10.1080/02640414.2019.1678363>
- Edman, K. A. (1988). Double-hyperbolic force-velocity relation in frog muscle fibres. *The Journal of Physiology*, 404(1), 301–321. <https://doi.org/10.1113/jphysiol.1988.sp017291>
- English, K. L., Loehr, J. A., Lee, S. M. C., & Smith, S. M. (2014). Early-phase musculoskeletal adaptations to different levels of eccentric resistance after 8 weeks of lower body training.

- European Journal of Applied Physiology*, 114(11), 2263–2280. <https://doi.org/10.1007/s00421-014-2951-5>
- Farley, C. T., & González, O. (1996). Leg stiffness and stride frequency in human running. *Journal of Biomechanics*, 29(2), 181–186. [https://doi.org/10.1016/0021-9290\(95\)00029-1](https://doi.org/10.1016/0021-9290(95)00029-1)
- Farthing, J. P., & Chilibeck, P. D. (2003). The effects of eccentric and concentric training at different velocities on muscle hypertrophy. *European Journal of Applied Physiology*, 89(6), 578–586. <https://doi.org/10.1007/s00421-003-0842-2>
- Fleiss, J. (1999). *Design and Analysis of Clinical Experiments* (Wiley Classics Library, pp. 6–7). John Wiley & Sons.
- Friedmann-Bette, B., Bauer, T., Kinscherf, R., Vorwald, S., Klute, K., Bischoff, D., Müller, H., Weber, M.-A., Metz, J., Kauczor, H.-U., Bärtsch, P., & Billeter, R. (2010). Effects of strength training with eccentric overload on muscle adaptation in male athletes. *European Journal of Applied Physiology*, 108(4), 821–836. <https://doi.org/10.1007/s00421-009-1292-2>
- Frohm, A., Halvorsen, K., & Thorstensson, A. (2005). A new device for controlled eccentric overloading in training and rehabilitation. *European Journal of Applied Physiology*, 94(1–2), 168–174. <https://doi.org/10.1007/s00421-004-1298-8>
- Gonzalo-Skok, O., Tous-Fajardo, J., Valero-Campo, C., Berzosa, C., Bataller, A. V., Arjol-Serrano, J. L., Moras, G., & Mendez-Villanueva, A. (2017). Eccentric-overload training in team-sport functional performance: Constant bilateral vertical versus variable unilateral multidirectional movements. *International Journal of Sports Physiology and Performance*, 12(7), 951–958. <https://doi.org/10.1123/ijsp.2016-0251>
- Goode, A. P., Reiman, M. P., Harris, L., DeLisa, L., Kauffman, A., Beltramo, D., Poole, C., Ledbetter, L., & Taylor, A. B. (2015). Eccentric training for prevention of hamstring injuries may depend on intervention compliance: A systematic review and meta-analysis. *British Journal of Sports Medicine*, 49(6), 349–356. <https://doi.org/10.1136/bjsports-2014-093466>
- Guilhem, G., Cornu, C., & Guével, A. (2010). Neuromuscular and muscle-tendon system adaptations to isotonic and isokinetic eccentric exercise. *Annals of Physical and Rehabilitation Medicine*, 53(5), 319–341. <https://doi.org/10.1016/j.rehab.2010.04.003>
- Guilhem, G., Cornu, C., Maffiuletti, N. A., & Guével, A. (2013). Neuromuscular adaptations to isoload versus isokinetic eccentric resistance training. *Medicine and Science in Sports and Exercise*, 45(2), 326–335. <https://doi.org/10.1249/MSS.0b013e31826e7066>
- Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011). Three methods of calculating force-time variables in the rebound jump squat. *Journal of Strength and Conditioning Research*, 25(3), 867–871. <https://doi.org/10.1519/JSC.0b013e3181c69f0a>
- Haugen, T. A., Breitschädel, F., & Seiler, S. (2019). Sprint mechanical variables in elite athletes: Are force-velocity profiles sport specific or individual? *PLOS ONE*, 14(7), e0215551. <https://doi.org/10.1371/journal.pone.0215551>
- Helland, C., Hole, E., Iversen, E., Olsson, M. C., Seynnes, O., Solberg, P. A., & Paulsen, G. (2017). Training strategies to improve muscle power: Is olympic-style weightlifting relevant? *Medicine & Science in Sports & Exercise*, 49(4), 736–745. <https://doi.org/10.1249/MSS.0000000000001145>
- Henneman, E., Somjen, G., & Carpenter, D. O. (1965). Functional significance of cell size in spinal motoneurons. *Journal of Neurophysiology*, 28(3), 560–580. <https://doi.org/10.1152/jn.1965.28.3.560>
- Higbie, E. J., Cureton, K. J., Warren, G. L., & Prior, B. M. (1996). Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *Journal of Applied Physiology*, 81(5), 2173–2181. <https://doi.org/10.1152/jappl.1996.81.5.2173>

