THE USE OF LOWER-BODY ECCENTRIC RESISTANCE TRAINING TO ENHANCE STRENGTH AND POWER IN ELITE YOUTH ATHLETES

BENJAMIN DRURY

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ABSTRACT

Resistance training (RT) is effective for developing strength and power in youth athletes. Previously, research has mainly examined the effects of traditional resistance training (TRT) in which the load during both the eccentric and concentric phases are equal. Such an approach limits the development of eccentric strength and power qualities as greater forces are produced during eccentric muscle actions versus concentric. Eccentric resistance training (ERT) methods that can overload the eccentric phase of an exercise should be prescribed for youth athletes. In *Publication 1*, a narrative review appraised the physiological responses, benefits and current literature of ERT for youth athletes to enhance performance and reduce injury risk. *Publication 2* surveyed the perceptions and current practices of ERT for youth athletes by 64 strength and conditioning (S&C) coaches. Results showed that whilst 96% of S&C coaches agreed that the inclusion of ERT for youth athletes was important, most only begun prescribing ERT in late adolescence compared to TRT which was largely implemented from childhood. *Publication 3* reported that eccentric hamstring strength (EHS) can be reliably assessed by the Nordic hamstring exercise (NHE) in 64 youth male football players for both pre peak height velocity [PHV] (TE = 0.22-9.30N, CV = 4.8-5.7%) and mid-post PHV players (TE = 0.30-22.5N, CV = 7.2-8.5%). *Publication 4* found six-weeks of NHE training increased EHS in both pre PHV (n = 8, d = 0.83) and post PHV (n = 16, d = 0.53) youth male soccer players. Results imply that less biologically mature players are perhaps more sensitive to increases in EHS from the NHE and that the training prescription for the NHE in more biologically mature players requires greater specificity. *Publication 5* found prescribing either a one-minute (short) or three-minute (long) inter-set rest period (ISRI) between sets of the NHE did not significantly ($p > 0.05$) affect force production in 10 young male soccer players. However, results showed significant reductions in peak force from repetition four onwards in both dominant and non-dominant limbs (d = 0.58-1.28), indicating that the set configuration for the NHE requires consideration for youth athletes. *Publication 6* reported similar increases in lower-body strength and power measures following six-weeks of either TRT (n = 8, d = 0.27-0.88) or flywheel inertia training (n = 8, d = 0.22-0.55) in elite academy rugby union players. Taken together, the findings from these publications demonstrate the safety, importance and application of ERT to enhance the performance of elite youth athletes.

Key Words: long-term athletic development, eccentric training, youth athletes, athletic performance, hamstrings strength, maturation

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ABBREVIATIONS

RM	Repetition maximum
AMSC	Athletic motor skill competencies
BA	Biological age
CA	Chronological age
CMJ	Countermovement jump
COD	Change of direction
CV	Coefficient of variation
D	Cohen’s effect size
DJ	Drop jump
EHS	Eccentric hamstring strength
EMG	Electromyography
ERT	Eccentric resistance training
FIT	Flywheel inertia training
HSI	Hamstring strain injury
ISRI	Inter set rest interval
LTAD	Long term athletic development
N	Newton
NHE	Nordic hamstring exercise
PHV	Peak height velocity
REPS	Repetitions
RSI	Reactive strength index
RT	Resistance training
S&C	Strength and conditioning
SJ	Squat jump
TRT	Traditional resistance training
YPD	Youth physical development

PREFACE

The focus of the peer reviewed publications included in this thesis is the use of ERT to develop strength and power in elite youth athletes. **Chapter 1** outlines the research topic, its aims, scope, and the included publications which contribute new knowledge to the topic area. **Chapter 2** provides a contextual overview of the importance of strength and power for youth athletes, highlights the benefits of RT to increase strength and power for youth athletes, and provides an overview of how biological maturation influences adaptations to strength and power throughout youth. This chapter also details the benefits of eccentric exercise for developing strength before presenting some of the key literature surrounding the importance of eccentric strength and power for athletic performance in youth. Finally, this section concludes with an overview of the ERT methods that were used in the experimental studies in this thesis. **Chapter 3** details the structure of the following chapters which comprise of a brief overview of the study background, 'thread' between studies and key findings of the full included peer reviewed publications for the thesis. In **Chapter 4 (Publication One)**, a narrative review of literature was completed to critically appraise the efficacy of using ERT for youth athletes. This included an analysis of the physiological responses to eccentric exercise in youth, evaluating the role of eccentric strength and power for enhancing athletic performance in youth athletes and offering evidence-based guidelines for the implementation of ERT based on available empirical research. In **Chapter 5 (Publication Two)**, S&C coaches' perceptions, and current practices of ERT in youth athletes was surveyed. In **Chapter 6 (Publication Three)**, the reliability of a field-based device to measure EHS during the NHE in elite youth male athletes was investigated. In **Chapter 7 (Publication Four)**, the influence of maturity status on changes in EHS following a six-week training programme of the NHE was examined in elite male youth athletes. In **Chapter 8 (Publication Five)**, the effects of using either a short (one minute) or long (three minute) inter-set rest period (ISRI) on eccentric hamstring force production during the NHE in elite young male athletes was investigated. Finally, in **Chapter 9 (Publication Six)**, the effects of a four-week training intervention of FIT compared to TRT on changes in lower-body strength and power measures in elite academy male rugby union players was investigated. In **Chapter 10**, the thesis is summarised, along with directions for future research and a conclusion provided.

LIST OF INCLUDED PEER REVIEWED PUBLICATIONS

Chapter 4: Drury, B., Ratel, S., Clark, C. C., Fernandes, J. F., Moran, J., and Behm, D. G. (2019). Eccentric Training in Youth: Perspectives for Long-Term Athletic Development. *Journal of Functional Morphology and Kinesiology*, *4*(4), pp.70. https://doi.org/10.3390/jfmk4040070

Chapter 5: Drury, B., Clarke, H., Moran, J., Fernandes, J. F., Henry, G., and Behm, D. G. (2021). Eccentric Resistance Training in Youth: A Survey of Perceptions and Current Practices by Strength and Conditioning Coaches. *Journal of Functional Morphology and Kinesiology*, *6* (1), pp.21. https://doi.org/10.3390/jfmk6010021

Chapter 6: Fernandes, J. F., Moran, J., Clarke, H., and **Drury, B.** (2020). The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers. *Translational Sports Medicine*, *3*(2), pp.148-153. https://doi.org/10.1002/tsm2.124

Chapter 7: Drury, B., Green, T., Ramirez-Campillo, R., and Moran, J. Drury, B., Green, T., Ramirez-Campillo, R. and Moran, J., (2020). Influence of maturation status on eccentric hamstring strength improvements in youth male soccer players after the Nordic hamstring exercise. *International Journal of Sports Physiology and Performance*, 15(7), pp.990-996. https://doi.org/10.1123/ijspp.2019-0184

Chapter 8: Drury, B., Peacock, D., Moran, J., Cone, C., and Ramirez-Campillo, R. (2021). Different Inter-Set Rest Intervals during the Nordic Hamstrings Exercise in Young Male Athletes. *Journal of Athletic Training*. 56 (9): pp.952–959. https://doi.org/10.4085/318-20

Chapter 9: Murton, J., Eager, R., and **Drury, B.** (2021). Comparison of Flywheel versus Traditional Resistance Training in Elite Academy Rugby Players. *Journal of Research in Sports Medicine*. pp.1-14. https://doi.org/10.1080/15438627.2021.1954518

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DECLARATION

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree and does not incorporate any material already submitted for a degree.

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CHAPTER 1 - INTRODUCTION

1.1 Overview

Research examining the effects of ERT in elite youth athletes is still in its infancy. To date, no practical guidelines for the implementation of ERT or its training prescription in youth athletes are available. Additionally, there is currently no information regarding the use of ERT by S&C coaches in youth athletes. This limited guidance is likely reflected by the low number of studies which have been conducted on ERT methods in youth athletes such as eccentric overload training and eccentric hamstring training. Because of these limitations, S&C coaches may be unaware of the potential applications of ERT for youth athletes, and if they are aware, will likely lack knowledge of how to implement it effectively. Such a knowledge gap could leave youth athletes with chronically undertrained eccentric strength and power qualities. This is important to address since eccentric strength and power qualities underpin many sporting tasks that youth athletes must perform (e.g., jumping, CoD, sprinting, rebounding) as well as being associated with injury risk factors (e.g. low EHS). Thus, ERT is not an advanced strategy for youth athletes, it is an essential strategy. Therefore, increasing the knowledge base of the practical applications of ERT for youth athletes offers both S&C coaches and researchers with important information of how this method can be utilised.

The purpose of the publications included in this thesis were to contribute new knowledge regarding the use of ERT for elite youth athletes. A particular success from this body of work has been the ability to conduct research in both a population and topic area that is especially difficult to do so. For example, conducting research in elite athletes is known to be challenging due to aspects such as injuries, illness, competition, and training routines (Bishop, 2008). Also, research in elite youth athlete provides additional challenges due to their dual career (i.e., education and sport), limited and specific times of training (e.g., mainly evenings) as well as the ethical considerations for this population. Navigating the aforementioned factors becomes even more difficult when research involves eccentric exercise due to the high levels of muscle damage and neuromuscular fatigue that occur following its cessation (Proske and Morgan, 2001). Indeed, S&C coaches have noted the concerns of using eccentric exercise for athletes due to the high levels of muscle soreness and fatigue experienced by athletes, as well as the practicality of implementing ERT within a session being a barrier (Harden *et al.* 2020). The studies included here have been able to overcome such obstacles, to provide a significant contribution to the topic area by undertaking rigorous research of both qualitative and quantitative nature.

By conducting empirical research on the topic area, the findings contribute to a deeper understanding of the benefits and practical applications of ERT in youth. Little was known about the influence of maturation on changes to strength and power following ERT in youth athletes and therefore an aim was to examine how maturation status influences the magnitude of change following ERT. Additionally, the undertaking of training interventions within the topic area were limited and therefore the methods presented in the included studies provide both researchers and S&C coaches with evidenced-based data relating to the specific training prescription of ERT in youth athletes. Importantly, these studies were conducted within the athletes typical training structure to bridge the gap between science and practice and have therefore resulted in the creation of real-world, ecologically valid training programmes that S&C coaches can use. Furthermore, whilst team sport athletes were primarily used as participants for the undertaken research, the findings offer youth athletes of all sports who require the development of lower-body strength and power evidence-based guidelines which can be implemented into their training programmes. Overall, this body of work has generated new information that S&C coaches can use to further optimise the development of strength and power in elite level youth athletes.

1.2 Aims of the Research

This research aimed to contribute new knowledge to existing literature concerning the use of ERT for elite youth athletes. The purpose of the included peer reviewed publications that make up **Chapters 4-9** are intended to extend this knowledge with the following aims;

1. Critically appraise the efficacy of ERT and provide evidenced-based guidelines for its implementation in youth athletes.
2. Survey the current perceptions and practices of ERT methods in youth athletes by S&C coaches.
3. Investigate the usefulness of the NHE to assess and develop EHS in elite youth athletes.
4. Compare the effects of FIT to TRT for developing lower-body strength and power in elite youth athletes.

1.3 Intended Sequence of Publications

The peer reviewed publications included in this thesis provide novel practical information on the topic area. All studies were designed with a focus of gaining a better understanding of ERT for elite youth athletes. Due to the nature of journal article publishing, implications of Covid-19 and other external factors, some publications entered and concluded the peer-review process at different times. This has meant that the publication dates for some of the journal papers are not always in chronological order.

1.4 Statement Regarding Ethical Approval

All publications included within this thesis received ethical approval from the Hartpury University Ethics Committee prior to beginning data collection with all studies completed in accordance with the Declaration of Helsinki. This information is explicitly stated within the Methods section of the full version of the studies with journals requiring a declaration to be signed by the authors to confirm this prior to submission.

1.5 Statement Regarding Authorship Contributions

Table 1 outlines the authorship contributions for the peer reviewed publications included in **Chapters 4-9**. Authorship requirements for all publications were met in accordance with criteria which were stipulated by the respective journal prior to submission;

- Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
- Drafting the work or revising it critically for important intellectual content; AND
- Final approval of the version to be published; AND
- Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Table 1. Study Authorship Contributions

Publication	Contribution(s)
Drury, B., Ratel, S., Clark, C. C., Fernandes, J. F., Moran, J., and Behm, D. G. (2019). Eccentric Resistance Training in Youth: Perspectives for Long-Term Athletic Development.	**Drury:** Led the conception/design of work, interpretation of the work, drafting the work, final approval, and submission process.
Drury, B., Clarke, H., Moran, J., Fernandes, J. F., Henry, G., and Behm, D. G. (2021). Eccentric Resistance Training in Youth: A Survey of Perceptions and Current Practices by Strength and Conditioning Coaches.	**Drury:** Led the conception/design of work, acquisition, analysis, and interpretation of data, drafting the work, final approval and submission process.
Fernandes, J. F., Moran, J., Clarke, H., and **Drury, B.** (2020). The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers.	**Drury:** Led the conception/design of work, acquisition of data, critical revision of the work and final approval. Co-led the analysis and interpretation of data.
Drury, B., Green, T., Ramirez-Campillo, R., and Moran, J. (2020). Influence of Maturation Status on Eccentric Hamstring Strength Improvements in Youth Male Soccer Players following the Nordic Hamstring Exercise.	**Drury:** Led the conception/design of work, acquisition, analysis, and interpretation of data, drafting the work, final approval and submission process.
Drury, B., Peacock, D., Moran, J., Cone, C., and Ramirez-Campillo, R. (2021). Effects of Different Inter-Set Rest Intervals during the Nordic Hamstring Exercise in Young Male Athletes.	**Drury:** Led the conception/design of work, acquisition, analysis, and interpretation of data, drafting the work, final approval and submission process.
Murton, J., Eager, R., and **Drury, B.** (2021). Comparison of Short-Term Flywheel versus Traditional Resistance Training in Elite Academy Rugby Players.	**Drury:** Led the conception/design of work, analysis, and interpretation of data, drafting the work, final approval, and submission process.

CHAPTER 2 – CONTEXTUAL BACKGROUND

2.1 Importance of Strength and Power for Youth Athletes

Muscular strength has been defined as the ability to exert force on an external object or resistance (Stone *et al*. 2000). The development of muscular strength is considered vital for athletic performance due to its association with the performance of sport specific tasks such as jumping, sprinting and CoD (Faigenbaum *et al*. 2016). This can be explained by the ability to exert high levels of ground reaction forces which results in greater propulsive forces and the acceleration of body mass (Nagahara *et al*. 2018). Moreover, high levels of muscular strength (i.e., peak force) underpin other important force-time characteristics such as rate of force development and mechanical power (Taber *et al*. 2016). This is because power output is the product of force and velocity and is defined and limited by the force-velocity relationship (Hill, 1938). On this basis, maximal power output may improve by an increased ability to develop force at a given velocity and/or velocity at a given force. Consequently, an initial focus on developing a foundation of muscular strength in athletes is recommended for athletic populations (Suchomel *et al*. 2018).

In youth athletes, a foundation of muscular strength is deemed highly important for athletic performance (Faigenbaum *et al*. 2016). This is because all athletic movements require a certain level of force production and force attenuation (Lloyd *et al*. 2015a). Empirical support has been provided in a meta-analysis conducted by Behm *et al*. (2017) in which improvements in strength or power training interventions were compared for measures of lower-body strength, power, and sprint performance in children (6-12 years) and adolescents (13-18 years). Analyses reported strength training was more effective for increasing muscular strength (d = 1.14) whilst both strength and power training resulted in similar improvements in power (d = 0.53 and 0.69, respectively). The authors also reported that regardless of performing strength or power training, untrained youth athletes achieved greater improvements than trained youth athletes, and children improved to a greater extent than adolescents too. Indeed, younger individuals have been reported to achieve greater improvements in performance compared to those with previous strength training experience with blunted results occurring due to a ceiling effect of potential adaptation in the latter (Behringer *et al*. 2011). Therefore, the development of muscular strength for youth athletes should be considered a primary focus for S&C coaches to plan for.

In youth athletes, strength and power has been shown to differentiate between playing standards. For example, compared to a maturation control group that had not previously played soccer at an elite academy or professional level, elite youth male soccer players displayed greater lower-body vertical and horizontal power as well as lower-body isometric maximum force (Murtagh *et al*. 2018; Brownlee *et al*. 2018). In rugby union, male academy players were stronger in the 3RM bench press (d = 1.27) compared to age matched school players (Jones *et al*. 2018). Additionally, in junior rugby league, elite players have been shown to achieve greater (d = 0.65) vertical jump height than sub-elite players (Gabbett *et al*. 2009). Moreover, in sports such as rugby union, lower-body strength, and power measures such as the squat jump (SJ) and countermovement jump (CMJ) predict player who will go on to play at either international or national senior standards with an accuracy of 81% and 77%, respectively (Fontana *et al*. 2017). Therefore, based upon currently available research, youth athletes need to engage in training methods which enhance strength and power qualities to support both short and long-term playing success.

2.2 Resistance Training for Youth Athletes

Resistance training (RT) is an effective method to increase strength and power in youth athletes (Granacher *et al*. 2016). RT refers to a variety of methods, but primarily relates to machines and/or free-weights (McQuilliam *et al*. 2020) with the objective being to increase one’s ability to exert or resist force (Myers, Beam and Fakhoury, 2017). For free-weight exercises this includes barbells, dumbbells and medicine balls whilst for machine-based exercises this includes plate-loaded, electronically braked devices, springs and rubber band devices (Stone *et al*. 2000). Overall, RT programmes in youth athletes have shown positive improvements in muscular strength and power whether using free-weights, machines, and body-weight movements (Drenowatz and Greier, 2018). The rationale for choosing the appropriate RT method in youth should consider aspects such as the individual’s maturation status, training age, technical competency, sex, and motivation (Fort-Vanmeerhaeghe *et al*. 2016). Furthermore, whilst there have been historical concerns regarding the potential susceptibility of youths to suffer injuries when performing RT, these do not appear to be greater than other sports and recreational activities (Faigenbaum and Myer, 2010). Therefore, if the prescribed RT method for youth athletes is progressively overloaded, technique focused and supervised by qualified professionals, their inclusion should be considered safe and effective for developing strength and power.

In recent years, several publications have provided evidence to overcome long held myths regarding the detrimental effects (e.g., damage to growth plates, high injury risk) of RT in youth (Granacher *et al*. 2018). Whilst previous concerns for using RT in youth focused on what would happen if a child lifted weights, a more recent focus has turned toward what will happen if a child does not lift weights (Stricker *et al*. 2020). Indeed, several longitudinal studies have demonstrated the benefits of beginning RT in childhood to increase strength and power. Sadres *et al*. (2001) reported significantly greater increases in knee extensor strength after two years of twice-weekly RT in school children (9.2 ± 0.3 years) compared to children (9.4 ± 0.3 years) who continued to only participate in standard physical education. Keiner *et al*. (2014) found additional (1 to 2 times per week) strength and plyometric training over a two-year period in 9 to 12-year-old soccer players resulted in greater improvements in lower-body power (SJ, CMJ and DJ) compared to a control group who only performed soccer training. Further, Lloyd *et al*. (2022) reported significantly larger improvements in strength and power in male children who performed RT twice-weekly (12.0 ± 1.3 years) compared to once-weekly (12.2 ± 1.3 years) and control groups (11.7 ± 1.6 years) over a six-month period. In accordance with these findings, well-structured, regularly performed RT programmes beginning in childhood can have long-term positive effects on strength and power. Therefore, knowledge of RT strategies that can further optimise the development of strength and power from childhood onwards are important to investigate.

2.3 Biological Maturation and Resistance Training

Biological age (BA) is different to that of chronological age (CA) in that BA refers to a progression towards a biologically mature state whilst CA reflects the person's actual age (Lloyd *et al*. 2014). Importantly, BA and CA can differ by up to five years (Malina, Bouchard and Bar-Or, 2004). Therefore, CA does not fully consider the individual youth athlete which can limit the specificity of the physical training stimulus prescribed (Lloyd *et al*. 2015b). Considering this fact, measuring maturation throughout youth is deemed a necessary requirement to ensure that training can be prescribed and monitored effectively (Salter *et al*. 2021). For instance, peak height velocity (PHV), a non-invasive, somatic measure, which requires measures of the individual's body stature, body mass and date of birth can be used to predict biological age (Mirwald *et al*. 2002). PHV refers to the maximum velocity of growth in stature during youth and has been used to characterise developments in performance relative to the adolescent growth spurt (Malina *et al*. 2004). Accordingly, youths can be classified as pre PHV (childhood), PHV (adolescence) or post PHV (late adolescence) to reflect their current maturity timing (Figure 1) as well as identifying those who may be maturing either early, "on time" or late (Malina *et al*. 2004). Essentially, this enables S&C coaches to use this information to categorise athletes so that training prescription can account for their biological status.

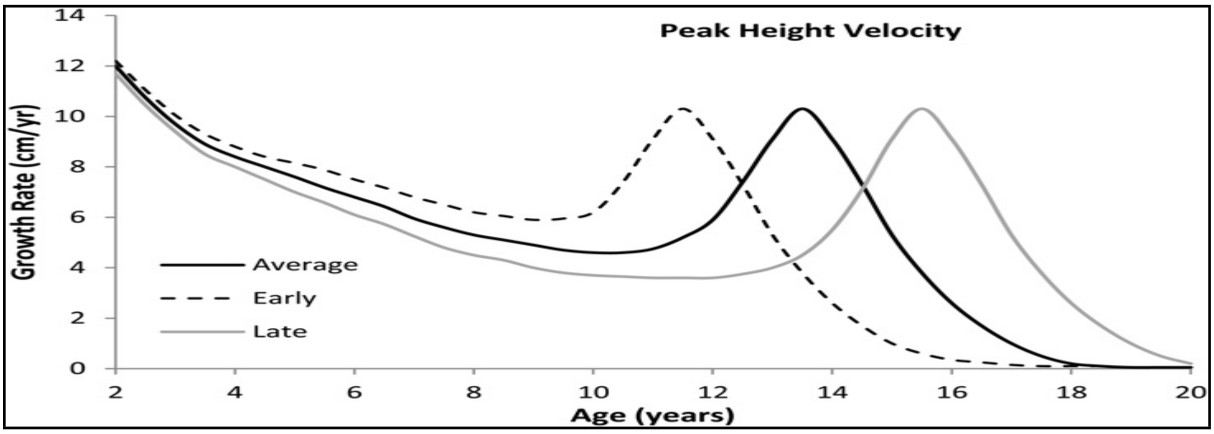

Figure 1. Change in growth rates (centimetres per year) with chronological age (years) for early-, average-, and late-maturing individuals (Lloyd et al. 2014). The assessment of PHV was used in publications three and four of this thesis.

The maturity status of a youth athlete has important implications for the prescription of RT. For instance, Moran *et al*. (2017) conducted a meta-analysis examining the influence of maturation on increases in strength in youth athletes and reported greater increases in PHV (d = 1.11) and post PHV (d = 1.01) compared to pre PHV (d = 0.50). These increased "functional" changes in more biologically mature individuals are underpinned by physiological adaptations in the hormonal, nervous, muscular-tendinous, and skeletal systems that enhance the production of force (Legerlotz *et al*. 2016). For instance, in male youth athletes, post PHV athletes possess greater levels of testosterone (Sekine *et al*. 2021), increased muscle architecture properties (Sekine *et al.* 2019), and a higher voluntary activation level (Gillen *et al*. 2021). However, despite the adaptive effects of maturation on strength, PHV also represents a time point of increased injury risk in youth athletes. This is explained by the phenomenon of "adolescent awkwardness," whereby the trunk and lower limb length increase but soft tissues have yet to adapt to the size and weight of the frame, causing abnormal movement mechanics (Sheehan and Lienhard, 2019). Indeed, during PHV youth athletes have been reported to grow in stature by 7-12 cm per year (Mirwald *et al*. 2002). Numerous studies have reported a greater occurrence of injuries during PHV compared to pre PHV in youth athletes (van der Sluis *et al*. 2014; Johnson *et al*. 2020). Thus, it is vital that RT programmes prescribed for youth athletes understand how biological maturation may influence the response to the provided training stimulus such as RT.

2.4 Long-Term Athletic Development

Long-Term Athletic Development (LTAD) focuses upon physiological principles for children and adolescents in combination with successful training methods to enhance sporting performance (Ford *et al*. 2011). For this purpose, several theoretical models have been put forward over the last three decades to support the athletic development of youth. These models include the ‘Development Models of Sports Participation’ (Côté, 1999), ‘Long-Term Athletic Development’ (Balyi and Hamilton, 2004) and the ‘Youth Physical Development’ (YPD) model (Lloyd and Oliver, 2012). Overall, these models provide a framework that promotes the need for athletic training in youth to be specific to the individual, provide a broad spectrum of training modalities and to be enjoyable (Pichardo *et al*. 2018). However, it was only the LTAD and YPD models that specifically suggested that growth and maturation should be taken into consideration to further help structure the training process in youth. In particular, in the LTAD model, the training of physical qualities was based upon the concept of “windows of opportunity” in which there are “critical periods” to target the training of certain physical qualities (e.g., strength, speed, stamina, skill and suppleness) and failure to do so will result in inhibited development and the athlete will experience a ‘‘ceiling’’ effect on performance (Balyi and Hamilton, 2004). However, this assumption has been strongly refuted as numerous studies have established that at all stages of maturation, gains in all physical qualities appear to be possible (Lloyd and Oliver, 2012).

Considering the limitations of the LTAD model, Lloyd and Oliver (2012) published the youth physical development (YPD) model (Figure 2) as a framework to target the development of all physical qualities throughout youth in conjunction with maturity status. Compared to the LTAD model, the YPD model offers many advantages due to its more holistic approach in which a broader range of physical qualities are developed (e.g., hypertrophy, power) as well as considering factors such as training status and sex. Amongst S&C coaches, the YPD model is the developmental model that most are familiar with (Till *et al*. 2022). Specifically, the YPD uses different font sizes to emphasise the importance of the physical quality, whilst the light blue boxes refer to preadolescent periods of adaptation and dark blue boxes refers to adolescent periods of adaptation. For instance, whilst pre PHV athletes can increase strength these changes are greater from PHV onwards (Moran *et al*. 2017). Hence, whilst youth athletes should train all physical qualities, at certain periods the prioritisation of some may be preferable due to their “sensitivity” for adaptation (Van Hooren and De Ste Croix, 2020). For that reason, understanding how different physical qualities can be developed at specific stages of maturation enables a greater level of specificity and individualisation of training prescription for the youth athlete.

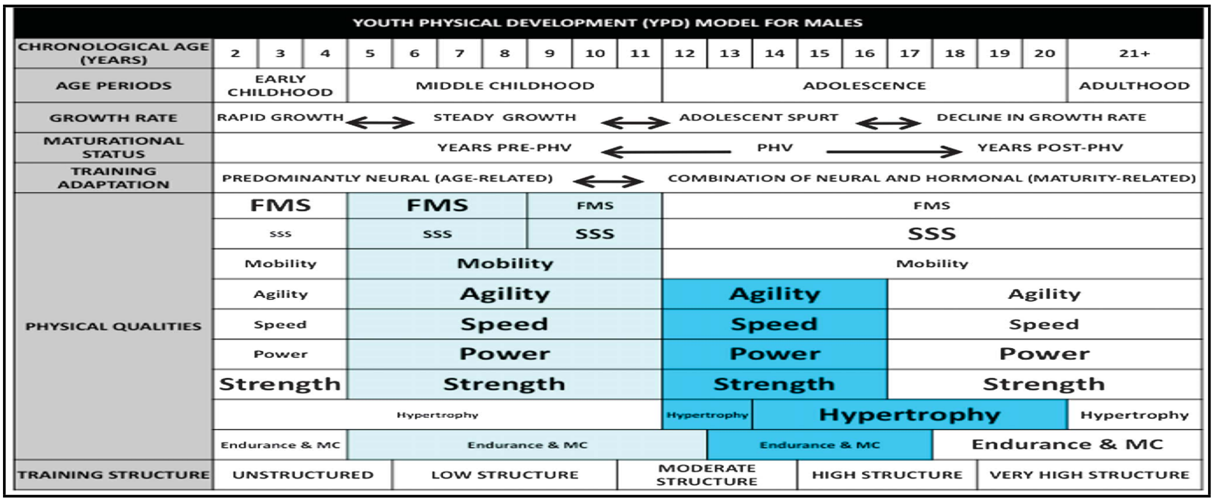

Figure 2. Youth Physical Development Model for youth males (Lloyd and Oliver, 2012).

Within the YPD model, muscular strength is to be targeted throughout youth due its underpinning of physical qualities such as agility, speed, power, and movement skills (Lloyd and Oliver, 2012). Subsequently, RT methods which can develop muscular strength throughout youth are essential for the youth athlete. However, although the development of strength and power is deemed a priority throughout all of youth (Lloyd and Oliver, 2012), the types of muscle action (i.e., concentric, isometric and eccentric) that can be used to develop strength and power is not discussed. Whilst specific discussion of muscle action types may not be the primary purpose of the YPD model, available RT guidelines for youth athletes also fail to address this and base RT prescription upon concentric intensities (Figure 3). However, strength and power can be enhanced using eccentric (Suchomel *et al*. 2019a), isometric (Lum *et al*. 2021) and isoinertial (Sakamoto *et al*. 2016) RT methods. Furthermore, different muscle actions underpin the performance of specific sporting actions. For example, whilst concentric peak knee power and concentric peak ankle power explain 57% of variation in jump height (McErlain-Naylor, King and Pain, 2014), eccentric knee extensor strength is a determinant of CoD performance (Jones, Bampouras and Marrin, 2009). As a result, the inclusion of RT methods that target the specific development of strength for different muscle action types may offer youth athletes an effective strategy to enhance performance and reduce injury risk.

Training Experience	Beginner	Intermediate	Experienced	Advanced
Volume (sets x reps)	1-2 x 8-12	2-4 x 6-10	2-4 x 5-8	2-5 x 2-5
Total number of exercises per session	6-10	3-6	3-6	2-5
Intensity (%1RM)	Body weight, or 50-70% 1RM	60-80%	70-85%	85-100%
Repetition Velocity (speed of movement)	Moderate-Fast	Moderate-Fast	Fast-Maximal	Maximal
Rest intervals (minutes)	1	1-2	2-3	2-5
Frequency (sessions per week)	2-3	2-3	2-4	2-5
Recovery (hours in between sessions)	72-48	72-48	48	48-24

Figure 3. Youth resistance training guidelines (Lloyd *et al*. 2012). The bold red box highlights the focus on prescribing RT methods in youth athletes using concentric 1RM and therefore concentric strength development.

2.5 Application of Eccentric Resistance Training for Youth Athletes

Eccentric exercise refers to the lengthening of skeletal muscle when activated as opposed to the shortening that occurs during concentric actions (Franchi *et al*. 2017). Compared to concentric actions, eccentric actions differ greatly in their neuromuscular, hormonal, and molecular response to exercise (Douglas *et al*. 2017). Forces produced during eccentric actions are greater than during concentric actions by ~20-50% (Bamman *et al*. 2001). The greater forces produced during eccentric muscle actions are suggested to be explained by factors including the number of attached cross-bridges, changes in sarcomere length storage and release of elastic potential energy in titin (Minozzo and Lira, 2013). Due to the greater forces produced during eccentric actions, RT methods require a focus on overloading the eccentric phase of the movement by using a greater load than during the concentric phase (Wagle *et al*. 2017). However, this is not possible during traditional resistance training (TRT) as the external load remains the same (e.g., 80% 1RM during the back squat exercise) throughout both descent and ascent phases of the exercise (Walker *et al*. 2016). As a result, TRT methods have an inability to sufficiently load the eccentric phase of an exercise (Suchomel *et al*. 2019b). This is an issue as without overloading the eccentric phase of the movement athletes will chronically under develop eccentric strength qualities.

Despite the potential advantages of eccentric muscle actions, a greater time to recover for both neuromuscular and peripheral factors have been found compared to other muscle action types. Greater levels of muscle damage can occur following eccentric actions explained by the disrupted sarcomeres in myofibrils and damage to the excitation–contraction (E–C) coupling system (Proske and Morgan, 2001). The myofibrils of a muscle fiber become stretched while contracting, causing the sarcomeres to become progressively weaker until there is no overlap between the myofilaments leading to membrane damage (Proske and Allen, 2005). This leads to symptoms such as strength loss, pain, swelling, stiffness, and elevations of muscle enzymes and proteins in the blood such as creatine kinase and myoglobin (McHugh and Tyler, 2019). In particular, the loss of strength is considered the most valid marker of muscle damage (Damas *et al*. 2016). Souro, Nosaka and Jubeau (2018) investigated the effects of performing eccentric versus concentric exercise of the knee extensors until a 40% reduction in maximal voluntary contraction (MVC) torque occurred and found MVC torque to only decrease post exercise in concentric (~50%) but remained depressed post four-days following eccentric exercise (~20%). In addition to these central and peripheral factors, muscle damage following eccentric exercise also negatively influences motor control with previous research reporting changes in running kinematics (Tsatalas *et al*. 2013) and jumping performance (Tsatalas *et al*. 2021). Individuals with no prior exposure to eccentric actions experience greater levels of muscle damage compared to those of trained status (Newton *et al*. 2008). Therefore, whilst eccentric muscle actions offer many benefits, its prescription for athletes needs to consider their prior exposure to the stimulus.

Previous research has urged caution for the inclusion of eccentric exercise in youth. Kilding, Tunstall and Kuzmi (2008) excluded the use of lower-body eccentric exercise in young (10.4 ± 1.4 years) male soccer players when investigating the effects of the FIFA 11 training programme on changes in strength, speed, and power. The authors stated that its exclusion was based upon physiotherapists and sports physicians not considering eccentric exercise appropriate for the age group. To date, the FIFA 11 warm up still does not include the use of lower-body eccentric exercise until 14 years of age. However, an explanation of why eccentric exercise is not perceived as appropriate in childhood is unknown. De Ste Croix, Deighan and Armstrong (2007) suggested that concerns for performing eccentric exercise in youth may be due to its potential for high muscle force production and predisposing children to a higher risk of muscle injury. However, it is well established that children and adolescents produce less force than adults (Dotan *et al*. 2013). Although, as youth athletes biologically mature their ability to produce force also increases, which elicits a concomitant increased fatigue and muscle damage response. Indeed, there is a progressive withdrawal of physiological protection against high-intensity exercise-induced fatigue during puberty (Patikas, Williams and Ratel, 2018). For example, after maximal eccentric exercise of the elbow flexor muscles, an age-dependent effect has been shown in both males and females with greater muscle damage responses and fatigue occurring from childhood to adolescence, and adolescent to adulthood (Chen *et al*. 2014; Lin *et al*. 2018). Based upon these findings, fears surrounding the inclusion of eccentric exercise in youth for aspects such as injury risk and muscle damage appear to be unfounded based upon the current literature.

2.5.1 Eccentric Overload Training for Youth Athletes

Not only is eccentric exercise appropriate for youth athletes, the development of eccentric strength qualities in youth athletes is a necessity. Indeed, the importance of eccentric strength and power qualities for performance in youth athletes has been demonstrated. Markovic *et al*. (2020) found a large inverse relationship ($r = -0.52$) between eccentric hamstring strength (EHS) and 20m sprint performance in U12–U18 trained male youth footballers. Rumpf *et al*. (2013) reported eccentric power of the lower limbs to best predict maximum sprinting velocity for pre PHV ($r^2 = 68\%$) and post PHV ($r^2 = 61\%$) young males. Harper, Jordan, and Kiely (2021) showed isokinetic eccentric quadriceps strength to have large correlations with linear deceleration ability in male youth (16.8 ± 0.9 years) soccer players. Floría *et al*. (2016) found youth rugby players (17 years) who achieved greater vertical jump height produced higher forces and rate of force development (RFD) during the braking phase of the downward movement. As such, the development of eccentric strength and power qualities in youth athletes is needed to optimise performance. Therefore, RT methods that can develop eccentric strength and power qualities are important to use by youth athletes.

A RT method that has been shown to be effective for providing eccentric overload for athletes is flywheel inertia training (FIT). During FIT, the user rotationally accelerates the flywheel during the concentric phase of the movement, resulting in flywheel kinetic energy and inertial torque that imparts high linear resistance during the succeeding eccentric phase of the movement (McErlain-Naylor and Beato, 2021). As a result, during the eccentric phase of the movement a breaking eccentric muscle action (Figure 4) must be performed by the athlete to resist the pull of the flywheel (Maroto-Izquierdo, García-López and de Paz, 2017). Furthermore, when using FIT devices such as the kBox (Figure 4), previous research has shown using heavier inertia wheels enables greater eccentric overload to be produced (Carroll *et al*., 2019) with both high construct (Bollinger *et al*. 2020) and criterion (Weakley *et al*. 2019) validity previously reported. Compared to TRT, FIT has been shown to result in greater muscle activation (Alkner and Bring, 2019), increased fascicle length (Presland *et al*.

2020) and increased muscle thickness (Maroto-Izquierdo *et al*. 2017). These results are likely due to the greater mechanical loading that is provided via the eccentric muscle action during FIT which generates greater force output, increased work completed and lower energy expenditure (Douglas *et al*. 2017). Raya-González *et al*. (2021a) conducted a meta-analysis on the effects of FIT on main sporting actions and reported improvements in jumping (d = 0.65), sprinting (d = 1.33) and change of direction (d = 1.36). However, whilst the inclusion criteria required studies to include a control group, several control groups included in the analysis completed their normal sport training, not RT. Therefore, the benefits of FIT compared to TRT in athletic populations are not entirely clear and this methodological issue (i.e., no RT for the control groups) has been raised (Beato and Iacono, 2020).

Figure 4. Posterior view of the bilateral squat being performed on the kBox flywheel inertia device by one of the participants in publication six included for this thesis. The player is at the bottom phase of the squat following the eccentric overload being provided by the flywheel which is located at the front of the system and then attached to athlete from the cable to the harness.

In youth athletes, the benefits of FIT compared to TRT are also unclear. Whilst many studies have reported increases in lower-body strength, power and speed measures following FIT, the control groups did not complete any form of RT (Raya-Gonzalez *et al*. 2021b; Suarez-Arrones *et al*. 2018; De Hoyo *et al*. 2015a). Additionally, although other studies have attempted to compare FIT versus TRT on changes in strength and power in youth athletes, the prescribed exercises in the FIT or TRT programmes were completely different and therefore comparisons regarding their effectiveness cannot be made (Fiorilli *et al*. 2020; Nuñez *et al*. 2019; Di Cagno *et al*. 2020). However, Stojanović *et al*. (2021) compared the effects of eight-weeks equal volume FIT versus TRT in well-trained male youth basketball players (17 years). Both groups performed the half-squat and Romanian deadlift exercises with the FIT using an inertia load of 0.075 $kg \cdot m^2$ and the TRT performing the exercises at 85% 1RM. The authors reported greater improvements in CMJ height, CoD performance and 5 m sprint time in the FIT group but no differences in the changes in maximal strength between groups. Westblad *et al*. (2021) also directly compared the effects of FIT versus TRT over a four-week period in youth athletes (11.8 ± 0.9 years) from an athletic club on SJ height, CMJ height and sprint performance. The FIT performed the squat using an inertia load of 0.025 $kg \cdot m^2$ to 0.05 $kg \cdot m^2$ whilst the TRT group used a load between 10-75 kg. Results showed only significant improvements for SJ height with changes similar in both groups.

Overall, due to the small number of FIT studies in youth athletes conducted, the lack of studies directly comparing the effects of FIT versus TRT, the equivocal findings of these and the lack of unilateral exercises included within training programmes, further research is required to establish the effectiveness of this method for youth athletes. Furthermore, Sabido, Hernández-Davó and Pereyra-Gerber (2018) reported that at least three familiarisation sessions are needed for stable measures to be obtained during FIT in adult athletes. Comparatively, the Westblad *et al*. (2021) and Stojanović *et al*. (2021) studies barely met this criteria (three and two sessions, respectively) meaning that potentially a large portion of the training programme their participants undertook was spent further familiarising themselves with the device and equipment rather than ahdering to the RT principles of progression and overload. Therefore, it is vital that training studies implementing FIT, especially in youth athletes who likely already have lower RT experience compared to adult athletes, are afforded sufficient time to become accustom to this method of training prior to the beginning of the intervention.

2.5.2 Eccentric Hamstring Training for Youth Athletes

The development of EHS in youth athletes may also have important implications for the prevention of hamstring strain injuries (HSI). Athletes with lower levels of EHS have been shown to be more than four times more likely to sustain a HSI compared to those with greater EHS (Opar *et al*. 2015; Timmins *et al*. 2016). Whilst research examining the association between EHS and HSI in youth athletes is limited, long-term retrospective studies have shown HSI to be the most burdensome injury type in 12 to 18-year-old sprinters (Martinez-Silván *et al*. 2020) and the hamstring muscles to be the most frequent anatomical site of injury in elite academy soccer players (Raya-González *et al*. 2020). It is unsurprising that HSI are highly prevalent in youth athletes who participant in sports which include high levels of sprinting and high-speed running. Indeed, HSI often occurs in running sports during explosive actions such as sprinting (Entwisle *et al*. 2017). These injuries have been suggested to occur during sprinting mainly in the late swing phase in which the hamstrings are highly activated at longer lengths and therefore create high levels of stress on the musculotendinous [MTU] (Chumanov, Heiderscheit and Thelen, 2011). Since the hamstrings are at greater risk when performing lengthening actions, the inclusion of exercises which target the development of EHS are recommended for athletes (Bourne *et al*. 2018). However, literature surrounding the use of eccentric hamstring exercises for youth athletes is sparse.

An eccentric hamstring exercise which has received large attention in the literature for athletes is the Nordic hamstring exercise (NHE). During the NHE, athletes kneel on the floor in an upright posture with their ankles secured in place before then gradually lowering their upper body to the floor by contracting the hamstrings (Figure 5). During the NHE, the hamstrings have been shown to actively lengthen (Raiteri, Beller and Hahn, 2021). Furthermore, whilst the NHE selective activates the semitendinosus (ST), it also more strongly activates the biceps femoris (BF) higher than any other hamstring exercise (Bourne *et al*. 2017). As the NHE affords the ability to replicate the lengthening action of the hamstring muscles during sprinting, it makes for an effective injury prevention exercise. Indeed, a meta-analysis by van Dyk, Behan, and Whiteley (2019) reported the NHE to reduce HSI by up to 51% in athletic populations. Moreover, the NHE offers multiple purposes for injury prevention. For instance, the NHE can be used to reliably (CV = 5.8-8.5%) assess EHS in adult athletes (Opar *et al*. 2013). However, its reliability in youth athletes is yet to be determined. Further, low EHS assessed by the NHE have been associated with future HSI in athletes (Opar *et al*. 2015; Timmins *et al*. 2016). Additionally, short hamstring fascicle length, a risk factor for HSI (Timmins *et al*. 2016) has been found to significantly increase following NHE training interventions in athletes (Pollard *et al*. 2019; Alonso-Fernandez, Docampo□Blanco, and Martinez□Fernandez, 2018). Finally, a meta-analysis by Bautista *et al*. (2021) which examined the literature pertaining to the effects of the NHE on sprint performance in athletes reported beneficial effects. Overall, the NHE offers many benefits for both injury prevention and performance factors.

Figure 5. Technique of the Nordic hamstring exercise (NHE) being performed by one of the participant's during publication four included for this thesis - the same exercise was also performed in publications three and five included in this thesis.