- Hollander, D. B., Kraemer, R. R., Kilpatrick, M. W., Ramadan, Z. G., Reeves, G. V., Francois, M., Hebert, E. P., & Tryniecki, J. L. (2007). Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise: *Journal of Strength and Conditioning Research*, *21*(1), 37–40. <https://doi.org/10.1519/00124278-200702000-00007>
- Hopkins, W. G. (2015). Spreadsheets for the analysis of validity and reliability. *Sportscience*, *19*, 36–42.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science: *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. <https://doi.org/10.1249/MSS.0b013e31818cb278>
- Hopkins, W. G., Schabert, E. J., & Hawley, J. A. (2001). Reliability of power in physical performance tests. *Sports Medicine*, *3*(31), 211–234.
- Hori, N., Newton, R. U., Kawamori, N., McGuigan, M. R., Kraemer, W. J., & Nosaka, K. (2009). Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *Journal of Strength and Conditioning Research*, *23*(3), 874–882. <https://doi.org/10.1519/JSC.0b013e3181a00ca2>
- Hortobágyi, T., Hill, J. P., Houmard, J. A., Fraser, D. D., Lambert, N. J., & Israel, R. G. (1996). Adaptive responses to muscle lengthening and shortening in humans. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *80*(3), 765–772. <https://doi.org/10.1152/jappl.1996.80.3.765>
- Hortobágyi, T., & Katch, F. I. (1990). Eccentric and concentric torque-velocity relationships during arm flexion and extension: Influence of strength level. *European Journal of Applied Physiology and Occupational Physiology*, *60*(5), 395–401. <https://doi.org/10.1007/BF00713506>
- Hortobágyi, T., & Katch, F. I. (1990). Eccentric and concentric torque-velocity relationships during arm flexion and extension: Influence of strength level. *European Journal of Applied Physiology and Occupational Physiology*, *60*(5), 395–401. <https://doi.org/10.1007/BF00713506>
- Iga, J., Fruer, C., Deighan, M., Croix, M. D., & James, D. V. (2012). ‘Nordic’ hamstrings exercise – engagement characteristics and training responses. *International Journal of Sports Medicine*, *33*(12), 1000–1004. <https://doi.org/10.1055/s-0032-1304591>
- Ishøi, L., Hölmich, P., Aagaard, P., Thorborg, K., Bandholm, T., & Serner, A. (2018). Effects of the Nordic hamstring exercise on sprint capacity in male football players: A randomized controlled trial. *Journal of Sports Sciences*, *36*(14), 1663–1672. <https://doi.org/10.1080/02640414.2017.1409609>
- Ishøi, L., Sørensen, C. N., Kaae, N. M., Jørgensen, L. B., Hölmich, P., & Serner, A. (2016). Large eccentric strength increase using the Copenhagen Adduction exercise in football: A randomized controlled trial: Strength increase using Copenhagen Adduction. *Scandinavian Journal of Medicine & Science in Sports*, *26*(11), 1334–1342. <https://doi.org/10.1111/sms.12585>
- Isner-Horobeti, M.-E., Dufour, S. P., Vautravers, P., Geny, B., Coudeyre, E., & Richard, R. (2013). Eccentric exercise training: Modalities, applications and perspectives. *Sports Medicine*, *43*(6), 483–512. <https://doi.org/10.1007/s40279-013-0052-y>
- Jiménez-Reyes, P., Samozino, P., & Morin, J.-B. (2019). Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. *PLOS ONE*, *14*(5), e0216681. <https://doi.org/10.1371/journal.pone.0216681>
- Komi, P. V. (1973). Measurement of the force-velocity relationship in human muscle under concentric and eccentric contractions. In S. Cerquiglini, A. Venerando, & J. Wartenweiler

- (Eds.), *Medicine and Sport Science* (Vol. 8, pp. 224–229). S. Karger AG. <https://doi.org/10.1159/000393754>
- Komi, P. V. (2000). Stretch-shortening cycle: A powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, *33*(10), 1197–1206. [https://doi.org/10.1016/S0021-9290\(00\)00064-6](https://doi.org/10.1016/S0021-9290(00)00064-6)
- Krommes, K., Petersen, J., Nielsen, M. B., Aagaard, P., Hölmich, P., & Thorborg, K. (2017). Sprint and jump performance in elite male soccer players following a 10-week nordic hamstring exercise protocol: A randomised pilot study. *BMC Research Notes*, *10*(1). <https://doi.org/10.1186/s13104-017-2986-x>
- Laffaye, G., & Wagner, P. (2013). Eccentric rate of force development determines jumping performance. *Computer Methods in Biomechanics and Biomedical Engineering*, *16*(sup1), 82–83. <https://doi.org/10.1080/10255842.2013.815839>
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, *4*. <https://doi.org/10.3389/fpsyg.2013.00863>
- Lavender, A. P., & Nosaka, K. (2008). A light load eccentric exercise confers protection against a subsequent bout of more demanding eccentric exercise. *Journal of Science and Medicine in Sport*, *11*(3), 291–298. <https://doi.org/10.1016/j.jsams.2007.03.005>
- Leong, C. H., McDermott, W. J., Elmer, S. J., & Martin, J. C. (2014). Chronic eccentric cycling improves quadriceps muscle structure and maximum cycling power. *International Journal of Sports Medicine*, *35*(7), 559–565. <https://doi.org/10.1055/s-0033-1358471>
- Lindstedt, S. L., LaStayo, P. C., & Reich, T. E. (2001). When active muscles lengthen: Properties and consequences of eccentric contractions. *Physiology*, *16*(6), 256–261. <https://doi.org/10.1152/physiologyonline.2001.16.6.256>
- Lindstedt, S. L., Reich, T. E., Keim, P., & LaStayo, P. C. (2002). Do muscles function as adaptable locomotor springs? *Journal of Experimental Biology*, *15*(205), 2211–2216.
- Liu, C., Chen, C.-S., Ho, W.-H., Füle, R. J., Chung, P.-H., & Shiang, T.-Y. (2013). The effects of passive leg press training on jumping performance, speed, and muscle power. *Journal of Strength and Conditioning Research*, *27*(6), 1479–1486. <https://doi.org/10.1519/JSC.0b013e31826bde9f>
- López Mangini, F., & Fábrega, G. (2016). Mechanical stiffness: A global parameter associated to elite sprinters performance. *Revista Brasileira de Ciências Do Esporte*, *38*(3), 303–309. <https://doi.org/10.1016/j.rbce.2016.02.004>
- Lorah, J. (2018). Effect size measures for multilevel models: Definition, interpretation, and TIMSS example. *Large-Scale Assessments in Education*, *6*(1), 8. <https://doi.org/10.1186/s40536-018-0061-2>
- Malliaras, P., Kamal, B., Nowell, A., Farley, T., Dhamu, H., Simpson, V., Morrissey, D., Langberg, H., Maffulli, N., & Reeves, N. D. (2013). Patellar tendon adaptation in relation to load-intensity and contraction type. *Journal of Biomechanics*, *46*(11), 1893–1899. <https://doi.org/10.1016/j.jbiomech.2013.04.022>
- Maroto-Izquierdo, S., García-López, D., & de Paz, J. A. (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. *Journal of Human Kinetics*, *60*(1), 133–143. sph.
- Maroto-Izquierdo, S., García-López, D., Fernandez-Gonzalo, R., Moreira, O. C., González-Gallego, J., & de Paz, J. A. (2017). Skeletal muscle functional and structural adaptations after eccentric overload flywheel resistance training: A systematic review and meta-analysis. *Journal of Science & Medicine in Sport*, *20*(10), 943–951. <https://doi.org/10.1016/j.jsams.2017.03.004>