Several studies over the last decade have shown the NHE to improve EHS in youth athletes. Tansel *et al*. (2008) reported a significant increase (d = 0.61) in isokinetic eccentric hamstring peak torque in 10-12-year-old male basketball players following five-weeks of performing the NHE at a frequency of 1-3 times per week, 2-3 sets and 5-12 repetitions, with no inter-set rest interval (ISRI) reported. Freeman *et al*. (2019) reported small (d = 0.39) improvements in eccentric hamstring peak force in young males and female team sport athletes (16.21 ± 1.34 years) following four weeks of twice per week NHE using 2-3 sets, 4-6 reps and three minutes of IRSI. Lacome *et al*. (2020) investigated the effects of using either a weekly high (4 sets x 6 reps) or low (1 set x 6 reps) volume 12-week NHE programme in elite youth male soccer players (17 years) and found moderate increases in eccentric hamstring peak force for both low (d = 1.18) and high (d = 0.63) groups, with no ISRI reported. Whilst the aforementioned studies demonstrate the benefits of using the NHE in youth athletes to increase EHS, a number of other studies have reported the NHE to be effective for enhancing physical qualities in youth athletes, although these did not measure changes in EHS (Rey *et al*. 2017; Álvarez-Ponce and Guzmán-Muñoz, 2019; Hammami *et al*. 2020; Panagoulis *et al*. 2020). Based upon these results, the use of the NHE appears to be an effective exercise to increase EHS in youth athletes. However, few studies have been conducted so far that have specifically examined changes in EHS. None of the previous studies to date have examined the influence of maturation of EHS changes following the NHE and provide incomplete information regarding training prescription variables (e.g., no ISRI noted). At this time, important information regarding how to prescribe the NHE effectively for youth athletes is still missing.

2.6 Limitations of Current Research

Despite the potential benefits of youth athletes developing eccentric strength and power qualities, limited research exists regarding how ERT can be applied for youth athletes. Granacher *et al*. (2016) proposed a conceptual model for the inclusion of RT which included the training prescription of ERT. However, the model has several limitations that require addressing. Firstly, the model suggested that ERT should **only begin once the youth athlete enters adolescence.** This is somewhat questionable considering that other RT methods such as plyometric training, which requires high levels of eccentric forces to be produced (Kipp *et al*. 2019) are prescribed for youth athletes. Secondly, the model did not provide details regarding **exercise selection** for ERT in youth athletes. Lastly, the model provided no information for RT variables such as **reps, sets and rest periods**. Therefore, whilst the model should be commended for its recognition that youth athletes should perform ERT, further work is needed to generate **evidence-based training guidelines** for its use. By doing so, S&C coaches will be provided with evidence-based guidelines for how to achieve this. For instance, whilst the training methods outlined in the previous sections such as FIT and the NHE offer viable solutions for youth athletes to use, **further research** is still required to examine how these methods can be optimally prescribed for elite youth athletes.

Few studies have reported positive effects in using FIT and the NHE in youth athletes, and questions remain concerning their **training prescription**. For instance, researchers have regularly not assessed **changes** in EHS following NHE training or studied the influence of **maturity status** on EHS. This is problematic due to the lack of an outcome measure being able to directly assert the **efficacy** of NHE in youth athletes. Moreover, since maturation influences changes in strength and power following TRT, how this affects the **magnitude** of changes to ERT is still largely untested. Previous research has not examined the reliability of field-based devices to assess **EHS** in elite youth athletes. Since financial, time and staff factors are barriers for implementing injury prevention exercises for youth athletes, more evidence is needed regarding cost-effective methods to **reliably** measure EHS in youth athletes. From the small number of FIT studies that have been conducted in youth athletes, the majority have not made **direct comparisons** to TRT. Also, the training programmes utilised in these studies **lacked a holistic approach** of including bilateral, unilateral and hamstring exercises to develop a range of AMSC. Therefore, research examining the effects of well-designed FIT vs ecologically valid TRT programmes in youth athletes is required.

3.0 STRUCTURE OF INCLUDED PUBLICATIONS

To support the reading of the included peer reviewed publications for this thesis, the information provided throughout **Chapter 4** to **Chapter 9 (Publications 1-6)** has been structured with the objective to make it clear to the reader how the studies link together and their contributions to the literature. This includes the background of the study, aim of the study and the main findings from the study. By establishing how the studies form a cohesive body of work to answer the overarching aims of this thesis this should enable the reader to see how the collective studies offer novel contributions to literature. Publications in this thesis have been ethically approved, peer reviewed by industry experts and published in recognised journals that hold a registered impact factor or CiteScore. As a result, this has enabled a number of high-quality outputs to be produced in which both researchers and S&C coaches from around the world access to these works. Furthermore, despite the relatively early age of the included publications, they have received numerous citations (~20) and full text reads (~3,000 on ResearchGate alone) which demonstrates their significance and impact so far within my field. Whilst the following chapters aims provide a succinct overview of each publication, the reader is directed to the full version of each study which can be found at the end of this thesis document or by accessing the DOI link found on page number six of this thesis.

CHAPTER 4 - PUBLICATION ONE OVERVIEW

ECCENTRIC RESISTANCE TRAINING IN YOUTH: PERSPECTIVES FOR LONG-TERM ATHLETIC DEVELOPMENT

Background

Previous research has widely reported the benefits of RT in youth athletes for enhancing athletic performance but has considered the prescription of ERT. To this end, no previous research had critically appraised the responses to eccentric exercise in youth, reviewed the topic area in general or provided guidelines for the implementation of ERT in youth athletes. Unfortunately, this has led to limited information detailing the benefits, risks, and considerations for the use of ERT in youth athletes. In **Chapter 4** a narrative review was completed to critically appraise the current literature regarding the efficacy of ERT in youth athletes. Findings from this study would build upon existing evidence within the topic area whilst providing new perspectives for the practical use of ERT for youth athletes.

What was the central aim of the study?

What are the responses to eccentric exercise in youth and is ERT effective for youth athletes to enhance performance and reduce injury risk? This question addressed **Aim 1** of the thesis.

What were the main findings and their contribution to the topic area?

- Current research indicates children and adolescents experience lower levels of muscle damage and neuromuscular fatigue following the cessation of eccentric exercise compared to adults.
- Eccentric strength and power qualities are important for youth athletes to develop as they are associated with athletic movement competency tasks (e.g., sprinting, jumping, CoD) that underpin successful sporting performance.
- This study provided new knowledge to S&C coaches and researchers via evidence-based training guidelines for landing mechanics, FIT and eccentric hamstring training in youth athletes for enhancing performance and reducing injury risk.
- Further research is required to understand the implementation of ERT in youth athletes as well as how biological maturation may influence training adaptations.

CHAPTER 5 - PUBLICATION TWO OVERVIEW

ECCENTRIC RESISTANCE TRAINING IN YOUTH: A SURVEY OF PERCEPTIONS AND CURRENT PRACTICES BY STRENGTH AND CONDITIONING COACHES

Background

The findings from **Chapter 4** demonstrated that the inclusion of ERT is a safe and effective method for enhancing athletic performance and reducing injury risk factors in youth athletes. However, the current use of ERT methods in youth athletes by S&C coaches was unknown. In comparison, knowledge of the practices of ERT in adult athletic populations had already been surveyed (Harden *et al*. 2020; McNeill *et al*. 2020). Since the narrative review was the first study to address the topic area, it was therefore unclear how ERT was being implemented for youth athletes. **Chapter 5** looked to build upon the findings from the previous chapter by 'bridging' the gap between theory and practice by surveying current perceptions and practices of ERT in youth athletes by S&C coaches. Findings from this study would contribute new data to the literature by filling an information gap relating to the prescription of ERT for youth athletes. It would also help establish new questions regarding the challenges faced in implementing ERT for youth athletes.

What was the central aim of the study?

To determine S&C coaches current; (1) perceptions of ERT in youth athletes; (2) implementation of ERT in youth athletes; (3) training prescription of ERT in youth athletes; (4) barriers for the use of ERT in youth athletes. This question addressed **Aim 2** of the thesis.

What were the main findings and their contribution to the topic area?

- S&C coaches place high importance on developing eccentric strength in youth athletes with the main reason for its use being injury prevention, although most S&C coaches do not begin prescribing ERT until post-PHV.
- ERT methods used for youth athletes mainly focus upon body weight and machine-based exercises with TRT more frequently used compared to ERT.
- S&C coaches highlighted further research is required to generate practical guidelines to support the inclusion of ERT in youth athletes.
- The data from this study can address specific areas noted by S&C coaches to enhance the practical application of ERT in youth athletes.

CHAPTER 6 - PUBLICATION THREE OVERVIEW

THE INFLUENCE OF MATURATION ON THE RELIABILITY OF THE NORDIC HAMSTRING EXERCISE IN MALE YOUTH FOOTBALLERS

Background

The findings from **Chapter 5** provided novel information regarding how S&C coaches currently implement ERT for youth athletes as well as the challenges they face in doing so. S&C Coaches highlighted a) the need for normative data on eccentric strength b) use of cost-effective ERT methods c) eccentric hamstring training. Considering the high risk of hamstring injuries in youth athletes, methods of reliably measuring EHS offer the opportunity to potentially identify at risk individuals. **Chapter 6** builds upon the questions raised by respondents in the previous chapter by assessing the reliability of a field-based device to measure EHS in elite youth athletes of different maturity status. Findings from this study would contribute new methods of assessing EHS in youth athletes and provide new data for EHS from an elite youth athlete sample.

What was the central aim of the study?

Can EHS in elite youth athletes be reliably assessed during the NHE by a field-based hamstring device and does maturity status influence this? This question addressed **Aim 3** of the thesis.

What were the main findings and their contribution to the topic area?

- EHS can be measured reliably in both pre PHV and mid-post PHV elite youth soccer players using a field-based device.
- EHS asymmetries were found not to be reliably assessed and therefore caution is needed in reporting this metric in youth athletes.
- Normative data for EHS in elite level youth soccer players was produced which can be used by S&C coaches and researchers for making comparisons.
- Since EHS can be reliably measured by a field-based device during the NHE, further research is needed to determine if the NHE can generate meaningful changes in EHS following a training intervention in elite youth athletes.

CHAPTER 7 - PUBLICATION FOUR OVERVIEW

INFLUENCE OF MATURATION STATUS ON ECCENTRIC HAMSTRING STRENGTH IMPROVEMENTS IN YOUTH MALE SOCCER PLAYERS AFTER THE NORDIC HAMSTRING EXERCISE

Background

Findings from **Chapter 6** demonstrated that a field-based device could reliably measure EHS during the NHE in a sample of elite level youth athletes of different biological maturation. Previously, research had identified the high incidence of hamstring injuries in youth athletes as well as the association between EHS and sporting tasks such as sprinting. In adult athletes, numerous studies had shown the effectiveness of the NHE for increasing EHS. However, in youth athletes, studies investigating the effects of the NHE on EHS were sparse and many of these studies did not measure EHS. Moreover, research had not investigated the influence of maturity status on EHS changes following eccentric hamstring training. **Chapter 7** aimed to build upon the findings from the previous chapter by investigating the influence of maturity status on EHS following a six-week NHE programme in elite level youth athletes. Findings from this study would provide new information regarding the training prescription of the NHE in youth athletes for increasing EHS.

What was the central aim of the study?

Does the NHE increase EHS in elite level youth athletes and could maturity status (pre PHV vs mid-post-PHV) influence the magnitude of the improvement? This question addressed **Aim 1** and **Aim 3** of the thesis.

What were the main findings and their contribution to the topic area?

- Six-weeks of NHE can increase EHS in elite level youth athletes.
- Maturity status influences the increase in EHS with less biologically mature athletes increasing EHS to a greater magnitude compared to more biologically mature athletes.
- The NHE can increase EHS in elite youth athletes and it is appropriate to begin during pre PHV. Therefore, the reps and sets used in the study can be prescribed to increase EHS in youth athletes.
- Further research is required to understand how NHE training prescription for more biologically mature youth athletes can be optimised to increase EHS.

CHAPTER 8 - PUBLICATION FIVE OVERVIEW

EFFECTS OF DIFFERENT INTER-SET REST INTERVALS DURING THE NORDIC HAMSTRING EXERCISE IN YOUNG MALE ATHLETES

Background

Findings from **Chapter 7** showed for the first time that the NHE can increase EHS in both pre and mid-post PHV youth athletes. Interestingly, greater changes in EHS were found in less biologically mature players. This is largely contrary to other research examining strength and power changes following RT in youth athletes in which more biologically mature athletes demonstrate greater improvements. Previous literature has found more biologically mature individuals require a longer inter-set rest interval (ISRI) to recover and maintain force production during RT compared to less biologically mature athletes which can be explained by the greater levels of forces they produce and their lower reliance on aerobic metabolism for energy demands. In **Chapter 7**, the ISRI was the same for both maturity groups and this may have affected improvements in EHS for the mid-post PHV group. Therefore, to expand upon the findings from the previous chapter, **Chapter 8** compared the effects of using either a short (one-minute) or long (three-minute) ISRI during the NHE on EHS in elite adolescent male athletes. Findings from this study would provide new information specifying how the NHE could be optimally configured to increase EHS in youth athletes.

What was the central aim of the study?

Does the length of the ISRI impact eccentric hamstring force production during multiple sets of the NHE? This question addressed **Aim 1** and **Aim 3** of the thesis.

What were the main findings and their contribution to the topic area?

- A short ISRI is sufficient to maintain peak force-production qualities and inter-limb asymmetries between multiple sets of the NHE in well-trained youth athletes.
- Peak eccentric hamstring force can significantly decrease from repetition four onwards during a set of the NHE in both dominant and non-dominant limbs.
- The findings from this study provides new knowledge of how to prescribe the NHE in youth athletes. S&C coaches can use the rest periods outlined in this study to optimise the set configuration for the NHE.
- Further research is required to investigate the longitudinal changes in EHS strength using either a short or long ISRI as well as different set configurations.

CHAPTER 9 - PUBLICATION SIX OVERVIEW

COMPARISON OF SHORT-TERM FLYWHEEL VERSUS TRADITIONAL RESISTANCE TRAINING IN ELITE ACADEMY MALE RUGBY UNION PLAYERS

Background

In **Chapter 4**, evidence-based guidelines of FIT for youth athletes were put forward based upon contemporary research available at the time. In **Chapter 5**, S&C coaches stated they used FIT to develop eccentric strength in youth athletes as well as commenting that further research was needed to determine ERT guidelines in youth athletes. Whilst literature examining the effects of FIT in youth athletes exists, only a limited number of studies have been conducted. However, most of these studies only compared FIT to a control group that did not perform any form of RT. Moreover, the studies which did directly compare FIT versus TRT in youth athletes have not unanimously shown FIT to be superior to TRT or used elite level youth athletes as their participants. Furthermore, the familiarisation period of these studies may not have been long enough to establish if improvements were because of the training intervention. **Chapter 9** aimed to address this issue by comparing the effects of a four-week training programme of FIT versus TRT in elite youth athletes. Findings from this study would contribute new information regarding the training prescription of FIT to increase lower-body strength and power in youth athletes.

What was the central aim of the study?

Does FIT result in greater increases in lower body strength and power (e.g. CMJ height, SJ height, RSI) compared to TRT in elite academy rugby union players? This question addressed **Aim 1** and **Aim 4** of the thesis.

What were the main findings and their contribution to the topic area?

- Both FIT and TRT increased lower-body strength and power in elite academy rugby union players and therefore can be prescribed for adolescent athletes.
- Whilst changes in strength and power measures were similar between groups, the TRT displayed slightly greater magnitudes of improvements for most variables.
- Since only a small number of published FIT interventions in youth athletes exist, the programme used here provides specific guidelines for how FIT can be effectively prescribed in elite youth athlete settings.

CHAPTER 10 – DISCUSSION

10.1 General Summary

Based on the results presented in this body of work, the inclusion of ERT for youth athletes should be considered a safe and effective method to develop strength and power qualities. Whilst S&C coaches may prefer to begin the use of ERT methods later in adolescence, its inclusion is appropriate from childhood if it is appropriately prescribed and supervised. Indeed, children and adolescents experience less muscle damage and fatigue following eccentric exercise than adults. Further, eccentric strength and power qualities underpin many sporting movements that youth athletes are encouraged to develop and are associated with performance in these (e.g. jumping, sprinting, CoD). Therefore, S&C coaches should look to implement ERT throughout all stages of youth to help develop strength and power qualities aligned with the YPD model and they can use the training prescription guidelines outlined in the narrative review to guide them in this. S&C coaches can use the NHE in youth athletes for both reliably assessing and increasing EHS. This offers multiple benefits for both testing, injury prevention and performance purposes. In particular, should the aim be to develop the EHS of youth athletes, the NHE can be implemented from childhood with positive benefits occurring within a relatively short time frame (e.g., < six weeks). However, more biologically mature athletes may require a more tailored NHE programme and therefore manipulating training variables such as the ISRI, training volume or intensity are likely required. The superiority of FIT compared to TRT for increasing strength and power in youth athletes is still unclear. Nevertheless, the inclusion of FIT is an effective strategy for increasing strength and power in elite youth athletes who have had no prior exposure to eccentric training. Therefore, FIT offers an alternative viable option for youth athletes. S&C coaches may prescribe FIT once or twice per week using bilateral, unilateral, and posterior-chain exercises with TRT also included to target specific concentric power and velocity qualities. Overall, these findings enable research-informed decisions to be made regarding the training prescription of ERT methods for youth athletes. By doing so, developments in strength and power will occur which can positively influence physical performance and injury risk factors. Furthermore, the future generation of RT guidelines for youth athletes must also emphasise and consider the development of both ERT and TRT methods.

This current thesis outlined a series of aims in **Chapter 1 (section 1.2)** that have been achieved in **Chapters 4-9 (publications 1-6)**:

10.1.2 Aim 1 Summary - Critically appraise the efficacy of ERT for youth athletes and provide evidenced-based guidelines for its implementation in youth athletes. TRT methods to improve strength and power in youth athletes had been well established. However, previous research had primarily investigated TRT modalities that emphasised optimally loading the ascent (concentric) phase of an exercise. Contrastingly, the use of ERT in which the eccentric phase of the movement is overloaded compared to the concentric phase of the movement was less understood. Therefore, **Chapter 4** reviewed; the current literature surrounding the role of eccentric strength and power qualities for sporting performance in youth athletes; analysed the acute and chronic physiological responses to eccentric muscle actions in youth; and critically appraised current research that had investigated the effects of ERT methods on athletic performance in youth populations. The narrative review highlighted that eccentric strength and power qualities underpin several Athletic Movement Skill Competencies (AMSC) such as landing, jumping, sprinting and change of direction. Additionally, reviewing the previous literature regarding the physiological responses to eccentric exercise in youth, it is clear that children and adolescents are no more susceptible to muscle damage and fatigue following eccentric exercise when compared to adults. Finally, whilst a limited number of studies existed which had investigated the effects of ERT modalities on performance in youth athletes, those that had been conducted showed positive improvements in both physical qualities and injury risk measures. For the first time, a number of evidence-based training guidelines for the inclusion of ERT methods for youth athletes have been provided that offer specific evidence-based examples of how these methods can be progressed in accordance with maturity status.

10.1.3 Aim 2 Summary - Survey the current perceptions and practices of ERT in youth athletes by Strength and Conditioning Coaches. In adult athletic populations, the implementation of ERT by S&C coaches had been well documented. However, this knowledge did not exist for youth athletes. This was important to address since ERT research conducted in adult athletic populations does not, and should not, be attempted to be transferred to youth athletes. Chapter 5 gained an understanding of the current perceptions, practices, and barriers of ERT in youth athletes by S&C coaches. A total of 64 respondents completed an Online survey in which several novel and important factors were found. The findings showed that whilst S&C coaches agreed it was important to include ERT for youth athletes, most began including ERT in pre peak height velocity (PHV). The main reason for including ERT was for injury prevention purposes with training age and strength levels being considered a higher prerequisite for youth athletes to possess compared to when beginning TRT, respectively. Additionally, to implement ERT for youth athletes, respondents noted that they primarily used bodyweight, tempo, and free weights methods. Overall, the results from this study enabled a detailed understanding of the current knowledge, prescription and barriers faced for the implementation of ERT in youth athletes as well as several areas that required further investigation. These findings can be used by both researchers and S&C coaches to improve the implementation of ERT in youth athletes moving forwards.

10.1.4 Aim 3 Summary - Investigate the usefulness of the NHE to assess and develop EHS in elite youth athletes. Previous research had questioned the efficacy of prescribing eccentric hamstring exercises for youth athletes (Kilding *et al*. 2008). However, higher levels of EHS have been associated with both enhanced performances on sporting tasks and the lowering of injury risk factors in youth athletes. Consequently, the assessment and inclusion of exercises which increase EHS in youth athletes should be of high importance. However, limited research existed investigating the assessment and training prescription of EHS in youth athletes and the influence of maturity status on changes in eccentric strength. Therefore, **Chapter 6** examined the reliability of a field-based device (NordBord) during the NHE to measure EHS in an elite youth athlete sample. Results showed that the NHE could reliably assess bilateral eccentric hamstring strength for both pre PHV (TE = 8.4N, CV% = 4.9%) and post PHV (TE = 18.4N, CV% = 7.3%) groups. The results of **Chapter 6** served as a basis for **Chapter 7** in which the effects of a six-week NHE training programme on EHS in elite male youth athletes of different maturity status were investigated. Results showed moderate and large increases in bilateral EHS in both pre PHV (d = 0.83) and post PHV (ES = 0.53) groups. Due to the results in **Chapter 7** regarding less biologically mature athletes responding more positively to the NHE, **Chapter 8** investigated the effects of prescribing either a short (one minute) or long (three minute) inter-set rest period ISRP on eccentric hamstring force production during the NHE. Overall, results showed that the inclusion of a one-minute inter-set rest interval during multiple sets of the NHE was sufficient to maintain force production. However, results also showed that during the NHE peak force began to significantly decrease after three repetitions.

Cumulatively, the findings from **Chapters 6, 7 and 8** show the usefulness of the NHE to assess and increase EHS in youth athletes, with results providing specific information regarding important training prescription variables (i.e., volume and ISRI) for the exercise.

10.1.5 Aim 4 Summary - Compare the effects of eccentric overload training to traditional resistance training in elite youth athletes. TRT is an effective method to increase lower-body strength and power measures in youth athletes. However, a number of AMSC that youth athletes are required to possess are underpinned by eccentric forces. Additionally, eccentric strength is reported to be up to 50% greater than concentric. Therefore, prescribing RT methods that can provide eccentric overload for youth athletes should be of key interest for S&C coaches. However, whilst previous research had investigated the effects of using FIT to provide eccentric overload in youth athletes, this research has a number of limitations to their study design (e.g., lack of a control group), population (e.g. non-elite youth athletes) used and the overall small number of studies which have been conducted. Therefore, **Chapter 9** addressed these issues by comparing the effects of performing four-weeks of FIT or TRT in elite academy rugby union players on changes in lower-body strength and power measures. Results found increases in SJ height, CMJ height and the RSI in both FIT and TRT groups. However, the magnitude of the effects for many of the collected variables were marginally greater in the TRT group. It was found that FIT and TRT are effective in increasing lower-body strength and power qualities in elite youth athlete populations, although further research is required to determine the optimal prescription of FIT and its combination with TRT during the micro and meso-cycle.

10.2 Directions for Future Research

The peer reviewed publications included within this thesis provide significant data regarding the use of ERT for youth athletes. Despite the novel contributions to the literature presented, further research avenues exist which align with a) limitations of the included work b) practitioner responses from the undertaken survey c) recently published work within the topic area. Therefore, to further expand on the topic area of ERT for youth athletic populations, further research areas are proposed to continue to develop this area which are outlined below.

Effects of ERT on performance and injury risk factors in female youth athletes. The current body of work has contributed new knowledge and understanding of using ERT for youth male athletes. However, further research is still required to understand its benefits for youth female athlete populations. As highlighted in the narrative review from **Chapter 4**, youth females display "risky" landing mechanics that is associated with weak eccentric hamstring strength from childhood (Wild, Steele and Munro, 2013). Furthermore, compared to youth male athlete's, females have been shown to exhibit greater landing forces at all stages of maturation (Quatman *et al*. 2006). Therefore, future research should aim to investigate the effects of ERT methods to enhance performance and reduce injury risk in youth female athletes. Such research should focus on the implementation of long-term training studies to compare the effects of ERT to normal training or other forms of RT in female youth athletes. To support this work, we have recently been given ethical approval by the Hartpury University Ethics Committee (ETHICS2021-62) to investigate the effects of a short-term (five weeks) ERT injury prevention programme (NHE, flywheel squats, landing mechanics and plyometric training) on performance measures (CMJ, SJ and RSI) and injury risk factors (landing forces) in adolescent female ballet athletes. The aim of this research project is to build upon the findings presented in the present thesis along with the previous meta-analysis we have published in RT for female athletes. In these studies, we highlighted the current lack of research investigating the effects of RT (Moran *et al*. 2018) and plyometric training (Moran *et al*. 2019) in youth female athletes. The findings help create further knowledge for S&C coaches to use in their day-to-day practice for a population in which a huge data gap exists as well as providing researchers with new methods that can be built upon to further develop the literature base within the topic area.

Dose-response of eccentric hamstring training in youth athletes. The results from **Chapter 7** and **Chapter 8** provided important information regarding the training prescription to develop EHS in youth athletes. However, further research is still required to determine training prescription factors relating to the development of EHS in youth athletes. Firstly, due to the wide variety of NHE training volumes reported by researchers in pre PHV athletes, an understanding of the minimal effective dose is required. This is important for S&C coaches to understand since during childhood a focus needs to be on developing a broad range of physical qualities and movement competencies. Secondly, to the author's knowledge, only one study to date has measured changes in the fascicle length of the hamstrings in youth athletic populations following eccentric hamstring training which was done in U19's elite male soccer players (Lacome *et al*. 2020). Therefore, there is a need to better understand both the functional (e.g., hamstring strength) and mechanistic (e.g. fascicle length) adaptations to NHE in youth athletes of different maturity status and how detraining affects these changes. Thirdly, the NHE is just one of many exercises that can be used to increase EHS in athletes (Oakley, Jennings and Bishop, 2018). Considering the reported lack of compliance by athletes for the NHE in sports such as soccer (Chesterton *et al*. 2021), researchers should investigate a broader range of eccentric hamstring exercises in youth athletes and report changes in both functional and mechanistic measures.

Effects of FIT on MTU function in youth athletes. In recent years, research has reported an imbalance in the MTU during maturation which may influence injuries such as patellar tendinopathy (Mersmann *et al*. 2019). It is thought that these injuries may occur due to the greater increases in muscle force compared to tendon force which places excessive strain on the patellar tendon. Recently, Mersmann *et al*. (2021) reported positive changes in pain symptoms associated with patella tendinopathy following high-intensity RT, although changes in the MTU were not observed. In adult athletic populations, FIT has been shown to positively influence the mechanical properties of the patella tendon enabling it to be more resistant to deformation (Ruffino *et al*. 2021). **Chapter 9** demonstrated that it is possible FIT may offer a viable approach for youth athletes in which increases in eccentric strength and power qualities could be achieved whilst also improving physiological parameters such as tendon stiffness enabling a more balanced MTU to be developed. Further research investigating the potential 'dual' effect of FIT on functional and MTU adaptations in youth athletic populations is encouraged to assess the efficacy of this assertion.

10.3 Conclusion

Although the use of RT to enhance athletic performance in youth athletes had been extensively investigated, a dearth of information existed regarding the use of ERT for this population. Therefore, this thesis and its accompanying peer reviewed publications, set out to provide new insights into the use of ERT for youth athletes. As a result, the findings from these studies have achieved the following i) established new practical guidelines for the implementation of ERT in youth athletes ii) enhanced understanding of the current uses and barriers of ERT for youth athletes by S&C coaches iii) generated research-informed training prescription guidelines for the NHE and FIT for youth athletes. These novel contributions to the literature offer a number of significant implications for our industry. Firstly, S&C coaches can use the findings from the studies to now competently prescribe a range of ERT methods to their youth athletes. As a result, youth athletes will benefit from a greater level of training specificity which will enhance their physical performance and reduce the risk of injury, leading to a greater likelihood of both short-term and long-term sporting success. Secondly, S&C coaches can now have knowledge that ERT is a safe and effective RT method for youth athletes and that concerns regarding the potential excessive levels of muscle damage and fatigue following its use are not supported by the literature. Thus, many S&C coaches who may not have previously utilised ERT due these such concerns will have confidence in its use and will likely prescribe this form of training to their youth athletes providing them with further opportunities to enhance their athletic performance. Thirdly, and a particularly proud aspect of this work, is the inclusivity and sustainability of the practical applications for youth athletes. This is because the included work on training aspects such as the NHE and the training of landing mechanics only require bodyweight to perform such exercises. Importantly, this ensures that this body of work has wide reaching implications for youth athletes as this work can be implemented in settings such as schools, recreational/grassroots clubs or elite organisations. Therefore, as an industry, we can use these findings to improve the physical performance, injury prevention and ultimately support the short and long-term goals of youth athletes. Indeed, moving forwards, ERT should now not be thought of as an advanced strategy for youth athletes, but rather an essential strategy that all youth athletes should be exposed to from childhood onwards.

References

Alkner, B. A. and Bring, D. K. I. (2019). Muscle activation during gravity-independent resistance exercise compared to common exercises. *Aerospace Medicine and Human Performance*, 90(6), pp.506-512.

Alonso‐Fernandez, D., Docampo‐Blanco, P., and Martinez‐Fernandez, J. (2018) Changes in muscle architecture of biceps femoris induced by eccentric strength training with nordic hamstring exercise. *Scandinavian journal of medicine and science in sports*, 28(1), pp.88-94.

Álvarez-Ponce, D. and Guzmán-Muñoz, E. (2019) Effects of a program of eccentric exercises on hamstrings in youth soccer players. *Archivos de Medicina Del Deporte*, 36(1), pp.19-24.

Balyi, I. and Hamilton, A. (2004). Long-term athlete development: Trainability in childhood and adolescence. *Olympic coach*, 16(1), pp.4-9.

Bamman, M. M., Shipp, J. R., Jiang, J., Gower, B. A., Hunter, G. R., Goodman, A., McLafferty Jr, C. L. and Urban, R. J. (2001) Mechanical load increases muscle IGF-I and androgen receptor mRNA concentrations in humans. *American journal of physiology-endocrinology and metabolism*, 280(3), pp.383-390.

Bautista, I. J., Vicente-Mampel, J., Baraja-Vegas, L., Segarra, V., Martín, F. and Van Hooren, B. (2021). The effects of the Nordic hamstring exercise on sprint performance and eccentric knee flexor strength: A systematic review and meta-analysis of intervention studies among team sport players. *Journal of Science and Medicine in Sport*, 24(9), pp.931-938.

Beato, M. and Dello Iacono, A. (2020). Implementing flywheel (isoinertial) exercise in strength training: current evidence, practical recommendations, and future directions. *Frontiers in physiology*, 11, pp.569.

Behm, D. G., Young, J. D., Whitten, J. H., Reid, J. C., Quigley, P. J., Low, J., and Granacher, U. (2017). Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: a systematic review and meta-analysis. *Frontiers in physiology*, 8, pp.423.

Behringer, M., Vom Heede, A., Matthews, M. and Mester, J. (2011). Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. *Pediatric exercise science*, 23(2), pp.186-206.

Bishop, D. (2008). An applied research model for the sport sciences. *Sports Medicine*, 38(3), pp.253-263.

Bollinger, L. M., Brantley, J. T., Tarlton, J. K., Baker, P. A., Seay, R. F. and Abel, M. G. (2020). Construct validity, test-retest reliability, and repeatability of performance variables using a flywheel resistance training device. The *Journal of Strength & Conditioning Research*, 34(11), pp.3149-3156.

Bourne, M. N., Timmins, R. G., Opar, D. A., Pizzari, T., Ruddy, J. D., Sims, C., Williams, M. D., and Shield, A. J. (2018). An evidence-based framework for strengthening exercises to prevent hamstring injury. *Sports Medicine*, 48(2), pp.251-267.

Bourne, M. N., Williams, M. D., Opar, D. A., Al Najjar, A., Kerr, G. K. and Shield, A. J. (2017). Impact of exercise selection on hamstring muscle activation. *British journal of sports medicine*, 51(13), pp.1021-1028.

Brownlee, T. E., Murtagh, C. F., Naughton, R. J., Whitworth-Turner, C. M., O'Boyle, A., Morgans, R., and Drust, B. (2018). Isometric maximal voluntary force evaluated using an isometric mid-thigh pull differentiates English Premier League youth soccer players from a maturity-matched control group. *Science and Medicine in Football*, 2(3), pp.209-215.

Carroll, K. M., Wagle, J. P., Sato, K., Taber, C. B., Yoshida, N., Bingham, G. E., and Stone, M. H. (2019). Characterising overload in inertial flywheel devices for use in exercise training. *Sports biomechanics*, 18(4), pp.390-401.

Chen, T. C., Chen, H. L., Liu, Y. C., and Nosaka, K. (2014). Eccentric exercise-induced muscle damage of pre-adolescent and adolescent boys in comparison to young men. *European journal of applied physiology*, 114(6), pp.1183-1195.

Chesterton, P., Tears, C., Wright, M., and Portas, M. (2021). Hamstring injury prevention practices and compliance of the Nordic hamstring program in English professional football. *Translational Sports Medicine*, 4(2), pp.214-222.

Chumanov, E.S., Heiderscheit, B.C., and Thelen, D.G. (2011). Hamstring musculotendon dynamics during stance and swing phases of high speed running. *Medicine and science in sports and exercise*, 43(3), pp.525-532.

Côté, J. (1999). The influence of the family in the development of talent in sport. *The sport psychologist*, 13(4), pp.395-417.

De Ste Croix, M., Deighan, M., and Armstrong, N. (2007). Functional eccentric-concentric ratio of knee extensors and flexors in pre-pubertal children, teenagers and adult males and females. *International journal of sports medicine*, 28(9), pp.768-772.

Damas, F., Nosaka, K., Libardi, C.A., Chen, T.C., and Ugrinowitsch, C. (2016). Susceptibility to exercise-induced muscle damage: a cluster analysis with a large sample. *International Journal of Sports Medicine*, 37(8), pp.633-640.

de Hoyo, M., Pozzo, M., Sañudo, B., Carrasco, L., Gonzalo-Skok, O., Domínguez-Cobo, S., and 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), pp.46-52.

di Cagno, A., Iuliano, E., Buonsenso, A., Giombini, A., Di Martino, G., Parisi, A., and Fiorilli, G. (2020). Effects of Accentuated Eccentric Training Vs Plyometric Training on Performance of Young Elite Fencers. *Journal of Sports Science and Medicine*, 19(4), 703-713.

Dotan, R., Mitchell, C., Cohen, R., Gabriel, D., Klentrou, P., and Falk, B. (2013). Child–adult differences in the kinetics of torque development. *Journal of sports sciences*, 31(9), pp.945-953.

Douglas, J., Pearson, S., Ross, A., and McGuigan M. (2017) Eccentric exercise: physiological characteristics and acute responses. *Sports Medicine*, 47(4), pp.663-675.

Drenowatz, C. and Greier, K., (2018). Resistance training in youth—benefits and characteristics. *Journal of Biomedicine*, 3, pp.32-39.

Entwisle, T., Ling, Y., Splatt, A., Brukner, P., and Connell, D. (2017). Distal musculotendinous T junction injuries of the biceps femoris: an MRI case review. *Orthopaedic Journal of Sports Medicine*, 5(7).

Faigenbaum, A. D., Lloyd, R. S., MacDonald, J., and Myer, G. D. (2016). Citius, Altius, Fortius: beneficial effects of resistance training for young athletes: narrative review. *British journal of sports medicine*, 50(1), pp.3-7.

Faigenbaum, A.D. and Myer, G.D., (2010). Resistance training among young athletes: safety, efficacy and injury prevention effects. *British journal of sports medicine*, 44(1), pp.56-63.

Fiorilli, G., Mariano, I., Iuliano, E., Giombini, A., Ciccarelli, A., Buonsenso, A., and di Cagno, A. (2020). Isoinertial eccentric-overload training in young soccer players: Effects on strength, sprint, change of direction, agility and soccer shooting precision. *Journal of sports science and medicine*, 19(1), pp.213.

Floría, P., Gómez-Landero, L. A., Suárez-Arrones, L., and Harrison, A. J. (2016). Kinetic and kinematic analysis for assessing the differences in countermovement jump performance in rugby players. *Journal of Strength and Conditioning Research*, 30(9), pp.2533-2539.

Fontana, F. Y., Colosio, A. L., Da Lozzo, G., and Pogliaghi, S. (2017). Player's success prediction in rugby union: From youth performance to senior level placing. *Journal of science and medicine in sport*, 20(4), pp.409-414.

Ford, P., De Ste Croix, M., Lloyd, R., Meyers, R., Moosavi, M., Oliver, J., and Williams, C. (2011). The long-term athlete development model: Physiological evidence and application. *Journal of sports sciences*, *29*(4), pp.389-402.

Fort-Vanmeerhaeghe, A., Romero-Rodriguez, D., Lloyd, R. S., Kushner, A., and Myer, G. D., (2016). Integrative neuromuscular training in youth athletes. Part II: Strategies to prevent injuries and improve performance. *Strength and Conditioning Journal*, 38(4), pp.9-27.

Franchi, M. V., Reeves, N. D., and Narici, M. V. (2017). Skeletal muscle remodeling in response to eccentric vs.

concentric loading: Morphological, molecular, and metabolic adaptations. *Frontiers in Physiology*, 8, pp.1–16.

Freeman, B. W., Young, W. B., Talpey, S. W., Smyth, A. M., Pane, C. L., and Carlon, T. A. (2019). The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength. *The Journal of sports medicine and physical fitness*, 59(7), pp.1119-1125.

Gabbett, T., Kelly, J., Ralph, S., and Driscoll, D. (2009). Physiological and anthropometric characteristics of junior elite and sub-elite rugby league players, with special reference to starters and non-starters. *Journal of Science and Medicine in Sport*, 12(1), pp.215-222.

Gillen, Z.M., Housh, T.J., Schmidt, R.J., Herda, T.J., De Ayala, R.J., Shoemaker, M.E., and Cramer, J.T. (2021). Comparisons of muscle strength, size, and voluntary activation in pre-and post-pubescent males and females. *European Journal of Applied Physiology*, 121(9), pp.2487-2497.

Granacher, U., Lesinski, M., Büsch, D., Muehlbauer, T., Prieske, O., Puta, C., and Behm, D. G. (2016). Effects of resistance training in youth athletes on muscular fitness and athletic performance: a conceptual model for long-term athlete development. *Frontiers in physiology*, 7, pp.164.

Granacher, U., Puta, C., Gabriel, H. H., Behm, D. G., and Arampatzis, A. (2018). Neuromuscular Training and adaptations in youth athletes. *Frontiers in physiology*, 9, pp.1264.

Hammami, R., Duncan, M. J., Nebigh, A., Werfelli, H., and Rebai, H. (2020). The effects of 6 weeks eccentric training on speed, dynamic balance, muscle strength, power, and lower limb asymmetry in prepubescent weightlifters. *Journal of Strength and Conditioning Research*.

Harden, M., Bruce, C., Wolf, A., Hicks, K. M., and Howatson, G. (2020). Exploring the practical knowledge of eccentric resistance training in high-performance strength and conditioning coaches. *International Journal of Sports Science and Coaching*, 15(1), pp.41-52.

Harper, D. J., Jordan, A. R., and Kiely, J. (2021). Relationships between eccentric and concentric knee strength capacities and maximal linear deceleration ability in male academy soccer players. *The Journal of Strength and Conditioning Research*, 35(2), pp.465-472.

Hill, A.V. (1938). The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London. Series B-Biological Sciences*, 126(843), pp.136-195.

Johnson, D. M., Williams, S., Bradley, B., Sayer, S., Murray Fisher, J., and Cumming, S. (2020). Growing pains: maturity associated variation in injury risk in academy football. *European journal of sport science*, 20(4), pp.544-552

Jones, B., Weaving, D., Tee, J., Darrall-Jones, J., Weakley, J., Phibbs, P., and Till, K. (2018). Bigger, stronger, faster, fitter: the differences in physical qualities of school and academy rugby union players. *Journal of sports sciences*, 36(21), 2399-2404.

Jones, P.A., Bampouras, T., and Marrin, K. (2009). An investigation into the physical determinants of change of direction speed. *Journal of Sports Medicine and Physical Fitness*, 49(1), pp.97-104.

Keiner, M., Sander, A., Wirth, K., and Schmidtbleicher, D. (2014). The impact of 2 years of additional athletic training on the jump performance of young athletes. *Science and Sports*, 29(4), pp.39-46.

Kilding, A. E., Tunstall, H., and Kuzmic, D. (2008). Suitability of FIFA's "The 11" training programme for young football players–impact on physical performance. *Journal of sports science and medicine*, 7(3), pp.320-326.

Kipp, K., Kiely, M. T., Giordanelli, M. D., Malloy, P. J., and Geiser, C. F. (2018). Biomechanical determinants of the reactive strength index during drop jumps. *International Journal of Sports Physiology and Performance*, 13(1), pp.44-49.

Lacome, M., Avrillon, S., Cholley, Y., Simpson, B. M., Guilhem, G., and Buchheit, M. (2020). Hamstring eccentric strengthening program: does training volume matter? *International journal of sports physiology and performance*, 15(1), pp.81-90.

Legerlotz, K., Marzilger, R., Bohm, S., and Arampatzis, A. (2016). Physiological adaptations following resistance training in youth athletes—a narrative review. *Pediatric exercise science*, 28(4), pp.501-520.

Lesinski, M., Prieske, O., and Granacher, U. (2016). Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis. *British journal of* *sports medicine*, 50(13), pp.781-795.

Lin, M. J., Nosaka, K., Ho, C. C., Chen, H. L., Tseng, K. W., Ratel, S., and Chen, T. C. C. (2018). Influence of maturation status on eccentric exercise-induced muscle damage and the repeated bout effect in females. *Frontiers in physiology*, 8, pp.1118.

Lloyd, R. S. and Oliver, J. L. (2012). The youth physical development model: A new approach to long-term athletic development. *Strength and Conditioning Journal*, 34(3), pp.61-72.

Lloyd, R. S., Faigenbaum, A. D., Myer, G. D., Stone, M., Oliver, J., Jeffreys, I., and Pierce, K. (2012). UKSCA position statement: Youth resistance training. *Professional Strength and Conditioning Journal*, 26, pp.26-39.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Howard, R., De Ste Croix, M., Williams, C. A., and Myer, G. D. (2015a). Long-term athletic development-part 1: a pathway for all youth. *The Journal of Strength and Conditioning Research*, 29(5), pp.1439-1450.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Howard, R., De Ste Croix, M., Williams, C. A., and Myer, G. D. (2015b). Long-term athletic development, part 2: barriers to success and potential solutions. *The Journal of Strength and Conditioning Research*, 29(5), pp.1451-1464.

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Myer, G. D., and De Ste Croix, M. (2014). Chronological age vs. biological maturation: implications for exercise programming in youth. *The Journal of Strength and Conditioning Research*, 28(5), pp.1454-1464.

Lloyd, R.S., Dobbs, I. J., Wong, M. A., Moore, I. S., and Oliver, J. L. (2022). Effects of Training Frequency During a 6-Month Neuromuscular Training Intervention on Movement Competency, Strength, and Power in Male Youth. *Sports Health*, 14(1), pp.57-68.

Lum, D., Barbosa, T. M., Joseph, R., and Balasekaran, G. (2021). Effects of two isometric strength training methods on jump and sprint performances: A randomized controlled trial. *Journal of Science in Sport and Exercise*, 3(2), pp.115-124.

Malina RM, Bouchard C, Bar-Or O. Growth, Maturation, and Physical Activity. Champaign, IL: Human Kinetics, 2004. pp. 41–77

Markovic, G., Sarabon, N., Boban, F., Zoric, I., Jelcic, M., Sos, K., and Scappaticci, M. (2020). Nordic hamstring strength of highly trained youth football players and its relation to sprint performance. *The Journal of Strength and Conditioning Research*, 34(3), pp.800-807.

Maroto-Izquierdo, S., García-López, D., and 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), pp.133-143.

Martínez-Silván, D., Wik, E.H., Alonso, J.M., Jeanguyot, E., Salcinovic, B., Johnson, A., and Cardinale, M. (2021). Injury characteristics in male youth athletics: A five-season prospective study in a full-time sports academy. *British journal of sports medicine*, 55(17), pp.954-960.

McErlain-Naylor, S., King, M., and Pain, M. T. G. (2014). Determinants of countermovement jump performance: a kinetic and kinematic analysis. *Journal of sports sciences*, 32(19), pp.1805-1812.

McErlain-Naylor, S.A. and Beato, M. (2021). Concentric and eccentric inertia–velocity and inertia–power relationships in the flywheel squat. *Journal of sports sciences*, 39(10), pp.1136-1143.