- McGuigan, M. R., Doyle, T. L. A., Newton, M., Edwards, D. J., Nimphius, S., & Newton, R. U. (2006). Eccentric utilization ratio: Effect of sport and phase of training. *Journal of Strength and Conditioning Research*, 20(4), 992–995. <https://doi.org/10.1519/r-19165.1>
- McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2019). Eccentric training interventions and team sport athletes. *Journal of Functional Morphology and Kinesiology*, 4(4), 67. <https://doi.org/10.3390/jfmk4040067>
- McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2020). Survey of eccentric-based strength and conditioning practices in sport. *Journal of Strength and Conditioning Research*, 34(10), 2769–2775. <https://doi.org/10.1519/JSC.0000000000003778>
- McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Eccentric force-velocity characteristics during a novel squat protocol in trained rugby union athletes—Pilot study. *Journal of Functional Morphology and Kinesiology*, 6(2), 32. <https://doi.org/10.3390/jfmk6020032>
- Mendiguchia, J., Martinez-Ruiz, E., Morin, J. B., Samozino, P., Edouard, P., Alcaraz, P. E., Esparza-Ros, F., & Mendez-Villanueva, A. (2015). Effects of hamstring-emphasized neuromuscular training on strength and sprinting mechanics in football players: Hamstring training and performance. *Scandinavian Journal of Medicine & Science in Sports*, 25(6), e621–e629. <https://doi.org/10.1111/sms.12388>
- Meylan, C., Cronin, J., & Nosaka, K. (2008). Isoinertial assessment of eccentric muscular strength. *Strength and Conditioning Journal*, 30(2), 56–64. <https://doi.org/10.1519/SSC.0b013e31816a7037>
- Mike, J. N., Cole, N., Herrera, C., VanDusseldorp, T., Kravitz, L., & Kerksick, C. M. (2017). The effects of eccentric contraction duration on muscle strength, power production, vertical jump, and soreness. *Journal of Strength and Conditioning Research*, 31(3), 773–786. <https://doi.org/10.1519/JSC.0000000000001675>
- Mjølshes, R., Arnason, A., Østhaugen, T., Raastad, T., & Bahr, R. (2004). A 10-week randomized trial comparing eccentric vs. Concentric hamstring strength training in well-trained soccer players. *Scandinavian Journal of Medicine & Science in Sports*, 14(5), 311–317. sph.
- Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine*, 6(7), 6.
- Morin, J.-B., Jeannin, T., Chevallier, B., & Belli, A. (2006). Spring-mass model characteristics during sprint running: Correlation with performance and fatigue-induced changes. *International Journal of Sports Medicine*, 27(2), 158–165. <https://doi.org/10.1055/s-2005-837569>
- Newton, M. J., Morgan, G. T., Sacco, P., Chapman, D. W., & Nosaka, K. (2008). Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *Journal of Strength and Conditioning Research*, 22(2), 597–607. <https://doi.org/10.1519/JSC.0b013e3181660003>
- Nicol, C., Avela, J., & Komi, P. V. (2006). The Stretch-Shortening Cycle. *Sports Medicine*, 36(11), 977–999. <https://doi.org/10.2165/00007256-200636110-00004>
- Nimphius, S., Callaghan, S. J., Spiteri, T., & Lockie, R. G. (2016). Change of direction deficit: A more isolated measure of change of direction performance than total 505 time. *Journal of Strength and Conditioning Research*, 30(11), 3024–3032. <https://doi.org/10.1519/JSC.0000000000001421>
- Núñez, F. J., Santalla, A., Carrasquilla, I., Asian, J. A., Reina, J. I., & Suarez-Arrones, L. J. (2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLOS ONE*, 13(3), e0193841. <https://doi.org/10.1371/journal.pone.0193841>

- Oliveira, A. S., Corvino, R. B., Caputo, F., Aagaard, P., & Denadai, B. S. (2016a). Effects of fast-velocity eccentric resistance training on early and late rate of force development. *European Journal of Sport Science*, *16*(2), 199–205. <https://doi.org/10.1080/17461391.2015.1010593>
- Oliveira, A. S., Corvino, R. B., Caputo, F., Aagaard, P., & Denadai, B. S. (2016b). Effects of fast-velocity eccentric resistance training on early and late rate of force development. *European Journal of Sport Science*, *16*(2), 199–205. <https://doi.org/10.1080/17461391.2015.1010593>
- Paddon-Jones, D., Keech, A., Lonergan, A., & Abernethy, P. (2005). Differential expression of muscle damage in humans following acute fast and slow velocity eccentric exercise. *Journal of Science and Medicine in Sport*, *8*(3), 255–263.
- Paddon-Jones, D., Leveritt, M., Lonergan, A., & Abernethy, P. (2001). Adaptation to chronic eccentric exercise in humans: The influence of contraction velocity. *European Journal of Applied Physiology*, *85*(5), 466–471. <https://doi.org/10.1007/s004210100467>
- Papadopoulos, C., Theodosiou, K., Bogdanis, G. C., Gkantiraga, E., Gissis, I., Sambanis, M., Souglis, A., & Sotiropoulos, A. (2014). Multiarticular isokinetic high-load eccentric training induces large increases in eccentric and concentric strength and jumping performance. *Journal of Strength and Conditioning Research*, *28*(9), 2680–2688. <https://doi.org/10.1519/JSC.0000000000000456>
- Pérez-Castilla, A., Rojas, F. J., & García-Ramos, A. (2019). Reliability and magnitude of loaded countermovement jump performance variables: A technical examination of the jump threshold initiation. *Sports Biomechanics*, 1–15. <https://doi.org/10.1080/14763141.2019.1682649>
- Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men's soccer: A cluster-randomized controlled trial. *The American Journal of Sports Medicine*, *39*(11), 2296–2303. <https://doi.org/10.1177/0363546511419277>
- Picerno, P., Iannetta, D., Comotto, S., Donati, M., Pecoraro, F., Zok, M., Tollis, G., Figura, M., Valalda, C., Di Muzio, D., Patrizio, F., & Piacentini, M. F. (2016). 1RM prediction: A novel methodology based on the force–velocity and load–velocity relationships. *European Journal of Applied Physiology*, *116*(10), 2035–2043. <https://doi.org/10.1007/s00421-016-3457-0>
- Proske, U. (2019). Exercise, fatigue and proprioception: A retrospective. *Experimental Brain Research*, *237*(10), 2447–2459. <https://doi.org/10.1007/s00221-019-05634-8>
- Quarrie, K. L., Hopkins, W. G., Anthony, M. J., & Gill, N. D. (2013). Positional demands of international rugby union: Evaluation of player actions and movements. *Journal of Science and Medicine in Sport*, *16*(4), 353–359. <https://doi.org/10.1016/j.jsams.2012.08.005>
- Rey, E., Paz-Domínguez, Á., Porcel-Almendral, D., Paredes-Hernández, V., Barcala-Furelos, R., & Abelaíras-Gómez, C. (2017). Effects of a 10-week nordic hamstring exercise and russian belt training on posterior lower-limb muscle strength in elite junior soccer players: *Journal of Strength and Conditioning Research*, *31*(5), 1198–1205. <https://doi.org/10.1519/JSC.0000000000001579>
- Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B., & Reid, W. D. (2009). The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: A systematic review with meta-analysis. *British Journal of Sports Medicine*, *43*(8), 556–568. <https://doi.org/10.1136/bjism.2008.051417>
- Rosner, B. (2016). *Fundamentals of Biostatistics* (8th ed.). Cengage Learning.
- Sabido, R., Hernández-Davó, J. L., Botella, J., Navarro, A., & Tous-Fajardo, J. (2017). Effects of adding a weekly eccentric-overload training session on strength and athletic