McHugh, M. P. and Tyler, T. F. (2019). Muscle strain injury vs muscle damage: two mutually exclusive clinical entities. *Translational Sports Medicine*, 2(3), pp.102-108.

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

McQuilliam, S. J., Clark, D. R., Erskine, R. M., and Brownlee, T. E. (2020). Free-weight resistance training in youth athletes: A narrative review. *Sports Medicine*, 50(9), pp.1567-1580.

Mersmann, F., Laube, G., Marzilger, R., Bohm, S., Schroll, A., and Arampatzis, A. (2021). A functional high-load exercise intervention for the patellar tendon reduces tendon pain prevalence during a competitive season in adolescent handball players. *Frontiers in physiology*, 12, pp.282.

Mersmann, F., Pentidis, N., Tsai, M.S., Schroll, A., and Arampatzis, A. (2019). Patellar tendon strain associates to tendon structural abnormalities in adolescent athletes. *Frontiers in Physiology*, pp.963.

Minozzo, F. C. and Lira, C. A. B. D. (2013). Muscle residual force enhancement: a brief review. *Clinics*, 68, pp.269-274.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., and Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and science in sports and exercise*, 34(4), pp.689-694.

Moran, J., Sandercock, G. R., Ramírez-Campillo, R., Meylan, C., Collison, J., and Parry, D. A. (2017). A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *Journal of sports sciences*, 35(11), pp.1041-1051.

Moran, J., Sandercock, G., Ramirez-Campillo, R., Clark, C.C., Fernandes, J.F., and Drury, B. (2018). A meta-analysis of resistance training in female youth: its effect on muscular strength, and shortcomings in the literature. *Sports Medicine*, 48(7), pp.1661-1671.

Moran, J., Clark, C.C., Ramirez-Campillo, R., Davies, M.J., and Drury, B. (2019). A meta-analysis of plyometric training in female youth: its efficacy and shortcomings in the literature. *The Journal of Strength and Conditioning Research*, 33(7), pp.1996-2008.

Murtagh, C. F., Brownlee, T. E., O'Boyle, A., Morgans, R., Drust, B., and Erskine, R. M. (2018). Importance of speed and power in elite youth soccer depends on maturation status. *The Journal of Strength and Conditioning Research*, 32(2), 297-303.

Myers, A. M., Beam, N. W., and Fakhoury, J. D. (2017). Resistance training for children and adolescents. *Translational pediatrics*, 6(3), pp.137.

Nagahara, R., Mizutani, M., Matsuo, A., Kanehisa, H., and Fukunaga, T. (2018). Association of sprint performance with ground reaction forces during acceleration and maximal speed phases in a single sprint. *Journal of Applied Biomechanics*, 34(2), pp.104-110.

Newton, M. J., Morgan, G. T., Sacco, P., Chapman, D. W., and Nosaka, K. (2008). Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *The Journal of Strength and Conditioning Research*, 22(2), pp.597-607.

Nuñez, F. J., de Hoyo, M., López, A. M., Sañudo, B., Otero-Esquina, C., Sanchez, H., and Gonzalo-Skok, O. (2019). Eccentric-concentric ratio: a key factor for defining strength training in soccer. *International journal of sports medicine*, 40(12), pp.796-802.

Oakley, A. J., Jennings, J., and Bishop, C. J. (2018). Holistic hamstring health: not just the Nordic hamstring exercise. *British journal of sports medicine*, 52(13), pp.816-817.

Opar, D. A., Williams, M. D., Timmins, R. G., Duhig, S., and Shield, A. J. (2015). Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Medicine and Science in Sports and Exercise*, 47(4).

Opar, D. A., Piatkowski, T., Williams, M. D., and Shield, A. J. (2013). A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *Journal of Orthopaedic and Sports Physical Therapy*, 43(9), pp.636-640.

Panagoulis, C., Chatzinikolaou, A., Avloniti, A., Leontsini, D., Deli, C. K., Draganidis, D., and Fatouros, I. G. (2020). In-season integrative neuromuscular strength training improves performance of early-adolescent soccer athletes. *The Journal of Strength and Conditioning Research*, 34(2), pp.516-526.

Patikas, D. A., Williams, C. A., and Ratel, S. (2018). Exercise-induced fatigue in young people: advances and future perspectives. *European journal of applied physiology*, 118(5), pp.899-910.

Pichardo, A. W., Oliver, J. L., Harrison, C. B., Maulder, P. S., and Lloyd, R. S. (2018). Integrating models of long-term athletic development to maximize the physical development of youth. *International Journal of Sports Science and Coaching*, 13(6), pp.1189-1199.

Pollard, C. W., Opar, D. A., Williams, M. D., Bourne, M. N., and Timmins, R. G. (2019). Razor hamstring curl and Nordic hamstring exercise architectural adaptations: Impact of exercise selection and intensity. *Scandinavian journal of medicine and science in sports*, 29(5), pp.706-715.

Presland, J. D., Opar, D. A., Williams, M. D., Hickey, J. T., Maniar, N., Dow, C. L., Bourne, M. N., and Timmins, R. G. (2020). Hamstring strength and architectural adaptations following inertial flywheel resistance training. *Journal of Science and Medicine in Sport*, 23(11), pp.1093-1099.

Proske, U. and Allen, T.J. (2005). Damage to skeletal muscle from eccentric exercise. *Exercise and sport* *sciences reviews*, 33(2), pp.98-104.

Proske, U., and Morgan, D. L. (2001). Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *The Journal of physiology*, 537(2), pp.333-345.

Quatman, C. E., Ford, K. R., Myer, G. D. and Hewett, T. E. (2006). Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study. *The American journal of sports medicine*, 34(5), pp.806-813.

Raiteri, B.J., Beller, R., and Hahn, D. (2021). Biceps Femoris Long Head Muscle Fascicles Actively Lengthen During the Nordic Hamstring Exercise. *Frontiers in Sports and Active Living*, 3, pp.136.

Raya-González, J., Castillo, D., de Keijzer, K. L., and Beato, M. (2021b). The effect of a weekly flywheel resistance training session on elite U-16 soccer players' physical performance during the competitive season. A randomized controlled trial. *Research in Sports Medicine*, pp.1-15.

Raya-González, J., De Ste Croix, M., Read, P., and Castillo, D. (2020). A Longitudinal Investigation of muscle injuries in an elite Spanish male academy soccer club: A hamstring injuries approach. *Applied Sciences*, 10(5), pp.1610.

Raya-González, J., Prat-Luri, A., López-Valenciano, A., Sabido, R. and Hernández-Davó, J.L. (2021a). Effects of flywheel resistance training on sport actions. A systematic review and meta-analysis. *Journal of Human Kinetics*, 77(1), pp.191-204.

Raya-González, J., Torres Martin, L., Beato, M., Rodríguez-Fernández, A. and Sanchez-Sanchez, J. (2021). The effects of training based on Nordic hamstring and sprint exercises on measures of physical fitness and hamstring injury prevention in U19 male soccer players. *Research in Sports Medicine*, pp.1-16.

Rey, E., Paz-Domínguez, Á., Porcel-Almendral, D., Paredes-Hernández, V., Barcala-Furelos, R., and Abelairas-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. *The Journal of Strength and Conditioning Research*, 31(5), pp.1198-1205.

Ruffino, D., Malliaras, P., Marchegiani, S., and Campana, V. (2021). Inertial flywheel vs heavy slow resistance training among athletes with patellar tendinopathy: A randomised trial. *Physical Therapy in Sport*, 52, pp.30-37.

Rumpf, M. C., Cronin, J. B., Oliver, J. L. and Hughes, M. G. (2013). Vertical and leg stiffness and stretch-shortening cycle changes across maturation during maximal sprint running. *Human movement science*, 32(4), pp.668-676.

Sabido, R., Hernández-Davó, J. L., and Pereyra-Gerber, G. T. (2018). Influence of different inertial loads on basic training variables during the flywheel squat exercise. *International journal of sports physiology and performance*, 13(4), pp.482-489.

Sadres, E., Eliakim, A., Constantini, N., Lidor, R., and Falk, B. (2001). The effect of long-term resistance training on anthropometric measures, muscle strength, and self-concept in pre-pubertal boys. *Pediatric Exercise Science*, 13(4), pp.357-372.

Sakamoto, A., Sinclair, P. J., and Naito, H. (2016). Strategies for maximizing power and strength gains in isoinertial resistance training: Implications for competitive athletes. *The Journal of Physical Fitness and Sports Medicine*, 5(2), pp.153-166.

Salter, J., De Ste Croix, M., Hughes, J.D., Weston, M., and Towlson, C. (2021). Monitoring practices of training load and biological maturity in UK soccer academies. *International Journal of Sports Physiology and Performance*, 16(3), pp.395-406.

Sekine, Y. and Hirose, N., (2021). Maturity-Associated Variations in Resistance Exercise-Induced Hormonal Responses in Young Male Athletes. *Pediatric exercise science*, *1*(aop), pp.1-8.

Sekine, Y., Hoshikawa, S., and Hirose, N. (2019). Longitudinal Age-Related Morphological and Physiological Changes in Adolescent Male Basketball Players. *Journal of sports science and medicine*, 18(4), pp.751-757.

Sheehan, D. P. and Lienhard, K. (2019). Gross motor competence and peak height velocity in 10-to 14-year-old Canadian youth: A longitudinal study. *Measurement in Physical Education and Exercise Science*, 23(1), pp.89-98.

Slimani, M., Paravlic, A., and Granacher, U. (2018). A meta-analysis to determine strength training related dose-response relationships for lower-limb muscle power development in young athletes. *Frontiers in physiology*, *9*, pp.1155.

Souron, R., Nosaka, K., and Jubeau, M. (2018). Changes in central and peripheral neuromuscular fatigue indices after concentric versus eccentric contractions of the knee extensors. *European journal of applied physiology*, 118(4), pp.805-816.

Stojanović, M. D., Mikić, M., Drid, P., Calleja-González, J., Maksimović, N., Belegišanin, B., and Sekulović, V. (2021). Greater Power but Not Strength Gains Using Flywheel Versus Equivolumed Traditional Strength Training in Junior Basketball Players. *International Journal of Environmental Research and Public Health*, 18(3), pp.1181.

Stone, M. H., Collins, D., Plisk, S., Haff, G., and Stone, M. E. (2000). Training principles: Evaluation of modes and methods of resistance training. *Strength and Conditioning Journal*, 22(3), pp.65-76.

Stratton G, Oliver JL. The impact of growth and maturation on physical performance. In: Strength and Conditioning for Young Athletes: Science and Application. Lloyd R.S., Oliver J.L., eds. Oxford, United Kingdom: Routledge Publishing, 2013. pp. 3–18.

Stricker, P. R., Faigenbaum, A. D., McCambridge, T. M., LaBella, C. R., Brooks, M. A., Canty, G., Diamond, A. B., Hennrikus, W., Logan, K., Moffatt, K., and Nemeth, B.A. (2020). Resistance training for children and adolescents. *Pediatrics*, 145(6), pp.137-143.

Suarez-Arrones, L., Saez de Villarreal, E., Núñez, F. J., Di Salvo, V., Petri, C., Buccolini, A., and Mendez-Villanueva, A. (2018). In-season eccentric-overload training in elite soccer players: Effects on body composition, strength and sprint performance. *PloS one*, 13(10).

Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., and Stone, M. H. (2019a). Implementing eccentric resistance training—part 1: a brief review of existing methods. *Journal of Functional Morphology and Kinesiology*, 4(2), pp.38.

Suchomel, T. J., Wagle, J. P., Douglas, J., Taber, C. B., Harden, M., Haff, G. G., and Stone, M. H. (2019b). Implementing eccentric resistance training—part 2: practical recommendations. *Journal of Functional Morphology and Kinesiology*, 4(3), pp.55.

Suchomel, T. J., Nimphius, S., and Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports medicine*, 46(10), pp.1419-1449.

Suchomel, T. J., Nimphius, S., Bellon, C. R., and Stone, M. H. (2018). The importance of muscular strength: training considerations. *Sports medicine*, 48(4), pp.765-785.

Taber, C., Bellon, C., Abbott, H., and Bingham, G. E. (2016). Roles of maximal strength and rate of force development in maximizing muscular power. *Strength and Conditioning Journal*, 38(1), pp.71-78.

Tansel, R. B., Salci, Y., Yildirim, A., Kocak, S., and Korkusuz, F. (2008). Effects of eccentric hamstring strength training on lower extremity strength of 10–12-year-old male basketball players. *Isokinetics and Exercise Science*, 16(2), pp.81-85.

Till, K., Lloyd, R., McCormack, S., Williams, G., Baker, J., and Eisenmann, J. (2022). Optimising long-term athletic development: An investigation of coaches' knowledge, adherence, practices and challenges. *PLoS One.*

Timmins, R. G., Bourne, M. N., Shield, A. J., Williams, M. D., Lorenzen, C., and Opar, D. A. (2016). Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *British Journal of Sports Medicine*, 50(24), pp.1524-1535.

Towlson, C., Salter, J., Ade, J. D., Enright, K., Harper, L. D., Page, R. M., and Malone, J. J. (2021). Maturity-associated considerations for training load, injury risk, and physical performance in youth soccer: One size does not fit all. *Journal of sport and health science*, 10(4), pp.403-412.

Tsatalas, T., Giakas, G., Spyropoulos, G., Sideris, V., Lazaridis, S., Kotzamanidis, C., and Koutedakis, Y. (2013). The effects of eccentric exercise-induced muscle damage on running kinematics at different speeds. *Journal of sports sciences*, 31(3), pp.288-298.

Tsatalas, T., Karampina, E., Mina, M. A., Patikas, D. A., Laschou, V. C., Pappas, A., Jamurtas, A. Z., Koutedakis, Y., and Giakas, G. (2021). Altered drop jump landing biomechanics following eccentric exercise-induced muscle damage. *Sports*, 9(2), pp.24.

van der Sluis, A., Elferink-Gemser, M. T., Coelho-e-Silva, M. J., Nijboer, J. A., Brink, M. S., and Visscher, C. (2014). Sport injuries aligned to peak height velocity in talented pubertal soccer players. *International journal of sports medicine*, 35(04), pp.351-355.

Van Dyk, N., Behan, F. P., and Whiteley, R. (2019). Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *British journal of sports medicine*, 53(21), pp.1362-1370.

Van Hooren, B., and De Ste Croix, M. (2020). Sensitive periods to train general motor abilities in children and adolescents: do they exist? A critical appraisal. *Strength and Conditioning Journal*, 42(6), pp.7-14.

Wagle, J. P., Taber, C. B., Cunanan, A. J., Bingham, G. E., Carroll, K. M., DeWeese, B. H., and Stone, M. H. (2017). Accentuated eccentric loading for training and performance: A review. *Sports Medicine*, 47(12), pp.2473-2495.

Walker, S., Blazevich, A. J., Haff, G. G., Tufano, J. J., Newton, R. U., and Häkkinen, K. (2016). Greater strength gains after training with accentuated eccentric than traditional isoinertial loads in already strength-trained men. *Frontiers in physiology*, *7*, pp.149.

Weakley, J., Fernández-Valdés, B., Thomas, L., Ramirez-Lopez, C., and Jones, B. (2019). Criterion validity of force and power outputs for a commonly used flywheel resistance training device and bluetooth app. *The Journal of Strength & Conditioning Research*, 33(5), pp.1180-1184.

Westblad, N., Petré, H., Kårström, A., Psilander, N., and Björklund, G. (2021). The Effect of Autoregulated Flywheel and Traditional Strength Training on Training Load Progression and Motor Skill Performance in Youth Athletes. *International Journal of Environmental Research and Public Health*, 18(7), pp.3479.

Wild, C. Y., Steele, J. R., and Munro, B. J. (2013). Insufficient hamstring strength compromises landing technique in adolescent girls. *Medicine* & *Science* in *Sports* & *Exercise*, 45(3), pp.497-505.

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Review

Eccentric Resistance Training in Youth: Perspectives for Long-Term Athletic Development

Benjamin Drury [1,*], Sébastien Ratel [2], Cain C.T. Clark [3], John F.T. Fernandes [1], Jason Moran [4] and David G Behm [5]

1 Department of Applied Sport Sciences, Hartpury University, Gloucestershire GL19 3BE, England, UK; john.fernandes@hartpury.ac.uk
2 Laboratoire des Adaptations Métaboliques à l'Exercice en conditions Physiologiques et Pathologiques (AME2P, EA 3533), Université Clermont Auvergne, F-63000 Clermont-Ferrand, France; sebastien.ratel@uca.fr
3 Faculty of Health and Life Sciences, Coventry University, Coventry CV1 5RW, England, UK; ad0183@coventry.ac.uk
4 School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester CO4 3WA, UK; jmorana@essex.ac.uk
5 School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's Newfoundland and Labrador, A1C 5S7C, Canada; dbehm@mun.ca
* Correspondence: ben.drury@hartpury.ac.uk; Tel.: +44-1452-702463

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Abstract: The purpose of this narrative review is to discuss the role of eccentric resistance training in youth and how this training modality can be utilized within long-term physical development. Current literature on responses to eccentric exercise in youth has demonstrated that potential concerns, such as fatigue and muscle damage, compared to adults are not supported. Considering the importance of resistance training for youth athletes and the benefits of eccentric training in enhancing strength, power, speed, and resistance to injury, its inclusion throughout youth may be warranted. In this review we provide a brief overview of the physiological responses to exercise in youth with specific reference to the different responses to eccentric resistance training between children, adolescents, and adults. Thereafter, we discuss the importance of ensuring that force absorption qualities are trained throughout youth and how these may be influenced by growth and maturation. In particular, we propose practical methods on how eccentric resistance training methods can be implemented in youth via the inclusion of efficient landing mechanics, eccentric hamstrings strengthening and flywheel inertia training. This article proposes that the use of eccentric resistance training in youth should be considered a necessity to help develop both physical qualities that underpin sporting performance, as well as reducing injury risk. However, as with any other training modality implemented within youth, careful consideration should be given in accordance with an individual's maturity status, training history and technical competency as well as being underpinned by current long-term physical development guidelines.

Keywords: eccentric training; youth athletes; paediatric physiology; landing mechanics; flywheel training; eccentric hamstrings

1. Introduction

The physical development of youth athletes is an important component in promoting the qualities that underpin athletic performance [1]. A number of previous position statements provide practitioners working with youth athletes, training guidelines that support the long-term athletic development (LTAD) of the individual [2–5]. The overarching consensus of these statements is largely based upon the principles of the youth physical development (YPD) model, which offers a comprehensive approach to the development of both young males and females via the integration and prioritization of training different physical qualities throughout childhood, and beyond [6]. The rationale of this approach is underpinned by the influence of an individual's maturity status on physical and performance capacities in youth [7]. Central to the YPD model is the development of muscular strength, which should be targeted throughout youth, for both males and females, due to its underpinning of performance capabilities. Indeed, the importance of muscular strength in supporting young athletes' performances has been demonstrated on tasks such as change of direction [8,9], vertical jump [9–11], leg stiffness [11], sprint ability [9,12] and balance [13]. Accordingly, as muscular strength is an integral component of youth strength and conditioning programs for performance enhancement [2] and also for reducing the risk of sport-related injuries [14], training modalities that can further develop this component are necessary.

Developing muscular strength via the inclusion of resistance training (RT) methods is pivotal [15]. The use of RT for young athletes in developing strength and power qualities that support athletic performance has been strongly advocated [16] and the physiological adaptations underpinning such benefits discussed [17]. Similarly, a large body of evidence exists highlighting the efficacy of using RT methods to enhance the physical capabilities of youth athletes in both male [18] and female [19] populations. For example, recent meta-analyses on the use of RT in youth athletes have provided important information detailing the role of RT variables [20] as well as the different methods that can be used to improve strength, power and speed [21]. Practically, these studies have highlighted the necessity of a variety of training methods required to elicit further performance gains in individuals who are more mature and have a relatively longer training history. Therefore, for practitioners working with youth athletes, the knowledge of RT modalities that could be used for the development of physical qualities and reduce injury risk is beneficial.

Previously, the benefits of utilizing eccentric resistance training (ERT) to enhance performance has been discussed in detail [22]. Furthermore, the physiological responses and chronic adaptations to eccentric training have been outlined [23,24]. However, although the reported benefits of applying ERT methods to improve aspects such as strength, power, speed, change of direction, hypertrophy and injury resistance in adult athletic/trained individuals [25–59], limited information exists pertaining to its practical application within youth athletes. This is somewhat surprising given that specifically targeting the aforementioned physical qualities throughout youth are widely recommended [2]. Since athletic movements in youth will normally include performance of tasks such as changes of direction, deceleration, landing, and hopping, exposure to eccentric muscle actions may already occur within the demands of sport or even playground activities. Reasons for the paucity of research or application within youth are unknown. Though, it may be postulated that factors that are associated with eccentric exercise such as muscle damage [60], muscle strains [61] and the more detailed application of ERT in higher-trained athletes [62] may contribute to this dearth of research concerning applied training modalities. However, it has been recommended that the execution of eccentric training should be emphasized during later LTAD stages in youth [63]. Importantly, practitioners working with youth athletes should understand the acute responses to eccentric exercise as well as the necessity to include ERT modalities throughout maturation stages to enhance physical performance and injury prevention strategies. Therefore, the aim of this article is to provide an overview of the physiological responses to ERT in youth, and to discuss the potential applications of ERT within LTAD. It is hoped that this knowledge can provide practitioners working with youth athletes' greater awareness of the benefits of including ERT as well as potential training prescription and programming concepts.

1.1. Terminology

The terms 'children' and 'pre-pubertal' refer to girls and boys that are within the pre-peak height velocity maturation stage (pre-PHV), roughly defined as up to the age of 11 for girls and up to the age of 13 for boys. This differs from the terms 'pubertal' and 'adolescent' which normally include girls aged 12–18 years and boys aged 14–18 years old (circa and post-peak height velocity stages). The use of the word 'athlete' will refer to a person who competes in sport.

1.2. Literature Search

With no date restrictions, a Boolean logic systematic search from online databases including Google Scholar, PubMed and Web of Sciences was undertaken from which only English language articles were considered. The following terms were searched: 'eccentric training', 'eccentric exercise', 'youth athlete', 'maturation', 'nordic hamstring exercise', 'eccentric hamstring strength', 'landing kinematics', 'augmented eccentric training', 'tendon', 'fatigue', 'resistance training', 'flywheel inertia training', 'physiological responses', 'injury' 'muscle damage'. Boolean operators (AND, OR) were used to concentrate the search terms.

2. Neuromuscular and Metabolic Responses to Exercise in Youth

Although the benefits of younger individuals utilizing strength and power methods to enhance physical qualities have been widely documented [21], it is also acknowledged that children and adolescents produce lower levels of muscular force than adults, even when normalized to body mass [64–68]. These differences can be attributed to anatomical and physiological changes occurring throughout growth and maturation [69]. Such factors include muscle size, histology, internal and external joint leverage, tendon mechanical properties and the central nervous system [70]. Furthermore, it is acknowledged that children recover quicker from high-intensity exercise than adults and therefore the same training principles may not apply [71]. An understanding and awareness of these different responses to RT in youth compared to adults is important to allow for appropriate prescription as these responses and adaptations underpin the guidelines used to structure resistance training for youth athletes [6].

2.1. Fatigue Resistance

From a neuromuscular fatigue perspective, it has been demonstrated that younger individuals are more fatigue resistant than adults [72]. The lesser fatigue in youths compared to adults following exercise has been shown within a range of exercise modalities with pre-pubertal boys displaying a greater maintenance of peak torque than adults following dynamic maximum isokinetic [67,73–77] and isometric [65,78,79] actions of the knee extensors and flexors, maximal isometric exercise of the elbow flexors [68], and isometric exercise of the plantar flexors [64]. The lower reductions in force-generating capacity following resistance exercise-induced fatigue in youth compared to adults have been shown to occur in conjunction with smaller alterations of neuromuscular properties including sarcolemma excitability (i.e., M-wave amplitude), excitation–contraction coupling (i.e., low-to-high frequency tetanic force ratio or low-frequency fatigue), muscle contractility (i.e., high-frequency torque) and muscle oxygenation [63,64,68,71–73,78–81]. Conversely, during submaximal isometric RT, differences in fatigue responses including torque and surface electromyography (EMG) have not been observed between children and men [82,83]. The absence of differences during submaximal actions have been attributed to the likely predominance of slow twitch motor units used during submaximal exercise, which are activated according to the size principle [84]. An explanation for this may be that submaximal intensity fatigue protocols encourage both children and adults to initially recruit a low proportion of their fast twitch motor units, thus removing the inherited age-related differences in fatigue occurring during maximal muscular actions [68]. Lower levels of force decrement observed within a bout of resistance exercise in youths has also been accompanied by faster recovery between bouts. For instance, boys have been shown to require shorter rest intervals to maintain peak torque during multiple sets of isokinetic exercise of the knee extensors when compared to adolescents and adults [67,85,86]. Evidence also points to the faster recovery of agonist muscle activation levels following the cessation of resistance exercise in boys, compared to men, the execution of lower limb isokinetic exercise following both maximal [65,77] and submaximal [83] protocols. Similar findings have also been reported during upper-body resistance training exercise, in which boys and male adolescents achieve significantly greater repetitions than adults during the bench press [87] and chest press [88] exercises when completing the same between-set recovery period.

The lower levels of force produced by children compared to adolescents and adults appears to influence fatigue and recovery responses. Part of these differences have been attributed to the inability of children to voluntarily activate their motor units due to the lower central drive to the motor unit, which affects the resulting force production [70]. Confirmation of reduced voluntary activation (VA) in children compared to adults has been previously demonstrated [79,89–92] although some studies report no such differences [64,93,94]. Reasons for the discrepancies of these results have been proposed to be due to the sex and the muscle group investigated but also the mechanical conditions of muscle actions, and specifically the length at which the muscle was evaluated [70]. Notwithstanding, the lower VA levels observed in pre-pubertal children have been attributed to the immaturity of the corticospinal pathways in which the development of interneuronal synaptic connections both at the cortex and the spinal cord increases between the ages of 8 and 11 years [95]. However, some children may be unable to perform maximal-force muscle actions due to a lack of experience performing at a high intensity and, hence, discomfort and inexperience can impair their ability to fully activate [73]. It has also been proposed that pre-pubertal children possess a greater proportion of type I fibres than adults [96] and therefore have an inability to produce the high-power outputs that would be seen in more mature individuals who may possess a greater amount of type II muscle fibres. Equally, the higher electromyography threshold reported in both boys [97] and girls [98] compared to their adult counterparts might reflect a delayed and shorter onset of recruitment of type II motor units [99].

The variances in fatigue during exercise may be muscle-dependent as well as being influenced by the muscle-tendon unit (MTU) length. This has been observed during isometric fatiguing actions of the plantar flexor (PF) and knee extensor (KE) muscle groups in which boys fatigued similarly to men with the PF muscles but to a lower extent with the KE muscles than men [80]. With regards to the MTU length, neuromuscular fatigue at optimal and long MTU lengths are lower in children compared to adults, which are mainly accounted for by central fatigue (i.e., a reduction in drive to the muscle), rather than peripheral fatigue (i.e., failure in muscle contractility and excitation–contraction coupling (E–C). Conversely, at short MTU lengths, the differences in neuromuscular fatigue between children and adults are significantly reduced [80]. The lesser performance fatigability and peripheral fatigue at short MTU length could be partly explained by a lower torque level than at optimal length, where greater alterations in peripheral mechanisms (i.e., EC coupling) are observed. The longer exercise duration at short muscle length could also account for the greater central fatigue. These differences point to a specific effect of MTU length in boys and men. Subsequently, it would appear that MTU stiffness plays a role in mediating the force-generating capability during youth [99]. Indeed, it has been suggested that a compliant tendon may act as a mechanical buffer, which could additionally protect the muscles from any extensive damage and subsequent peripheral fatigue [100]. Lastly, the greater decrease in antagonist co-activation of the knee flexors during repeated maximal voluntary isometric contractions in pre-pubertal children may contribute to limit the loss of force of the knee extensors, and therefore to delay fatigue of the agonist muscles [101].

2.2. Metabolic Responses

Throughout youth, the metabolic responses to exercise change with growth and maturation [102]. Following resistance and short-term high-intensity exercise, children have been shown to elicit lower post-exercise peak blood lactate concentrations, faster blood lactate clearance rates [67,75,103–109], better blood acid-base regulation [110], lower phosphocreatine (PCr) depletion, faster PCr resynthesis rates [111–114] and faster heart rate recovery [67,75,108,115]. Explanations for the differential responses in youth have been attributed to factors such as accelerated blood circulation due to smaller body size [69], lower relative muscle mass [109] and lower reliance on glycolysis [67]. This predisposition of children to be more reliant on aerobic metabolism for energy demands has been proposed to occur due to age-dependent metabolic and hormonal responses to exercise compared to adolescents and adults [116]. Indeed, pre-pubertal children have a faster PCr recovery following exercise than adolescents and adults, suggesting that there is a progressive alteration in muscle oxidative capacity throughout youth [117]. A greater reliance on aerobic metabolism in children is also supported by findings that they possess a higher oxidative enzyme activity [118–121] and higher mitochondrial volume density than adults [122]. Due to these physiological predispositions it has been suggested that pre-pubertal children have a similar metabolic profile to that of well-trained endurance adult athletes due to their greater reliance on oxidative metabolism [123]. For example, recent work has shown that pre-pubertal children have a similar net contribution of energy derived from aerobic metabolism, a similar rate of fatigue (i.e., power loss) resulting from short-term high-intensity exercise and comparable post-exercise recovery of oxygen uptake to well-trained adult endurance athletes [115].

2.3. Exercise-Induced Muscle Damage

The previously discussed physical differences between youth and adults may also account for the magnitude of exercise-induced muscle damage (EIMD) in response to RT. Therefore, as children and adolescents mature, it is important to consider how EIMD affects muscle function [124]. For instance, it appears that there is a progressive withdrawal of physiological protection against high-intensity exercise-induced fatigue during puberty [125]. Subsequently, as the youth athlete matures and their ability to produce force also increases, there may be a concomitant increase in fatigue and muscle damage responses. Potential magnified responses should be particularly reviewed for eccentric exercise due to the high levels of muscle damage that is caused by this type of movement [60,126]. The muscle damage resulting from eccentric exercise is commonly indicated by decreases in muscle function, delayed onset muscle soreness (DOMS), and increased muscle enzymes and proteins, such as creatine kinase (CK) and myoglobin (Mb) in the blood, respectively [127,128]. Moreover, such effects can last for several days' post-exercise [129]. This is important to consider as EIMD can impair the physiological adaptations to training [130] and can subsequently influence the prescription of training stimuli [131]. The negative consequences EIMD may have on training exposure in youth is important to consider as higher resistance training frequencies are associated with increased performance improvements in youth athletes [132]. In particular, factors such as these should be planned for in youth to ensure that they can be integrated within the required periodization plan to enhance athletic development [133]. Moreover, prescription of ERT within an individuals' LTAD plan needs to consider improving physical qualities, but also reducing injury risk [134–136]. For that reason, the suggested inclusion of eccentric training during LTAD [63] requires careful deliberation.

It has been reported that children experience less EIMD than both adolescents and adults (Table 1). For instance, after eccentric exercise of the elbow flexor muscles, an age-dependent effect has been observed between children, adolescents, and adults in both females [137] and males [138]. Results of these studies reported reductions in maximal concentric strength of the elbow flexors, range of motion (ROM), muscle soreness, plasma CK, and Mb concentrations were reported to be lower in children than both adolescents and adults, and adolescents lower than adults. Moreover, following maximal eccentric voluntary muscle actions of the knee extensors in which relative total work completed was similar, men experienced more severe muscle damage than boys [139]. This was manifested through compromised muscle function (i.e., reduced eccentric, concentric and isometric peak torque) for several days in men whist children demonstrated no such changes. Similarly, greater increases in muscle damage markers (i.e., DOMS, ROM, CK) lasted up to 96 h for men whilst, in boys, these only persisted for up to 48 h. Differences in DOMS has also been reported in the upper-body too. For example, following completion of an augmented eccentric machine chest press exercise adults reported higher levels of soreness than children 48 h' post-exercise [140]. A similar augmented eccentric load was also used during the leg curl exercise in females in which CK measured one-, two-, three- and four-days post exercise was higher in adult females compared to female children [141]. Separately, EIMD protocols that have included high volume repetitive jumping, which subsequently expose participants to high landing forces and the associated eccentric control of these actions [142], have again demonstrated that children experience lower levels of muscle damage compared to adults [143–145]. Moreover, a number of other studies have reported lower symptoms of DOMS between younger individuals compared to adults following exercise modes of RT [146,147], aerobic exercise [148] and downhill running [149].

2.4. Repeated Bout Effect

Performing unaccustomed exercise results in a number of muscle damage responses that can be considered symptomatic (e.g., force loss, muscle soreness), systemic (e.g., increased circulating muscle proteins), or histologic (e.g., myofibrillar disruptions) [150]. Skeletal muscle possesses an intrinsic mechanism that reacts to EIMD via providing an adaptive response to subsequent EIMD stimuli (see [150] for more details). This phenomenon is known as the repeated bout effect (RBE) which has primarily been investigated following eccentric muscle actions due to its greater tendency to elicit a muscle damage response [151]. For example, it is well established that the first bout of eccentric-only exercise protects the respective muscle from further muscle damage during subsequent exercise sessions [152]. Indeed, attenuation of muscle damage markers during the second bout of exercise that is completed within several weeks of the initial bout has been evidenced [153]. Mechanisms explaining this improved response may include neural, muscle-tendon complex behaviours, extracellular matrix structural remodelling and a modified inflammatory response [150]. Although the specific mechanisms that are responsible for the RBE are unclear, it would appear that the RBE is multifactorial which is likely to be highly muscle and exercise specific [154]. The beneficial effects conveyed by the RBE is characterized by factors such as faster recovery of muscle strength and ROM, reduced increases in muscle proteins in the blood, and less significant development of swelling and muscle soreness [152,155].

Although muscle damage following eccentric exercise is lower in children and adolescents compared to adults, the RBE does occur in all populations, although to different magnitudes. The lower protective effect observed in the younger groups might be due to the lower levels of muscle damage evident following eccentric exercise. That is, a greater initial degree of muscle damage might induce a greater RBE. The magnitude of the RBE has been shown to correspond with the intensity of the first eccentric exercise bout, such that the higher the intensity, the greater the level of protection provided [156]. For example, after plyometric exercise an RBE was evident for all symptoms examined in men, but only for muscle soreness in boys [145]. Likewise, following plyometric exercise in children, young adults and elderly populations, isometric torque recovery was significantly greater after the second bout of plyometric exercise in all groups, but this improvement was accompanied by a higher level of voluntary activation only in young adult males [144]. Since children are less susceptible to eccentric exercise-induced muscle damage than adolescents and young adults, it may be that the RBE of children is not expressed as strongly. However, following eccentric exercise in both male and female pre-pubescent, pubescent youth, and adults, the magnitude of the RBE was similar [137,138].

The above discussed findings indicate that although children tend to experience less EIMD after the initial bout of eccentric exercise, they may potentially have similar adaptability to eccentric exercise as adults. However, it is necessary to highlight that participants in these prior studies were of untrained status and therefore responses may be different for those youth athletes who are engaged with regular resistance training. For example, it has recently been shown that athletes compared to non-athlete's experienced different responses in which athletes are able to recover quicker despite displaying a greater force decrement following the eccentric bout of exercise [153]. Furthermore, when comparing between resistance-trained and untrained individuals, resistance-trained individuals seem to show less RBE than untrained individuals [157]. Overall, based on current findings it would appear that children and adolescents may adapt to ERT in a similar way as adults. Subsequently, it has been suggested, that an approach of beginning with low-intensity, prior to gradually increasing the intensity and volume based on the progressive overload principal is suitable for both youth and adults [137]. However, further research investigating the RBE following ERT in well-trained youth athletes is warranted.

Table 1. Studies assessing fatigue and exercise induced muscle damage following resistance training between children, adolescents and adults.

Study	Age (years)	Sex	Exercise Protocol	Selected Measurements	Outcome
[137] Lin et al. (2018)	C: 9–10 (*n* 13) Ad: 14–15 (*n* 13) A: 20–24 (*n* 13)	F	5 × 6 reps of eccentric elbow flexors. Dumbbell weight set at 60% iMVC. 2 min rest between sets.	MVC, DOMS, CK, Mb, ROM, MPS.	A > Ad > C
[139] Deli et al. (2017)	C: 11.0 ± 0.2 (*n* 11) A: 35.3 ± 2.2 (*n* 15)	M	5 × 15 reps of eccentric knee extensors. Dynamometer Set at 60° s^{-1}. 2 min rest between sets.	MVC, DOMS, CK and ROM.	A > C
[143] Lazaridis et al. (2018)	C: 10 ± 0.7 (*n* 13) A: 25.3 ± 3.3 (*n* 13)	M	10 × 10 reps of CMJ. 30 s rest between sets.	iMVC, DJ, EMG, $K_{stiffness}$ and RPE.	A > C
[140] dos Santos et al. (2016)	C: 11.3 ± 0.82 (*n* 10) A: 24.5 ± 5.58 (*n* 10)	M + F	5 × 15 reps of eccentric machine chest press. Load set at 110% of 10RM concentric chest press. 3 min rest between sets.	DOMS.	NSD
[138] Chen et al. (2014)	C: 9.4 ± 0.5 (*n* 13) Ad: 14.3 ± 0.4 (*n* 13) A: 22.6 ± 2.0 (*n* 13)	M	5 × 6 reps of eccentric elbow flexors. Dynamometer set at 90° $s-^{1}$. 2 min rest between sets.	MVC, DOMS, CK, Mb, ROM and MPS.	A > Ad > C
[144] Gorianovas et al. (2013)	C: 11.8 ± 0.9 (*n* 11) A: 20.8 ± 1.9 (*n* 11) E: 63.2 ± 3.6 (*n* 11)	M	100 drop jumps. DJ box height set at 0.5 m. 30 s rest between reps.	iMVC, LFF, VA, DJ Height, DOMS, CK.	A > E > C
[146] Pullinen et al. (2011)	A: 31 ± 7 (*n* 8) Ad: 14 ± 0 (*n* 8)	M	3 × sets until exhaustion of concentric knee extensors. Load set at 40% of 1RM bilateral knee extension. 4 min rest between sets.	iMVC, CK, EMG, HR.	A > Ad
[145] Marginson et al. (2005)	C: 9.9 ± 0.3 (*n* 10) A: 22.2 ± 2.7 (*n* 10)	M	8 × 10 reps of CMJ. 1 min rest between sets.	iMVC, DOMS, CMJ, SJ.	A > C
[141] Arnett et al. (2000)	C: 10.5 ± 1.1 (*n* 15) A: 23.4 ± 6.9 (*n* 15) E: 59.4 ± 10.9 (*n* 10)	F	6 × 10 Reps of eccentric leg curl exercise Load Set at 110% 1RM concentric leg curl. 1 min rest between sets.	CK.	A > E > C
[148] Duarte et al. (1999)	Ad: 13.0 ± 0.5 (*n* 10) Ad: 13.2 ± 0.7 (*n* 10)	M	Box step up and down until exhaustion. Tempo Set at 1:1 (1 s up – 1 s down) vs 1:2.	iMVC, DOMS and CK.	1:2 > 1:1
[147] Soares et al. (1996)	C: 12.1 ± 0.2 (*n* 10) A: 28.3 ± 3.5 (*n* 10)	M	5 Sets × 80% 1RM concentric bench press until exhaustion. 90 s rest between sets.	iMVC, DOMS and CK.	A > C
[149] Webber et al. (1988)	C: 10.4 ± 0.3 (*n* 16) A: 27.1 ± 0.87 (*n* 15)	M + F	30 min downhill running @ 10% gradient.	DOMS and CK.	NSD

C: Children; **Ad:** Adolescents; **A:** Adults; **E:** Elderly; **M:** Male; **F:** Female; **Reps:** Repetitions. **MVC:** Maximal voluntary contraction; **iMVC:** Isometric maximal voluntary contraction; **CMJ:** Countermovement jump; **DJ:** Drop Jump; **DOMS:** Delayed onset muscle soreness; **EMG:** Electromyography activity; **CK:** Creatine kinase; **Mb:** Myoglobin; **RM:** repetition maximum strength; **LFF:** Low frequency fatigue; **HR:** Heart rate; **ROM:** Range of motion; **VA:** Voluntary; **NSD:** No significant difference.

2.5. Eccentric Resistance Training Safety Considerations for Youth Athletes

Current research demonstrates the maturation- and age-dependent effects on neuromuscular fatigue, recovery, and muscle damage in which there is a progressive transient from childhood through to adulthood. Particularly, concerns regarding the increased risk of muscle damage in children and adolescents compared to adults appears to be unfounded with younger individuals experiencing less severe symptoms following exercise. These differences may be explained due to the lower force production capacity of children and adolescents, leading to reduced fatigue and muscle damage symptoms. Furthermore, this may also be explained by the greater total work performed during ERT protocols in adults compared to adolescents and adolescents compared to children [138]. It should also be recognized that populations used in previous studies have largely been of untrained status and, therefore, responses in trained youth may be different. Despite this, current evidence suggests that the inclusion of ERT methods in youth should not cause concern with regard to increased levels of muscle damage, fatigue or injury risk when compared to other resistance training modalities in youth that are conventionally used. Indeed, it has previously been suggested that concerns for performing eccentric exercise in youth may be due to its potential for high muscle force production and potential for predisposing children to a higher risk of muscle injury [158]. However, although such concerns may be alleviated by the information presented in this section, the use of ERT in youth requires a well-structured approach that considers a range of elements such as the individual's maturity status, training experience, resistance training background, and movement competency. As such, the next section of this article will present the potential applications for ERT in youth and how these may be implemented within practice.

3. Implications for Eccentric Resistance Training in Youth

As denoted in Table 1, youths experience less EIMD than adults following exercise. These differences in muscle damage are observed not only in performance of tasks including jumping, running, and conventional RT but also ERT, too. Therefore, although further research is still warranted, concerns regarding the efficacy of using ERT during childhood and adolescence are not currently supported by current evidence. This is important to acknowledge as it is in the authors' experience that the use of ERT within youth is limited. However, youth athletes engage with movement skills such as landing, sprinting and change of direction (COD), which are key within the YPD model [6]. Thus, youth athletes are likely already exposed to such stimuli that requires high levels of force absorption. More advanced RT methods, such as plyometrics, which incorporate substantial eccentric muscle actions during landing, have been advocated for children and adolescents [21]. It is evident that current recommendations for youth athletes already include training modalities that emphasize eccentric muscle actions. However, we would suggest that a more holistic approach for the inclusion of ERT could be provided to support current RT guidelines for youth [41]. Additionally, the role of ERT for injury prevention throughout youth may be beneficial as during peak height velocity (PHV), rapid growth, and subsequent temporary disruptions in motor control can increase injury risk [159–162]. Given current recommendations for integrating ERT for injury preventions purposes in youth athletes [163], the inclusion of eccentric muscle actions into youth training may be particularly important. Therefore, the integration of ERT into current LTAD model(s) could have beneficial implications for those working with youths, particularly regarding performance enhancement and injury prevention. Consequently, the inclusion of ERT for the youth athlete is worth consideration.

3.1. Landing Mechanics

Tasks such as hopping and jumping are classified as fundamental movement skills in youth [164] and can be considered as the "building blocks" for further, more complex, movements [165]. Such movements are deemed important for athletic performance [166]. To perform these movements effectively the individual requires eccentric capabilities during the landing phase [142] to absorb kinetic energy and large vertical forces that are experienced to preserve the integrity of the lower limbs anatomical structures [167,168]. This is important as the inability to absorb such forces experienced during landing has been identified as a mechanism for lower-extremity injuries [169,170]. In particular, a focus on developing correct technique and force absorption qualities within youth is necessary as it has been demonstrated that maturity stage can promote inefficient kinematic and kinetic factors that are associated with increased injury risk [171]. Indeed, children as young as 10 years old demonstrate "risky" movement patterns during landing tasks [172,173], which include neuromuscular risk factors, such as low knee flexion angle ("stiff landing") and increased knee valgus [174,175]. Furthermore, both boys and girls displayed a longitudinal increase in external knee abduction moments throughout puberty [176,177]. Therefore, the early inclusion of developing appropriate landing mechanics as an injury prevention strategy should be implemented early to avoid these negative outcomes in order to reduce injury risk and promote long-term physical activity [178,179].