- performance in team-handball players. *European Journal of Sport Science*, 17(5), 530–538. <https://doi.org/10.1080/17461391.2017.1282046>
- Samozino, P., Rejc, E., Di Prampero, P. E., Belli, A., & Morin, J.-B. (2012). Optimal force–velocity profile in ballistic movements—*Altius: Medicine & Science in Sports & Exercise*, 44(2), 313–322. <https://doi.org/10.1249/MSS.0b013e31822d757a>
- Sanchez-Sanchez, J., Gonzalo-Skok, O., Carretero, M., Pineda, A., Ramirez-Campillo, R., & Nakamura, F. Y. (2019). Effects of concurrent eccentric overload and high-intensity interval training on team sports players’ performance. *Kinesiology*, 51(1), 119–126. <https://doi.org/10.26582/k.51.1.14>
- Schoenfeld, B. J., Ogborn, D. I., Vigotsky, A. D., Franchi, M. V., & Krieger, J. W. (2017). Hypertrophic effects of concentric vs. eccentric muscle actions: A systematic review and meta-analysis. *Journal of Strength and Conditioning Research*, 31(9), 2599–2608. <https://doi.org/10.1519/JSC.0000000000001983>
- Sharifnezhad, A., Marzilger, R., & Arampatzis, A. (2014). Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle. *The Journal of Experimental Biology*, 217(Pt 15), 2726–2733. <https://doi.org/10.1242/jeb.100370>
- Shepstone, T. N., Tang, J. E., Dallaire, S., Schuenke, M. D., Staron, R. S., & Phillips, S. M. (2005). Short-term high- vs. Low-velocity isokinetic lengthening training results in greater hypertrophy of the elbow flexors in young men. *Journal of Applied Physiology*, 98(5), 1768–1776. <https://doi.org/10.1152/jappphysiol.01027.2004>
- Shibata, K., Takizawa, K., Nosaka, K., & Mizuno, M. (2018). Effects of prolonging eccentric phase duration in parallel back-squat training to momentary failure on muscle cross-sectional area, squat one repetition maximum, and performance tests in university soccer players. *Journal of Strength and Conditioning Research*, 1–7. <https://doi.org/10.1519/JSC.0000000000002838>
- Simpson, A., Waldron, M., Cushion, E., & Tallent, J. (2021). Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. *Journal of Sports Sciences*, 39(1), 91–100. <https://doi.org/10.1080/02640414.2020.1805850>
- Spiteri, T., Cochrane, J. L., Hart, N. H., Haff, G. G., & Nimphius, S. (2013). Effect of strength on plant foot kinetics and kinematics during a change of direction task. *European Journal of Sport Science*, 13(6), 646–652. <https://doi.org/10.1080/17461391.2013.774053>
- Spiteri, T., Newton, R. U., Binetti, M., Hart, N. H., Sheppard, J. M., & Nimphius, S. (2015). Mechanical determinants of faster change of direction and agility performance in female basketball athletes. *Journal of Strength and Conditioning Research*, 29(8), 2205–2214. <https://doi.org/10.1519/JSC.0000000000000876>
- Spiteri, T., Nimphius, S., Hart, N. H., Specos, C., Sheppard, J. M., & Newton, R. U. (2014). Contribution of strength characteristics to change of direction and agility performance in female basketball athletes. *Journal of Strength and Conditioning Research*, 28(9), 2415–2423. <https://doi.org/10.1519/JSC.0000000000000547>
- Stasinaki, A.-N., Zaras, N., Methenitis, S., Bogdanis, G., & Terzis, G. (2019). Rate of force development and muscle architecture after fast and slow velocity eccentric training. *Sports*, 7(2), 41. <https://doi.org/10.3390/sports7020041>
- Suarez-Arrones, L. (2018). In-season eccentric-overload training in elite soccer players: Effects on body composition, strength and sprint performance. *PLoS One*, 13(10), 16. <https://doi.org/10.1371/journal.pone.0205332>
- Suchomel, T. J., Nimphius, S., Bellon, C. R., & Stone, M. H. (2018). The importance of muscular strength: Training considerations. *Sports Medicine*, 48(4), 765–785. <https://doi.org/10.1007/s40279-018-0862-z>

- Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., & Stone, M. H. (2019a). Implementing eccentric resistance training—part 1: A brief review of existing methods. *Journal of Functional Morphology and Kinesiology*, 4(2), 38. <https://doi.org/10.3390/jfmk4020038>
- Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., & Stone, M. H. (2019b). Implementing eccentric resistance training—part 2: Practical recommendations. *Journal of Functional Morphology and Kinesiology*, 4(3), 55. <https://doi.org/10.3390/jfmk4030055>
- Thompson, W. R., Gordon, N. F., & Pescatello, L. S. (2010). In *ACSM's Guidelines for Exercise Testing and Prescription*. (8th ed., pp. 90–91). Wolters Kluwer Health/Lippincott Williams & Wilkins.
- Toigo, M., & Boutellier, U. (2006). New fundamental resistance exercise determinants of molecular and cellular muscle adaptations. *European Journal of Applied Physiology*, 97(6), 643–663. <https://doi.org/10.1007/s00421-006-0238-1>
- Tous-Fajardo, J., Gonzalo-Skok, O., Arjol-Serrano, J. L., & Tesch, P. (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *International Journal of Sports Physiology and Performance*, 11(1), 66–73. <https://doi.org/10.1123/ijssp.2015-0010>
- Tous-Fajardo, J., Maldonado, R. A., Quintana, J. M., Pozzo, M., & Tesch, P. A. (2006). The flywheel leg-curl machine: Offering eccentric overload for hamstring development. *International Journal of Sports Physiology and Performance*, 1(3), 293–298. <https://doi.org/10.1123/ijssp.1.3.293>
- Vikne, H., Refsnes, P. E., Ekmark, M., Medbø, J. I., Gundersen, V., & Gundersen, K. (2006). Muscular performance after concentric and eccentric exercise in trained men. *Medicine and Science in Sports and Exercise*, 38(10), 1770–1781. <https://doi.org/10.1249/01.mss.0000229568.17284.ab>
- Vogt, M., & Hoppeler, H. H. (2014). Eccentric exercise: Mechanisms and effects when used as training regime or training adjunct. *Journal of Applied Physiology*, 116(11), 1446–1454. sph.
- Voigt, M., Bojsen-Møller, F., Simonsen, E. B., & Dyhre-Poulsen, P. (1995). The influence of tendon young's modulus, dimensions and instantaneous moment arms on the efficiency of human movement. *Journal of Biomechanics*, 28(3), 281–291. [https://doi.org/10.1016/0021-9290\(94\)00071-B](https://doi.org/10.1016/0021-9290(94)00071-B)
- von Lieres und Wilkau, H. C., Irwin, G., Bezodis, N. E., Simpson, S., & Bezodis, I. N. (2018). Phase analysis in maximal sprinting: An investigation of step-to-step technical changes between the initial acceleration, transition and maximal velocity phases. *Sports Biomechanics*, 1–16. <https://doi.org/10.1080/14763141.2018.1473479>
- Wagle, J. P., Taber, C. B., Cunanan, A. J., Bingham, G. E., Carroll, K. M., DeWeese, B. H., Sato, K., & Stone, M. H. (2017). Accentuated eccentric loading for training and performance: A review. *Sports Medicine*, 47(12), 2473–2495. <https://doi.org/10.1007/s40279-017-0755-6>
- Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *The Journal of Strength & Conditioning Research*, 19(1), 231–240. <https://doi.org/10.1519/15184.1>
- Wilson, J. M., & Flanagan, E. P. (2008). The role of elastic energy in activities with high force and power requirements: A brief review. *Journal of Strength and Conditioning Research*, 22(5), 1705–1715. <https://doi.org/10.1519/JSC.0b013e31817ae4a7>
- Wirth, K., Keiner, M., Szilvas, E., Hartmann, H., & Sander, A. (2015). Effects of eccentric strength training on different maximal strength and speed-strength parameters of the

lower extremity. *Journal of Strength and Conditioning Research*, 29(7), 1837–1845.
<https://doi.org/10.1519/JSC.0000000000000528>

Zacharia, E., Spiliopoulou, P., Methenitis, S., Stasinaki, A.-N., Zaras, N., Papadopoulos, C., Papadimas, G., Karampatsos, G., Bogdanis, G. C., & Terzis, G. (2019). Changes in muscle power and muscle morphology with different volumes of fast eccentric half-squats. *Sports*, 7(7), 164. <https://doi.org/10.3390/sports7070164>

Appendices

Survey of Eccentric-based Strength and Conditioning Practices in Sport

¹McNeill, C; ^{1,2}McMaster, D.T.; ¹Beaven, C.M.; ^{1,2}Gill, N

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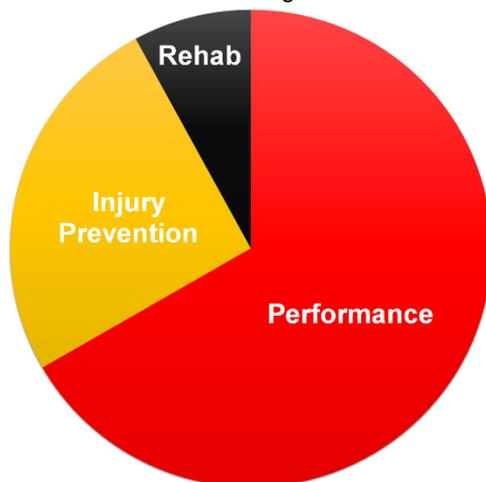
Introduction

Eccentric-based training (ECC) research suggests that neuromuscular factors contributing to eccentric force production and subsequent adaptation may be of interest to strength and conditioning practitioners. This study investigated the real world ECC practices in sport.

Methods

224 practitioners were electronically surveyed anonymously with 98 responses available for analysis.

Reasons for Including Eccentric-based Training



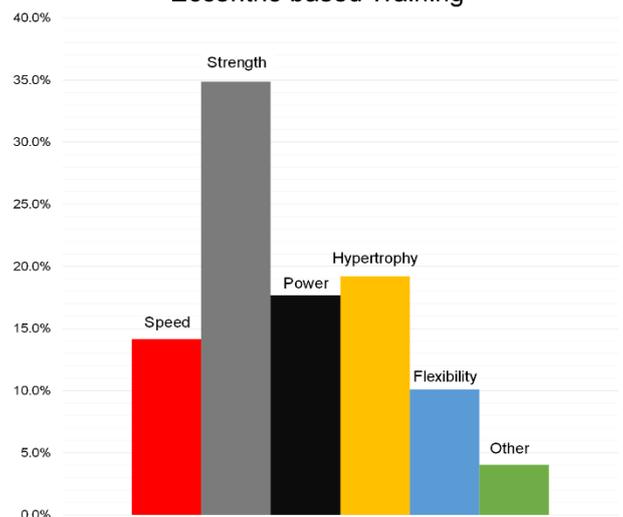
Summary

ECC is common among practitioners working with athletes. Respondents indicated muscle soreness and concurrent high-intensity activities were concerns during ECC but reported not using eccentric monitoring or testing.

Conclusions

A greater understanding of eccentric contribution to sport performance and injury prevention may help define testing and monitoring protocols for the prescription of ECC interventions. Practitioners should consider factors such as periodisation, soreness, and athlete monitoring when designing ECC programs. The findings of this survey indicate that no uniform strategies exist for the prescription of ECC among experienced practitioners.