Differences in landing mechanics in youth are also influenced by sex and maturation with females displaying more aberrant landing kinematics compared to males throughout all stages of maturation [176,178,180–187]. These differences between young females and male can also be explained by anatomical aspects including an increase in both Q-angle and joint laxity as well as a decrease in notch width [169]. Such maturational effects are not present to the same extent in young males as improvements in knee valgus scores have actually been found with advancing age and stage of maturation [188,189]. This is further confounded in that compared to females, male youth appear to improve their lower limb control, sagittal plane motion, and landing forces during landing as they mature [190–192]. Differences in neuromuscular performance between sexes during and following puberty may contribute to altered biomechanics and resultant forces on the knee. Excessive knee loads, especially in the frontal plane may explain the increased risk of anterior cruciate ligament (ACL) injury in females following puberty and may help identify the optimal time to implement injury prevention programs [176]. Therefore, it is important to ensure that force attenuation during landing is focused upon throughout youth. Although it has been found that a tendency occurs for more mature male players to reduce their knee valgus scores, a high frequency of circa-PHV and post-PHV players still demonstrated moderate and severe knee valgus scores [188]. Additionally, during circa-PHV in young males, increases in inter-limb knee-valgus asymmetries during landing have been observed as well as an increase in normalized landing forces [188,189], which can lead to temporary decrements in motor control and neuromuscular function due to the rapid growth in limb length [193]. Subsequently, it would appear that throughout maturation, despite there being perhaps certain maturity stages that require a specific focus on certain types of training, the correct execution of landing mechanics and the preparation for these tasks are important and an individualized approach for both females and males is required.

Practitioners implementing exercises to improve landing kinematics should carefully consider the prescription of jump-type activities, particularly the volume and intensity of take-off and landing phases to reduce the risk of injury [194]. The increased risk of injury becomes especially apparent as landing forces of approximately 3.5, 8 and 3 times one's bodyweight have been reported during a single-leg vertical jump, bilateral vertical jump to 50% maximum jump height and single leg hop to 75% maximal horizontal hop distance in youth [172,189,195], respectively. A high ground-reaction force loading rate indicates that an athlete is subjected to high ground-reaction forces upon the initial landing phase, making it difficult to adequately dissipate the forces reaching the knee joint [196]. Practitioners should, therefore, be mindful that greater ground reaction forces, which are present in children compared to adolescents [197,198], may increase risk of injury during landing [199]. For example, performing more intense landing tasks can increase ground reaction forces that negatively influence the frontal plane projection angle (FPPA) [193,200]. Consequently, it would appear that the ability to absorb ground reaction forces may be challenged due to the greater increases in landing forces that are required with increasing drop height during drop landing and drop jump tasks [201–204]. It is thus necessary to develop the ability to effectively absorb ground reaction forces upon landing via developing appropriate eccentric strength qualities to help reduce biomechanical risk factors such as increased knee valgus and joint moments. Indeed, strength training has been reported to positively change FPPA during landing [205]. In particular, eccentric muscle strength of the lower limbs has been shown to positively influence landing kinematics [206–212]. In accordance with these findings it is thus advisable for youth athletes to develop both technical proficiency and eccentric strength qualities to assist development of landing mechanics that may aid in the reduction of injury risk.

As provided in Figure 1, there are a number of approaches that can be proposed to develop force absorption ability throughout youth that should consider aspects of exercise volume, intensity, movement exploration and complexity. For example, the inclusion of activities such as parkour (Exploration) earlier in the child's development may a provide varied and diversified training programme [213] that provides individuals with the opportunity to sample different movements to manage forces [214,215]. Previously, it has been revealed that parkour participants are more effective at lowering the kinetic landing variables that are associated with a higher injury risk in comparison to recreationally trained individuals [216]. An approach that promotes movement exploration may be helpful in reducing future injury risk due to issues surrounding sport-specialized youth athletes landing biomechanics [217] and the reported anterior knee pain disorders compared to multi-sport athletes [218]. As the individual reaches PHV, further progressions could be included by integrating exercises that have a unilateral landing (Technical) focus in order to aid in the reduction of any asymmetries that may occur during this stage of maturation [188,219,220]. During this stage, increasing the complexity of the jump-landing can be achieved via increasing the jump velocity (intensity) which will subsequently challenge landing kinematics via achieving a greater jump height [221]. The inclusion of weightlifting derivatives (Specificity), which have been advocated previously in youth [222,223], could also be included, more specifically at the post-PHV period. Inclusion of weightlifting derivatives, such as the jump shrug, hang power clean and hang high pull, can be also used to improve load absorption characteristics [224,225]. Such an approach would further challenge movement complexity as well as developing concentric neuromuscular power during the propulsive phase of the movement and eccentric force qualities during the landing phase. Based upon previous recommendations to reduce injury risk in youth [226], we would suggest an approach based on participants' maturation status, exercise variations (variations), utilisation of verbal feedback (feedback) and, finally, exercise dosage (volume). Although limited information exists pertaining to the use of training volumes for landing mechanics in youth, it has been shown that sessions including up to six sets of six repetitions when completing the drop landing exercise have improved landing kinematics in adults [227]. As a result, it may be sensible to build training volume towards this level throughout the stages of youth. This may be achieved via varied exercise selection [226] with a frequency of two to three times per week which has been suggested for plyometric exercises in this population [228].

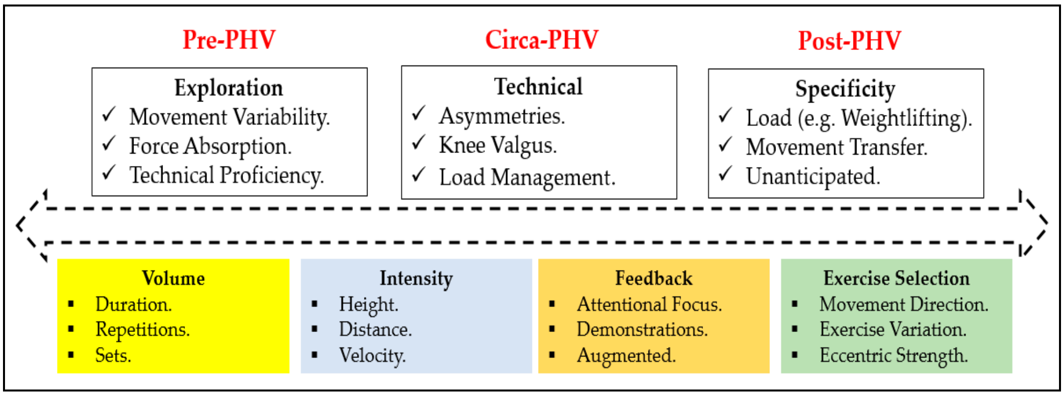

Figure 1. Example conceptual model for the development of landing kinematics throughout youth considering maturity status, injury risk factors and acute training variables. Pre-PHV = pre-peak height velocity. Circa-PHV = circa-peak height velocity. Post-PHV = post-peak height velocity.

3.2. Eccentric Hamstrings Strength

The inclusion of exercises to increase eccentric strength of the knee flexor muscles is considered necessary to help reducing the injury risk of the hamstrings muscles [229]. Typically, these injuries have been suggested to occur during sprinting mainly in the late swing phase in which the hamstrings are highly activated at longer lengths and therefore creating high levels of stress on the MTU [230–233]. Exercises such as the Nordic hamstrings exercise (NHE), used to strengthen the knee flexor muscles eccentrically, is deemed important not only from both an injury prevention perspective but for performance too (e.g., sprinting and change of direction) [50–52,234]. Furthermore, the NHE has also been shown to positively influence performance measures such as sprint speed, change of direction, and jumping in both youth males and females [235,236]. Yet, caution to the use of the NHE was previously been suggested on the basis that it was considered too intense for young, inexperienced athletes [237]. Despite this, as presented in Table 1, the use of eccentric muscle actions does not appear to place the youth athlete at greater risk of muscle damage than adults. Appropriate NHE prescription as well as other exercises that develop eccentric hamstrings strength [238–240] should be permissible in youth. Indeed, the NHE should form part of a holistic injury prevention program within youth to ensure that the hamstrings receive the specialist consideration that they require throughout youth [241]. In support of this, we have recently found eccentric hamstrings strength improvements in male youth soccer players from the age of 10 years [242].

Inclusion of ERT exercises within an injury prevention program (IPP) is advocated across a number of youth sports [243–247]. Although hamstrings strength has been shown to develop throughout all stages of youth [248–257], it is important to ensure that it is specifically trained throughout and begun early on in childhood to reduce future risk. This is particularly essential for girls as it has been shown that insufficient hamstrings strength is evident in childhood [190,258]. Moreover, it has been found that girls with reduced hamstrings strength display greater biomechanical ACL injury risk factors during landing actions [259]. Specific development of the medial hamstrings has been instructed in female youth to counteract the external knee valgus moments and knee outward rotation moments [260]. Use of the NHE for females may be particularly helpful considering its reported benefits in reducing ground reaction forces during landing [261] and reducing bilateral hamstrings strength imbalance [262]. Requirements for the development of hamstrings strength also applies to male youth as practitioners have reported that players aged 13–16 years are at the greatest risk of injury and that eccentric hamstrings strength is amongst the most important injury risk factors [263]. This would coincide with PHV in which the greatest rate of growth occurs and has been associated with increased injury risk [160–162]. Consequently, it is important to ensure that youth athletes are physically prepared for this accelerated period of growth. This is further evidenced by the reports of decreased hamstrings to quadriceps ratio towards the latter stages of adolescence [248,264] and reduced relative eccentric hamstrings strength scores decreasing at senior level [250]. As provided in Figure 2, eccentric hamstrings strength should be targeted throughout childhood, adolescence and adulthood. Attention needs to focus on areas such as reducing asymmetry throughout the PHV stage and ensuring exercise compliance [265] to help maintain eccentric hamstrings strength levels. Once athletes enter the senior level, training and competition commitments may limit the development of this eccentric hamstrings strength.

Concerns regarding the inclusion of ERT at earlier stages in youth should have been alleviated by the information provided in Section 1 of this article. This is also supported by evidence that increases in hamstrings strength have been shown in basketball players aged 10–12 years following a five-week NHE programme [266]. However, as per previous recommendations, we would also suggest that the NHE should form part of a holistic hamstrings programme [267]. Therefore, although we feel that the inclusion of the NHE in youth should be viewed as a fundamental exercise used to increase eccentric hamstrings strength, other eccentric hamstrings exercises that target both distal and proximal hamstrings regions should be integrated [239] as well as inclusions of concentric [268], isometric [269] and sprinting [270] exercises. These should be completed with correct technique, appropriate progressions and in accordance with current RT guidelines for youth. Additionally, an emphasis during youth should be placed upon developing eccentric hamstrings strength across its full ROM due to the proposition that a shift in the optimum angle of peak torque provided by performing eccentric hamstrings exercises at long muscle lengths reduces hamstrings injury risk [58,271]. Moreover, both male and female senior players possess higher angle specific torque and functional range eccentric knee flexor values compared to their respective youth counterparts [272,273]. Ensuring that exercises target the full range of movement may also aid in the development of the hamstrings muscle architectural properties. This may be because shorter biceps femoris fascicle lengths can increase hamstrings injuries [274]. Considering the positive effects of eccentric exercise on properties such as fascicle length [54,271,274–282], as well as the relatively quick reversal of hamstrings muscle fascicle length and strength adaptations [278–280], perhaps the regular and structured inclusion of eccentric hamstrings exercises throughout youth could be viewed as a preparatory approach to developing architectural properties of the hamstrings and a foundation of eccentric hamstrings strength that can be maintained and progressed at senior levels. This is because it has been proposed that increases in fascicle length typically occur during the pre-pubescent period, whereas substantial increases in muscle cross-sectional area (CSA) typically occur during the pubescent period [283,284]. As a result, it may be advisable to develop structural properties and strength qualities earlier on in youth via the progression of training volume prior to increasing the intensity of the exercise post-PHV, once sufficient absolute and relative eccentric hamstrings strength has been achieved [285]. Indeed, it has been reported that additional loads are required during exercises such as the NHE in order to promote further eccentric hamstrings strength increases and fascicle length [286]. Subsequently, increases in muscle architecture properties at post-PHV status may also be targeted via performing the NHE either pre or post training to elicit specific morphological adaptations [287].

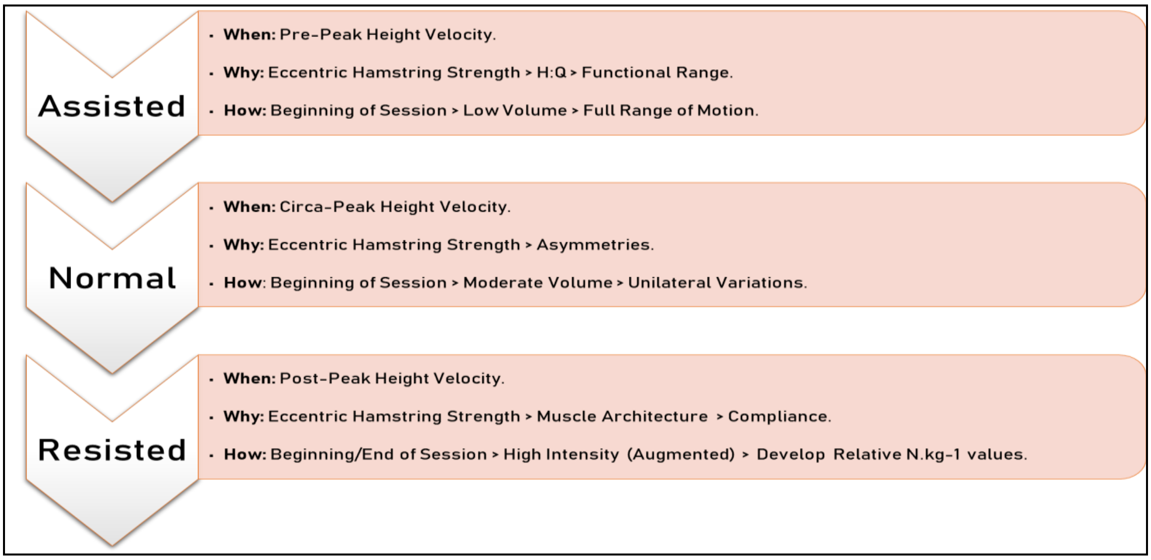

Figure 2. Example progressions for the NHE exercise throughout the different stages of maturation in which the progression of NHE intensity is achieved via assisted and resisted exercises. These progressions are proposed to align with different maturity stages to promote qualities that will aid in the prevention of hamstring injuries.

3.3. Flywheel Inertial Training

Typically, during RT, overload provided during the exercise remains constant for both eccentric and concentric portions of the exercise consequently leading to a lower relative load being lifted during the eccentric phase [288]. This is because greater forces are sustained during eccentric muscle actions compared to that of isometric and concentric actions [289,290]. For example, accentuated eccentric loading (AEL), which includes a load during the eccentric phase that is in excess of the concentric load [22] can be incorporated. AEL is considered an advanced training tactic [291]. Accordingly, we would suggest AEL to be included towards the latter stages of adolescence once an appropriate foundation of eccentric strength and resistance training skill competencies has been developed [63]. An alternative method to create eccentric overload in youth that may be appropriate is that of flywheel inertial training (FIT). FIT offers additional resistance throughout the entire ROM via the use of the inertia of a rotating flywheel to provide a greater overall load during coupled concentric and eccentric muscle actions [292]. The use of FIT in adult populations has been reported to provide many benefits including improvements in physiological, physical and performance factors, such as running economy [293], body composition [294], muscle activation [295,296], acute power enhancement [297–300], muscle architecture [35,301–304], change of direction [35,48,305] as well as force- and power-related qualities [25,305–308].

To date, some evidence does exist relating to the benefits of FIT in youth athletes. For example, in youth team sport athletes FIT has shown to improve performance in tasks such as jumping, sprinting, as well as the ability to increase breaking forces during change of direction [47,309,310]. Specifically relating to change of direction (COD), knee extensor eccentric strength has been associated with improved deceleration in youth (16.8 years) male soccer players [311]. Such findings could be expected considering that faster COD performance has been associated with higher levels of braking force application [312,313]. Since during adolescence greater increases in speed [314–316] and strength and power qualities [317–321] are observed it is important that the propulsive forces developed to achieve these are also balanced with the appropriate eccentric strength characteristics too. Without such a focus this may place the youth athlete at greater risk of injury as they may not be able to effectively decelerate from the increased running speeds they can achieve. Indeed, it has been shown that performing cutting movements at greater speeds negatively affects lower extremity biomechanics that are associated with ACL injury risk [222,322]. These factors warrant due attention as increases in body mass also accompany changes in maturity status [323]. These combined increases will likely result in greater amounts of momentum being produced. For example, in youth rugby union players it has been shown that maturity status is a significant predictor of momentum [324]. Accordingly, it is important that the youth athlete possesses the sufficient eccentric force qualities to tolerate the force demands from such tasks as COD and deceleration that they will be exposed to not only support performance but to aid in reducing injury risk.

Considering that physical qualities, such as COD, speed and strength, are recommended to be developed throughout all stages of youth [6] as well as the aforementioned benefits of FIT, its implementation within youth may be beneficial. This is appealing since the magnitude of eccentric forces encountered by a flywheel device during an exercise is proportionate to the preceding concentric forces [325]. Such an approach may be appropriate in youth as their lower concentric force capability would result in eccentric forces that would be proportionately lower [326]. In addition, it has been demonstrated that the use of higher flywheel inertias can concomitantly provide eccentric overload via increases of kinetic variables such as negative impulse during the descent phase of a movement [292,327,328]. Therefore, the introduction of low intensity flywheel inertia wheels may represent an appropriate starting point for training progressions along with lower training volumes prior to gradually increasing the load, volume and frequency to that which has been currently reported for FIT in adult populations [25,35,292,302,305] and which reflects current youth resistance training guidelines [17]. Such an approach is provided in Figure 3. Furthermore, since muscle damage following FIT have been shown to reflect those routinely reported following eccentric exercise [329], it important that as the individual reaches post-PHV the inclusion of eccentric overload training within the micro-cycle is further carefully deliberated. The potential greater increases in concentric force production during FIT that would be expected as a product of growth, maturation and training exposure will subsequently result in higher eccentric overload too, which may subsequently heighten fatigue and muscle damage responses that are observed in adults.

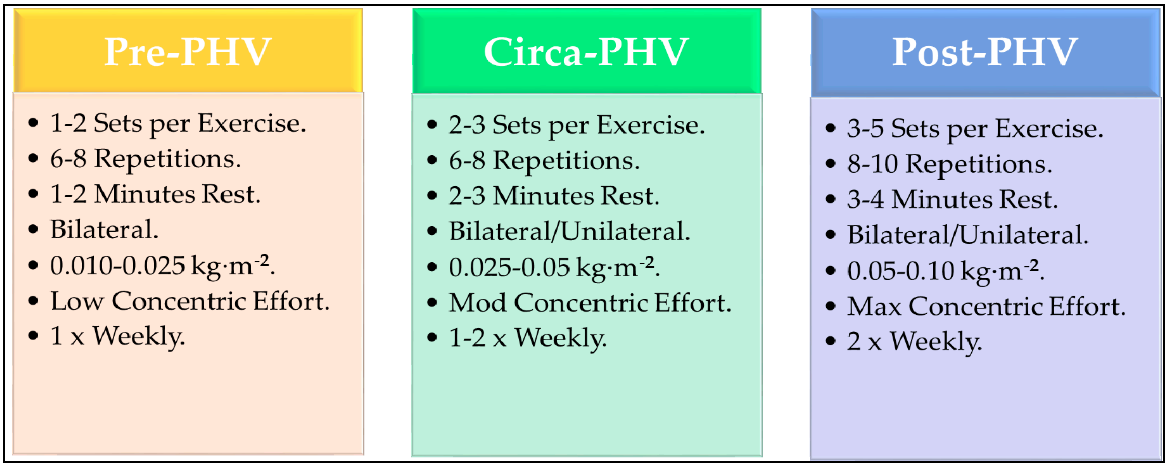

Figure 3. Proposed overview of incorporating FIT methods throughout childhood and adolescence. Please note, different exercises may require different flywheel inertia intensities. Pre-PHV = pre-peak height velocity. Circa-PHV = circa-peak height velocity. Post-PHV = post-peak height velocity. Mod = Moderate. Max = Maximal.

4. Other Programming Considerations

An important consideration for injury prevention throughout youth is the occurrence of conditions such as tendinopathies and how ERT may be able to aid with this. Prevention of these injuries should be targeted in children and adolescents as it is now understood that these may occur earlier than originally thought [330]. An early approach is necessary as knee-related pain injuries such as these can have a negative impact on athletes' future performance and career [331]. The risk for tendinopathy injuries throughout youth would appear to be contributed to by factors such as overuse due to the loading of tendons during sports or vigorous activity [332,333]. This is particularly prudent for the youth athlete as it has been shown that sport specific tendon adaptations such as greater tendon thickness occur in adolescent athletes compared to non-athletes [334,335]. Moreover, a higher prevalence of structural intratendinous changes have been observed in adolescent athletes with patellar tendinopathy symptoms than those without [336]. In addition, intratendinous alterations that were associated with tendinopathies have been reported in adolescent youth athletes compared to recreationally active controls [337]. However, such issues may not only be impacted by training activity but also impacted by growth and maturation processes due to increases in aspects such as moment arm lengths and muscle activation, which leads to a disproportionate increase of muscle strength [338]. Indeed, it has been observed that an imbalance exists between the development of the muscle and tendon in which the greater adaptations and development of the mechanical properties of the tendon occur towards the end stages of adolescence [339–341]. Furthermore, it has been demonstrated that adaptations to training during the earlier stages of youth result in increases in strength but not tendon stiffness [342]. Considering that adaptations of tendon properties to resistance exercise are slower than those of muscle strength [343,344] this may cause an imbalanced adaptation of the muscle and tendon and risk overload and tendon-related injuries [345]. Support for this concept within youth has recently been shown as high levels of tendon strain in adolescent basketball athletes were associated with micro-morphological deterioration of the collagenous network in the proximal patellar tendon, a frequent site affected by tendinopathy [346]. Furthermore, adolescent athletes have been found to reach greater strain magnitudes compared to non-athlete controls indicating an increased mechanical demand for the patellar tendon [347]. Therefore, in light of the aforementioned, specific training that increases tendon stiffness and facilitates a balanced adaptation between muscle and tendon might be important [345–347].