Physical Abilities Targeted with Eccentric-based Training



Results

Respondents were predominantly 25 to 34 years old (56%) working globally (USA, 30%; NZ, 25%; AU, 10%; UK, 8%). Fifty-seven percent had completed a Master's degree and 22% indicated "Academic journal" as their most common source of ECC information. Sport Performance (64%), Injury Prevention (24%), and Rehabilitation (8%) were the most common reasons to include ECC. Respondents programmed ECC for Strength (35%), Hypertrophy (19%), Power (18%), and Speed (14%). A majority of respondents did not monitor ECC load (58%) or use eccentric-specific testing (75%). 16 respondents commented that DOMS and high-intensity activities were actively avoided. ECC intensity was prescribed as % of 1RM (34%), RPE (20%) or Velocity (16%).



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Survey of Eccentric-Based Strength and Conditioning Practices in High Performance Sport

Start of Block: Introduction

Introduction Hello, my name is Conor McNeill and I want to thank you for taking the time to help with this project. My research team (Dr. Nic Gill, Dr. Martyn Beaven, and Dr. Travis McMaster) and I are conducting a survey on eccentric-based training methods with well-trained athletes. For our purposes “**eccentric-based training**” is an exercise where the downward portion of a movement is emphasised through tempo, load, velocity, etc. As a strength and conditioning coach and PhD student at the University of Waikato, these results will be included in my PhD thesis and will help athletes and coaches to design better training programs.

The goal of this survey is to describe how eccentric-based strength and conditioning practices are used by real world practitioners in the development of well-trained athletes.

If you would like to participate in this survey you understand that:

- You are free to withdraw from the survey at any time or to decline to answer any particular questions.
- The data might be published, so every effort will be made to ensure confidentiality and anonymity. However, anonymity cannot be guaranteed.
- All data will be treated with the strictest confidentiality. Your survey will be kept in a secure file by the principal investigator. Your organisation will not have access to your completed questionnaire.

Human Research Ethics Committee – Any questions about the ethical conduct of this research may be addressed to the Secretary of the Committee, email humanethics@waikato.ac.nz, postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.

Q1 Do you agree to participate in this survey under these conditions?

Yes (1)

No (2)

Skip To: End of Survey If Do you agree to participate in this survey under these conditions? != Yes

End of Block: Introduction

Start of Block: Coach Demographic

Q2.1 What is your age?

18-24 years old (1)

25-34 years old (2)

35-44 years old (3)

45-54 years old (4)

55-64 years old (5)

65-74 years old (6)

75 years or older (7)

Q2.2 Gender?

- Female (1)
 - Male (2)
 - Prefer not to say (3)
 - Prefer to self-describe (4)
-

Q2.3 Ethnicity?

- Asian (1)
 - Black/ African (2)
 - Caucasian (3)
 - Hispanic/ Latin (4)
 - Native American (5)
 - Pacific Islander (6)
 - Prefer not to answer (7)
 - Prefer to self-describe (8)
-



Q2.4 In which country do you currently work?

▼ Afghanistan (1) ... Zimbabwe (1357)

Q2.5 How many years have you worked as a strength and conditioning practitioner?

- < 2 years (1)
 - 3-5 years (2)
 - 6-8 years (3)
 - 9-11 years (4)
 - 12-14 years (5)
 - 15-17 years (6)
 - 18-20 years (7)
 - > 20 years (8)
-

Q2.6 Which of your sports do you prescribe eccentric-based training? (Check all that apply)

- American football (1)
 - Athletics (2)
 - Australian rules football (3)
 - Baseball (4)
 - Basketball (5)
 - Football (6)
 - Ice Hockey (7)
 - Rugby League (8)
 - Rugby Union (9)
 - Swimming (10)
 - Volleyball (11)
 - Other (Please specify) (12)
-

- None (13)
-

Q2.7 What level does your team currently compete at?

- Professional (1)
- Elite/nonprofessional (2)
- Semi-professional (3)
- Representative (Provincial/National) (4)
- Other (Please specify) (5)

Q2.8 Please indicate any professional certifications you hold in the field of strength and conditioning, and how long you have held them. (Check all that apply)

- Australian Strength and Conditioning Association (1)

- Collegiate Strength and Conditioning Coaches Association (2)

- National Strength and Conditioning Association (3)

- United Kingdom Strength and Conditioning Association (4)

- Other (5) _____

Q2.9 What is the highest degree or level of school you have completed? If currently enrolled, highest degree received.

- No schooling completed (1)
- High school graduate, diploma or the equivalent (for example: GED) (2)
- Some college credit, no degree (3)
- Associate degree (4)
- Bachelor degree (5)
- Master degree (6)
- Doctorate degree (7)

Q2.10 Please leave any comments or feedback on the Coach Demographic section in the space below.

Page Break

End of Block: Coach Demographic

Start of Block: Perceptions of Eccentric Training

Q3.1 Which, if any, of the following have you used as a source of eccentric-based training knowledge? (Check all that apply)

- Academic journal (1)

 - Website (2) _____
 - Book (3) _____
 - Conference (4) _____
 - Workshop (5) _____
 - Professional colleagues/ other programs (6)

 - Other (Please specify) (7)

 - None (8)
-

Q3.2 In your opinion, please rate the balance between the risks and benefits of implementing eccentric-based training compared to traditional training methods.

Risks outweigh benefits	Neutral	Benefits outweigh risks
0	50	100



Q3.3 Please rate the efficacy of eccentric-based training compared to traditional training methods.

Not effective at all	Moderately effective	Very effective
0	50	100



Q3.4 Have you prescribed eccentric-based training for your athletes in the past 24 months?

- Yes (1)
- No (2)

Display This Question:
If Have you prescribed eccentric-based training for your athletes in the past 24 months? = No

Q3.5 Please briefly explain your main reasons for excluding eccentric-based training.

Page Break

End of Block: Perceptions of Eccentric Training

Start of Block: Athlete Demographics

Q4.1 What is the biological age range, in years, of the athletes you design training programs for?
(Check all that apply)

- < 17 years (1)
 - 17 to 20 years (2)
 - 21 to 25 years (3)
 - 26 to 30 years (4)
 - 31 to 35 years (5)
 - > 35 years (6)
-

Q4.2 What is the training age range of the athletes you design training programs for? (Check all that apply)

- < 6 months (1)
 - 6 months to 1 year (2)
 - 1 to 2 years (3)
 - 3 to 5 years (4)
 - 6 to 8 years (5)
 - 9 to 11 years (6)
 - > 11 years (7)
-

Q4.3 Please describe the sex of your athletes.

- Female (1)
 - Male (2)
 - Mixed (3)
 - Prefer to self-describe (4)
-

Q4.4 Please leave any comments or feedback on the Athlete Demographic section in the space below.

End of Block: Athlete Demographics

Start of Block: Program Design

Q5.1 At what time in a yearly training cycle do you prefer to implement eccentric-based training?
(Check all that apply)

- Post-season (1)
- Off-season (2)
- Pre-season (3)
- Early competition phase (4)
- Late competition phase (5)
- Playoffs (6)
- Other (7) _____



Q5.2 Please rank the reasons you might include eccentric-based training in your program. (Include all that apply)

Reasons to include eccentric-based training

_____ General Physical Performance (1)

_____ Sport Specific Performance (2)

_____ Injury Prevention (3)

_____ Injury Rehabilitation (4)

_____ Other (5)

_____ Other (6)

Q5.3 Which athletic abilities do you intend to improve with eccentric-based training? Please explain. (Check all that apply)

Speed (1) _____

Strength (2) _____

Power (3) _____

Hypertrophy (4) _____

Flexibility (5) _____

Other (6) _____

Q5.4 What other athletic abilities do you target within the same training block? Please explain.
(Check all that apply)

Speed (1) _____

Strength (2) _____

Power (3) _____

Hypertrophy (4) _____

Flexibility (5) _____

Other (6) _____

Q5.5 What other forms of training are performed during an eccentric-based training block? Please explain (Check all that apply)

Speed (1) _____

Skill (2) _____

Technical/ Tactical (3)

Team training (4) _____

Fitness/ Energy system development/ Conditioning (5)

Other (6) _____

Q5.6 Do you actively avoid any specific athletic ability or form of training during an eccentric-based training block?

Q5.7 What is the duration, in weeks, of a typical eccentric-based training block?

- < 1 week (1)
 - 1 to 3 weeks (2)
 - 4 to 6 weeks (3)
 - 7 to 9 weeks (4)
 - 10 to 12 weeks (5)
 - > 12 weeks (6)
-

Q5.8 Do you currently use any form of training monitoring to quantify eccentric-based training load or fatigue? Please explain.

- Yes (1) _____
 - No (2)
-

Q5.9 Do you use any eccentric-specific testing to assess physical performance? Please explain.

- Yes (1) _____
 - No (2)
-

Q5.10 Please rank the most important exercises you use when prescribing eccentric-based training.
(Include all that apply)

Most important eccentric exercises

_____ Back Squat (1)

_____ Bench Press (2)

_____ Bent Over Row (3)

_____ Deadlift (4)

_____ Pull Up (5)

_____ Rear-foot Elevated Squat/ Bulgarian (6)

_____ Other (7)

_____ Other (8)

_____ Other (9)

Q5.11 How do you typically modify the eccentric phase of the exercises listed above? Please explain.
(Check all that apply)

Tempo (1) _____

Velocity (2) _____

Load (3) _____

Special equipment (4)

Technique (5) _____

Other (6) _____

Q5.12 Please rank the equipment you use for eccentric-based training. (Include all that apply)

Eccentric-based training equipment

_____ Barbell (1)

_____ Dumbbell (2)

_____ Plate-loaded Machines (3)

_____ Cable/ pulley Machines (4)

_____ Inertial Flywheel (5)

_____ Isokinetic Dynamometer (6)

_____ Bodyweight (7)

_____ Other (8)

_____ Other (9)

_____ Other (10)

Q5.13 Within a single training session, where do you typically sequence eccentric-based exercises?

- Potentiation (before the primary exercise) (1)
- Primary (the main exercise of a training session) (2)
- Assistance (after the primary exercise) (3)
- Finisher (the end of the training session) (4)
- Other (5) _____

Q5.14 How frequently, within a week, do you prescribe eccentric-based training for the same movement pattern or body part?

< 1 day (1)

1 day (2)

2 days (3)

3 days (4)

4 days (5)

5 days (6)

> 5 days (7)



Q5.15 How many recovery days would you typically give between eccentric-based training sessions for the same movement/ body part?

< 1 day (1)

1 day (2)

2 days (3)

3 days (4)

4 days (5)

5 days (6)

> 5 days (7)

Other (8) _____

Q5.16 How do you quantify the intensity of eccentric-based training? Please describe the range of intensity you typically prescribe. (Check all that apply)

% of one repetition maximum (1)

% of bodyweight (2)

Absolute load (3) _____

Rate of perceived exertion (4)

Velocity (5) _____

Other (6) _____

Q5.17 How many sets do you typically prescribe in an eccentric-based training session? (Check all that apply)

- 1 set (1)
 - 2 sets (2)
 - 3 sets (3)
 - 4 sets (4)
 - 5 sets (5)
 - 6 sets (6)
 - 7 sets (7)
 - 8 sets (8)
 - 9 sets (9)
 - 10 sets (10)
 - > 10 sets (11)
-

Q5.18 How many repetitions per set do you typically prescribe in an eccentric-based training session?
(Check all that apply)

- 1 rep (1)
- 2 reps (2)
- 3 reps (3)
- 4 reps (4)
- 5 reps (5)
- 6 reps (6)
- 7 reps (7)
- 8 reps (8)
- 9 reps (9)
- 10 reps (10)
- 11 reps (11)
- 12 reps (12)
- > 12 reps (13)
- Other (14) _____

Q5.19 How much rest, in minutes, do you prescribe between sets of eccentric-based training?

- < 1 minute (1)
- 1 to 2 minutes (2)
- 3 to 4 minutes (3)
- 5 to 6 minutes (4)
- > 6 minutes (5)
- Other (6) _____

Q5.20 Is there any other aspect of your prescription method for eccentric-based training that we might have missed?

Q5.21 Please leave any comments or feedback on the Program Design section in the space below.

Page Break

Appendix C. Ethical approvals.

Appendix C1. Ethical approval for Chapter 3 and 4

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Karsten Zegwaard
Telephone: +64 7 838 4892
Email: humanethics@waikato.ac.nz



24-10-2018

Conor McNeill
By email: conor.mcneill51@gmail.com

Dear Conor

UoW HREC(Health)2018#60 : Development and Application of an Eccentric Force-Velocity Profile

Thank you for submitting your amended application HREC(Health)2018#60 for ethical approval.

This project had previously been granted preliminary approval.

We are now pleased to provide formal full approval for your project within the parameters outlined within your application.

If you need to make any changes to the elements approved within the application that requires ethical approval, please contact with committee (humanethics@waikato.ac.nz), quoting the approval number, and seek an amendment to your application. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,



Karsten Zegwaard PhD
Acting Chairperson
University of Waikato Human Research Ethics Committee

Appendix C2. Ethical approval for Chapter 5 and 6

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Julie Barbour
Telephone: +64 7 837 9336
Email: humanethics@waikato.ac.nz



20th February 2019

Conor McNeill
By email: conor.mcneill51@gmail.com

Dear Conor

UoW HREC(Health)2019#01: Development and Application of an Eccentric Force-Velocity Profile and Training Interventions

Thank you for submitting your amended application HREC(Health)#2019#01 for ethical approval.

We are now pleased to provide formal approval for your project including two studies of athletes from the Bay of Plenty Rugby Union. The studies will begin with the collection of basic information (height, age, body mass) and a Force-Velocity profile. The first study will be a six week individual training intervention based on the results of the Force-Velocity profile. The second study will compare propulsion and landing under two conditions. Both studies will conclude with a second Force-Velocity profile.

We have received the locality approval from Bay of Plenty Rugby Union, and we are happy with the monitoring protocol that you have introduced to ensure participant soreness is monitored through the research, and attended to as needed.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,



Julie Barbour PhD
Chairperson
University of Waikato Human Research Ethics Committee

Appendix D. Co-authorship forms

Appendix D1. Co-authorship form for Chapter 2



Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2019). Eccentric training interventions and team sport athletes. *Journal of Functional Morphology and Kinesiology*, 4(4), 67.

Nature of contribution by PhD candidate

Development of the research question, literature search, study selection, qualitative assessment, form creation and data extraction, analysis and interpretation of results, manuscript preparation, and journal submission

Extent of contribution by PhD candidate (%)

85%

CO-AUTHORS

Name	Nature of Contribution
Nic Gill	Development of the research question, supervision of all stages, revision of the manuscript
Christopher Martyn Beaven	Qualitative assessment, revision of the manuscript
Daniel Travis McMaster	Development of the research question, qualitative assessment, revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Nic Gill		13/12/2021
Christopher Martyn Beaven		13/12/2021
Daniel Travis McMaster		12/12/2021

July 2015

Appendix D2. Co-authorship form for Chapter 3



Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2020). Survey of eccentric-based strength and conditioning practices in sport. *The Journal of Strength & Conditioning Research*, 34(10), 2769-2775.

Nature of contribution by PhD candidate

Development of the research question, development of the survey tool, participant recruitment, data extraction and analysis, interpretation of results, manuscript preparation, and journal submission

Extent of contribution by PhD candidate (%)

85%

CO-AUTHORS

Name	Nature of Contribution
Nic Gill	Development of the research question, supervision of all stages, development of the survey tool, participant recruitment, revision of the manuscript
Christopher Martyn Beaven	Development of the research question, interpretation of results, revision of the manuscript
Daniel Travis McMaster	Participant recruitment, revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Nic Gill		13/12/2021
Christopher Martyn Beaven		13/12/2021
Daniel Travis McMaster		12/12/2021

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Appendix D3. Co-authorship form for Chapter 4



Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

McNeill, C., Beaven, C. M., McMaster, D. T., & Gill, N. (2021). Eccentric force-velocity characteristics during a novel squat protocol in trained Rugby Union athletes—Pilot study. *Journal of Functional Morphology and Kinesiology*, 6(2), 32.

Nature of contribution by PhD candidate

Development of the research question and testing protocol, participant recruitment, data extraction and analysis, interpretation of results, manuscript preparation, and journal submission

Extent of contribution by PhD candidate (%)

85%

CO-AUTHORS

Name	Nature of Contribution
Nic Gill	Development of the research question, supervision of all stages, revision of the manuscript
Christopher Martyn Beaven	Interpretation of results, revision of the manuscript
Daniel Travis McMaster	Data extraction and analysis, revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Nic Gill		13/12/2021
Christopher Martyn Beaven		13/12/2021
Daniel Travis McMaster		12/12/2021

July 2015

Appendix D4. Co-authorship form for Chapter 5



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Co-Authorship Form

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

McNeill, C., Beaven, C. M., McMaster, D. T., Ward, P., & Gill, N. (2021). Eccentric force-velocity-load relationship in trained Rugby Union athletes. *The Journal of Strength & Conditioning Research*

Nature of contribution by PhD candidate	Development of the research question and testing protocol, participant recruitment, data extraction and analysis, interpretation of results, manuscript preparation, and journal submission
Extent of contribution by PhD candidate (%)	80%

CO-AUTHORS

Name	Nature of Contribution
Nic Gill	Development of the research question, supervision of all stages, revision of the manuscript
Christopher Martyn Beaven	Interpretation of results, revision of the manuscript
Daniel Travis McMaster	Data extraction and analysis, revision of the manuscript
Patrick Ward	Statistical analysis support, revision of the manuscript

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Nic Gill		13/12/2021
Christopher Martyn Beaven		13/12/2021
Daniel Travis McMaster		12/12/2021
Patrick Ward		12/12/2021

July 2015

Appendix D5. Co-authorship form for Chapter 6



Co-Authorship Form

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This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in your appendices for all the copies of your thesis submitted for examination and library deposit (including digital deposit).

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

McNeill, C., Beaven, C. M., McMaster, D. T., Ward, P., & Gill, N. (2021). Physical performance changes following fast- and controlled- tempo eccentric-based training in rugby union athletes. *The Journal of Strength & Conditioning Research*

Nature of contribution by PhD candidate

Development of the research question, participant recruitment, data extraction and analysis, interpretation of results, manuscript preparation, and journal submission

Extent of contribution by PhD candidate (%)

85%

CO-AUTHORS

Name	Nature of Contribution
Nic Gill	Development of the research question, supervision of all stages, revision of the manuscript
Christopher Martyn Beaven	Interpretation of results, revision of the manuscript
Daniel Travis McMaster	Development of the research question

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Nic Gill		13/12/2021
Christopher Martyn Beaven		13/12/2021
Daniel Travis McMaster		12/12/2021

July 2015

Appendix E. Author's research publications not related to the PhD thesis.

McMaster, D. T., Mayo, B., Stebbing, T., Gill, N., **McNeill, C.**, & Beaven, C. M. (2018). Effect of drop jump training frequency on reactive strength in rugby athletes. In 11th International Conference on Strength Training 2018 (pp. 11–11). Conference held Perth, Australia: ICST.