In youth it has been proposed that a combination of growth and loading could act as a "dual" stimulus for tendon growth and improvement of its material properties, increasing the tendon's stiffness throughout maturation [348]. Furthermore, it has been demonstrated that tendon growth from RT, even in pre-pubertal children can occur [349]. It is plausible that training modalities, such as ERT, may be efficacious in not only enhancing force absorption qualities in youth but also reducing tendinopathies by reducing tendon strain via development of the mechanical properties of the tendon. For example, eccentric muscle actions have been shown to positively influence the mechanical properties of the tendon including CSA and stiffness in adult males [350–352]. Indeed, the efficacy of using eccentric training in treating tendinopathies has been provided previously in adults [353,354]. The use of ERT may provide a favourable modality as morphological adaptations and mechanical properties of the tendon respond more positively to high action intensities (≥85% isometric muscle voluntary action) and long action durations (≥3 s;) [355–357]. Indeed, the use of ERT modalities such as FIT has been shown to positively influence the mechanical properties of both the Achilles and patellar tendons enabling them to be more resistant to deformation post-exercise in adult males [358,359]. Also, six weeks of FIT leg press exercise in adult males suffering with chronic patellar tendinopathy improved tendon pain symptoms as well as strength and neuromuscular activation [360]. Interestingly, the inclusion of FIT in adults who are at risk of patellar tendinopathy have shown it to be appropriate during the in-season of basketball and volleyball players in which no complaints regarding patellar tendon pain were provided as well as displaying improvements in lower limb muscle power [361]. Therefore, training modalities that can provide an increase in tendon stiffness that as well as the force generating capacity of the neuromuscular system may be efficacious to help protect against increased strain during maximum muscle actions [345]. As a result, a potential approach in reducing tendinopathy issues throughout youth, particularly patellar tendinopathy, may benefit from a combination of eccentric strength and force absorption approaches that involve (1) development of effective landing mechanics qualities that help reduce joint moments and ground reaction forces (Figure 1); (2) use of ERT methods such as the FIT to aid in the potential development of the MTU (Figure 3); and (3) increasing eccentric muscular strength to further support landing kinematics. However, further research is required to investigate these areas to support this in youth.

5. Conclusions

The inclusion of ERT throughout youth can be incorporated within a well-designed LTAD program that follows current proposed guidelines [6]. However, it should be acknowledged that current research within ERT for youth athletes is its infancy and areas such as training intensities, training volumes, recovery periods and its effects on performance tasks and injury prevention require further investigation. Implementing ERT should be considered as part of a holistic athletic development training programme within youth that should begin during the pre-pubescent stage and progressed throughout all stages of maturation taking into account the individuals technical proficiency, training history, maturity status, and current physical qualities. Initial approaches to the inclusion of ERT may begin within an integrated injury prevention warm up similar to those injury prevention program commonly used for youth but to also ensure a balanced emphasis quality such as landing kinematics, eccentric hamstrings strength, deceleration and COD ability, neuromuscular strength and tendon mechanical properties. Thereafter, specific consideration is required during PHV when injury risk may increase due to maturation-related processes in both male and female adolescents. Once the athlete reaches post-PHV status, further specificity can be provided to elicit greater adaptations due to the athletes' training history and increased benefits observed from RT as this stage [18,19,69]. However, considering that during youth there is a progressive increase of exercise-induced fatigue [125], the inclusion of ERT at this stage may also accompany increased levels of muscle damage symptoms and therefore this should be planned and educated to the youth athlete. Furthermore, we would encourage that recent articles published on the implementation of eccentric training [62,362] act as a point of reference for youth athletes reaching senior levels of performance that is underpinned by a sufficient training history of ERT throughout youth as presented in this article.

Although there may be concerns with regard to the introduction of ERT in youth athletes compared to adults due to factors such as increased risk of fatigue, muscle damage or injury, current evidence would not support these assumptions. Therefore, concomitant to the physiological demands that youth individuals will be exposed to within their sport, it is important that eccentric force qualities are developed throughout youth and not seen as an advanced RT modality. Indeed, in youth, the use of ERT can be viewed as developing aspects such as force absorption/attenuation during tasks such as landing/COD, reducing strength ratios to reduce injury risk as well as potentially acting as a structural mechanism to develop tendon mechanical properties. Importantly, the inclusion of ERT in youth should be seen as part of a holistic LTAD programme that support the development of physical qualities encouraged within LTAD models such as strength, speed, agility, and other factors. Furthermore, throughout childhood and adolescence the use of ERT should be considered a preparatory approach to sufficiently prepare athletes for the demands of elite performance levels and the more intense and specific eccentric training methods that may be trained throughout this period. To improve the current literature, future work should identify the effects of youth eccentric training with regards to training intensity, volumes, recovery periods and its effect on injury prevention in youth. Until such work has been produced, ERT in youth should implemented on an individual approach with low dosages and small progressions in volume and intensity. However, it would appear that the inclusion of ERT in youth may confer numerous benefits and so practitioners working with this population should contemplate its inclusion within LTAD.

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References

1. Ford, P.; de Ste Croix, M.; Lloyd, R.; Meyers, R.; Moosavi, M.; Oliver, J.; Till, K.; Williams, C. The Long-Term Athlete Development Model: Physiological Evidence and Application. *J. Sports Sci.* **2011**. [CrossRef] [PubMed]
2. Lloyd, R.S.; Cronin, J.B.; Faigenbaum, A.D.; Haff, G.G.; Howard, R.; Kraemer, W.J.; Micheli, L.J.; Myer, G.D.; Oliver, J.L. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *J. Strength Cond. Res.* **2016**, *30*, 1491–1509. [CrossRef] [PubMed]
3. Bergeron, M.F.; Mountjoy, M.; Armstrong, N.; Chia, M.; Côté, J.; Emery, C.A.; Faigenbaum, A.; Hall, G.; Kriemler, S.; Léglise, M.; et al. International Olympic Committee Consensus Statement on Youth Athletic Development. *Br. J. Sports Med.* **2015**. [CrossRef] [PubMed]
4. LaPrade, R.F.; Agel, J.; Baker, J.; Brenner, J.S.; Cordasco, F.A.; Côté, J.; Engebretsen, L.; Feeley, B.T.; Gould, D.; Hainline, B.; et al. AOSSM Early Sport Specialization Consensus Statement. *Orthop. J. Sport. Med.* **2016**. [CrossRef] [PubMed]
5. Lloyd, R.S.; Faigenbaum, A.D.; Stone, M.H.; Oliver, J.L.; Jeffreys, I.; Moody, J.A.; Brewer, C.; Pierce, K.C.; McCambridge, T.M.; Howard, R.; et al. Position Statement on Youth Resistance Training: The 2014 International Consensus. *Br. J. Sports Med.* **2014**. [CrossRef] [PubMed]
6. Lloyd, R.S.; Oliver, J.L. The Youth Physical Development Model: A New Approach to Long-Term Athletic Development. *Strength Cond. J.* **2012**. [CrossRef]
7. Pearson, D.T.; Naughton, G.A.; Torode, M. Predictability of Physiological Testing and the Role of Maturation in Talent Identification for Adolescent Team Sports. *J. Sci. Med. Sport.* **2006**. [CrossRef]
8. Bourgeois, F.; Gamble, P.; Gill, N.; McGuigan, M. Effects of a Six-Week Strength Training Programme on Change of Direction Performance in Youth Team Sport Athletes. *Sports* **2017**, *5*, 83. [CrossRef]

9. Thomas, C.; Comfort, P.; Jones, P.A.; Dos'Santos, T. A Comparison of Isometric Midthigh-Pull Strength, Vertical Jump, Sprint Speed, and Change-of-Direction Speed in Academy Netball Players. *Int. J. Sports Physiol. Perform.* **2017**. [CrossRef]
10. McKinlay, B.J.; Wallace, P.J.; Dotan, R.; Long, D.; Tokuno, C.; Gabriel, D.A.; Falk, B. Isometric and Dynamic Strength and Neuromuscular Attributes as Predictors of Vertical Jump Performance in 11- to 13-Year-Old Male Athletes. *Appl. Physiol. Nutr. Metab.* **2017**. [CrossRef]
11. Secomb, J.L.; Lundgren, L.E.; Farley, O.R.L.; Tran, T.T.; Nimphius, S.; Sheppard, J.M. Relationships between Lower-Body Muscle Structure and Lower-Body Strength, Power, and Muscle-Tendon Complex Stiffness. *J. Strength Cond. Res.* **2015**. [CrossRef] [PubMed]
12. Peñailillo, L.; Espíldora, F.; Jannas-Vela, S.; Mujika, I.; Zbinden-Foncea, H. Muscle Strength and Speed Performance in Youth Soccer Players. *J. Hum. Kinet.* **2016**. [CrossRef] [PubMed]
13. Hammami, R.; Chaouachi, A.; Makhlouf, I.; Granacher, U.; Behm, D.G. Associations between Balance and Muscle Strength, Power Performance in Male Youth Athletes of Different Maturity Status. *Pediatr. Exerc. Sci.* **2016**. [CrossRef] [PubMed]
14. Zwolski, C.; Quatman-Yates, C.; Paterno, M.V. Resistance Training in Youth: Laying the Foundation for Injury Prevention and Physical Literacy. *Sports Health.* **2017**. [CrossRef]
15. Peitz, M.; Behringer, M.; Granacher, U. A Systematic Review on the Effects of Resistance and Plyometric Training on Physical Fitness in Youth- What Do Comparative Studies Tell Us? *PLoS ONE* **2018**. [CrossRef]
16. Faigenbaum, A.D.; Myer, G.D. Resistance Training among Young Athletes: Safety, Efficacy and Injury Prevention Effects. *Br. J. Sports Med.* **2010**. [CrossRef]
17. Legerlotz, K.; Marzilger, R.; Bohm, S.; Arampatzis, A. Physiological Adaptations Following Resistance Training in Youth Athletes-a Narrative Review. *Pediatric Exerc. Sci.* **2016**. [CrossRef]
18. Moran, J.; Sandercock, G.R.H.; Ramírez-Campillo, R.; Meylan, C.; Collison, J.; Parry, D.A. A Meta-Analysis of Maturation-Related Variation in Adolescent Boy Athletes' Adaptations to Short-Term Resistance Training. *J. Sports Sci.* **2017**, *35*, 1041–1051. [CrossRef]
19. Moran, J.; Sandercock, G.; Ramirez-Campillo, R.; Clark, C.C.T.; Fernandes, J.F.T.; Drury, B. A Meta-Analysis of Resistance Training in Female Youth: Its Effect on Muscular Strength, and Shortcomings in the Literature. *Sports Med.* **2018**. [CrossRef]
20. Lesinski, M.; Prieske, O.; Granacher, U. Effects and Dose-Response Relationships of Resistance Training on Physical Performance in Youth Athletes: A Systematic Review and Meta-Analysis. *Br. J. Sports Med.* **2016**, 781–795. [CrossRef]
21. Behm, D.G.; Young, J.D.; Whitten, J.H.D.; Reid, J.C.; Quigley, P.J.; Low, J.; Li, Y.; Lima, C.D.; Hodgson, D.D.; Chaouachi, A.; et al. Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis. *Front. Physiol.* **2017**. [CrossRef] [PubMed]
22. Wagle, J.P.; Taber, C.B.; Cunanan, A.J.; Bingham, G.E.; Carroll, K.M.; DeWeese, B.H.; Sato, K.; Stone, M.H. Accentuated Eccentric Loading for Training and Performance: A Review. *Sports Med.* **2017**. [CrossRef] [PubMed]
23. Douglas, J.; Pearson, S.; Ross, A.; McGuigan, M. Eccentric Exercise: Physiological Characteristics and Acute Responses. *Sports Med.* **2017**. [CrossRef] [PubMed]
24. Douglas, J.; Pearson, S.; Ross, A.; McGuigan, M. Chronic Adaptations to Eccentric Training: A Systematic Review. *Sports Med.* **2017**. [CrossRef]
25. Sabido, R.; Hernández-Davó, J.L.; Botella, J.; Navarro, A.; Tous-Fajardo, J. Effects of adding a weekly eccentric-overload training session on strength and athletic performance in team-handball players. *Eur. J. Sport Sci.* **2017**, *17*, 530–538. [CrossRef]
26. Walker, S.; Blazevich, A.J.; Haff, G.G.; Tufano, J.J.; Newton, R.U.; Häkkinen, K. Greater Strength Gains after Training with Accentuated Eccentric than Traditional Isoinertial Loads in Already Strength-Trained Men. *Front. Physiol.* **2016**, *7*. [CrossRef]
27. Papadopoulos, C.; Theodosiou, K.; Bogdanis, G.C.; Gkantiraga, E.; Gissis, I.; Sambanis, M.; Souglis, A.; Sotiropoulos, A. Multiarticular Isokinetic High-Load Eccentric Training Induces Large Increases in Eccentric and Concentric Strength and Jumping Performance. *J. Strength Cond. Res.* **2014**. [CrossRef]
28. Brandenburg, J.P.; Docherty, D. The Effects of Accentuated Eccentric Loading on Strength, Muscle Hypertrophy, and Neural Adaptations in Trained Individuals. *J. Strength Cond. Res.* **2002**. [CrossRef]

29. Vikne, H.; Refsnes, P.E.; Ekmark, M.; Medbø, J.I.; Gundersen, V.; Gundersen, K. Muscular Performance after Concentric and Eccentric Exercise in Trained Men. *Med. Sci. Sports Exerc.* **2006**. [CrossRef]
30. Douglas, J.; Pearson, S.; Ross, A.; McGuigan, M. Effects of Accentuated Eccentric Loading on Muscle Properties, Strength, Power, and Speed in Resistance-Trained Rugby Players. *J. Strength Cond. Res.* **2018**. [CrossRef]
31. Carothers, K.; Carothers, K.F.; Alvar, B.A.; Dodd, D.J.; Johanson, J.C.; Kincade, B.J.; Kelly, S.B. Comparison of Muscular Strength Gains Utilizing Eccentric, Standard and Concentric Resistance Training Protocols. *J. Strength Cond. Res.* **2010**. [CrossRef]
32. Dolezal, S.M.; Frese, D.L.; Llewellyn, T.L. The effects of eccentric, velocity-based training on strength and power in collegiate athletes. *Int. J. Exerc. Sci.* **2016**, *9*, 657. [PubMed]
33. Douglas, J.; Pearson, S.; Ross, A.; McGuigan, M. Reactive and eccentric strength contribute to stiffness regulation during maximum velocity sprinting in team sport athletes and highly trained sprinters. *J. Sports Sci.* **2019**, 1–9. [CrossRef] [PubMed]
34. Mike, J.N.; Cole, N.; Herrera, C.; Vandusseldorp, T.; Kravitz, L.; Kerksick, C.M. The Effects of Eccentric Action Duration on Muscle Strength, Power Production, Vertical Jump, and Soreness. *J. Strength Cond. Res.* **2017**. [CrossRef] [PubMed]
35. Núñez, F.J.; Santalla, A.; Carrasquila, I.; Asian, J.A.; Reina, J.I.; Suarez-Arrones, L.J. 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* **2018**. [CrossRef] [PubMed]
36. Doan, B.K.; Newton, R.U.; Marsit, J.L.; Triplett-McBride, N.T.; Koziris, L.P.; Fry, A.C.; Kraemer, W.J. Effects of Increased Eccentric Loading on Bench Press 1RM. *J. Strength Cond. Res.* **2002**. [CrossRef]
37. Gonzalo-Skok, O.; Tous-Fajardo, J.; Valero-Campo, C.; Berzosa, C.; Bataller, A.V.; Arjol-Serrano, J.L.; Moras, G.; Mendez-Villanueva, A. Eccentric-Overload Training in Team-Sport Functional Performance: Constant Bilateral Vertical versus Variable Unilateral Multidirectional Movements. *Int. J. Sports Physiol. Perform.* **2017**. [CrossRef]
38. Bridgeman, L.A.; McGuigan, M.R.; Gill, N.D.; Dulson, D.K. The Effects of Accentuated Eccentric Loading on the Drop Jump Exercise and the Subsequent Postactivation Potentiation Response. *J. Strength Cond. Res.* **2017**. [CrossRef]
39. Munger, C.N.; Archer, D.C.; Leyva, W.D.; Wong, M.A.; Coburn, J.W.; Costa, P.B.; Brown, L.E. Acute Effects of Eccentric Overload on Concentric Front Squat Performance. *J. Strength Cond. Res.* **2017**. [CrossRef]
40. Sheppard, J.; Newton, R.; McGuigan, M. The Effect of Accentuated Eccentric Load on Jump Kinetics in High-Performance Volleyball Players. *Int. J. Sports Sci. Coach.* **2007**. [CrossRef]
41. Friedmann-Bette, B.; Bauer, T.; Kinscherf, R.; Vorwald, S.; Klute, K.; Bischoff, D.; Müller, H.; Weber, M.A.; Metz, J.; Kauczor, H.U.; et al. Effects of Strength Training with Eccentric Overload on Muscle Adaptation in Male Athletes. *Eur. J. Appl. Physiol.* **2010**. [CrossRef] [PubMed]
42. Sheppard, J.M.; Young, K. Using Additional Eccentric Loads to Increase Concentric Performance in the Bench Throw. *J. Strength Cond. Res.* **2010**. [CrossRef] [PubMed]
43. Aboodarda, S.J.; Byrne, J.M.; Samson, M.; Wilson, B.D.; Mokhtar, A.H.; Behm, D.G. Does Performing Drop Jumps with Additional Eccentric Loading Improve Jump Performance? *J. Strength Cond. Res.* **2014**. [CrossRef] [PubMed]
44. Hughes, J.D.; Massiah, R.G.; Clarke, R.D. The Potentiating Effect of an Accentuated Eccentric Load on Countermovement Jump Performance. *J. Strength Cond. Res.* **2016**. [CrossRef]
45. Ong, J.H.; Lim, J.; Chong, E.; Tan, F. The Effects of Eccentric Conditioning Stimuli on Subsequent Counter-Movement Jump Performance. *J. Strength Cond. Res.* **2016**. [CrossRef]
46. Sheppard, J.; Hobson, S.; Barker, M.; Taylor, K.; Chapman, D.; McGuigan, M.; Newton, R. The Effect of Training with Accentuated Eccentric Load Counter-Movement Jumps on Strength and Power Characteristics of High-Performance Volleyball Players. *Int. J. Sports Sci. Coach.* **2008**, *3*, 355–363. [CrossRef]
47. De Hoyo, M.; Pozzo, M.; Sañudo, B.; Carrasco, L.; Gonzalo-Skok, O.; Domínguez-Cobo, S.; Morán-Camacho, E. Effects of a 10-Week in-Season Eccentric-Overload Training Program on Muscle-Injury Prevention and Performance in Junior Elite Soccer Players. *Int. J. Sports Physiol. Perform.* **2015**. [CrossRef]
48. Tous-Fajardo, J.; Gonzalo-Skok, O.; Arjol-Serrano, J.L.; Tesch, P. Enhancing Change-of-Direction Speed in Soccer Players by Functional Inertial Eccentric Overload and Vibration Training. *Int. J. Sports Physiol. Perform.* **2016**. [CrossRef]

49. Krommes, K.; Petersen, J.; Nielsen, M.B.; Aagaard, P.; Hölmich, P.; Thorborg, K. Sprint and Jump Performance in Elite Male Soccer Players Following a 10-Week Nordic Hamstring Exercise Protocol: A Randomised Pilot Study. *BMC Res. Notes* **2017**. [CrossRef]
50. Siddle, J.; Greig, M.; Weaver, K.; Page, R.M.; Harper, D.; Brogden, C.M. Acute Adaptations and Subsequent Preservation of Strength and Speed Measures Following a Nordic Hamstring Curl Intervention: A Randomised Controlled Trial. *J. Sports Sci.* **2019**. [CrossRef]
51. Ishøi, L.; Hölmich, P.; Aagaard, P.; Thorborg, K.; Bandholm, T.; Serner, A. Effects of the Nordic Hamstring Exercise on Sprint Capacity in Male Football Players: A Randomized Controlled Trial. *J. Sports Sci.* **2017**, 1–10. [CrossRef] [PubMed]
52. Mendiguchia, J.; Martinez-Ruiz, E.; Morin, J.B.; Samozino, P.; Edouard, P.; Alcaraz, P.E.; Esparza-Ros, F.; Mendez-Villanueva, A. Effects of Hamstring-Emphasized Neuromuscular Training on Strength and Sprinting Mechanics in Football Players. *Scand. J. Med. Sci. Sports* **2015**. [CrossRef] [PubMed]
53. Coratella, G.; Schena, F. Eccentric Resistance Training Increases and Retains Maximal Strength, Muscle Endurance, and Hypertrophy in Trained Men. *Appl. Physiol. Nutr. Metab.* **2016**. [CrossRef] [PubMed]
54. Franchi, M.V.; Atherton, P.J.; Reeves, N.D.; Flück, M.; Williams, J.; Mitchell, W.K.; Selby, A.; Beltran Valls, R.M.; Narici, M.V. Architectural, Functional and Molecular Responses to Concentric and Eccentric Loading in Human Skeletal Muscle. *Acta Physiol.* **2014**. [CrossRef]
55. Mjølsnes, R.; Arnason, A.; Østhagen, T.; Raastad, T.; Bahr, R. A 10-Week Randomized Trial Comparing Eccentric vs. Concentric Hamstring Strength Training in Well-Trained Soccer Players. *Scand. J. Med. Sci. Sport* **2004**. [CrossRef]
56. Bourne, M.N.; Opar, D.A.; Williams, M.D.; Shield, A.J. Eccentric Knee Flexor Strength and Risk of Hamstring Injuries in Rugby Union. *Am. J. Sports Med.* **2015**. [CrossRef]
57. Al Attar, W.S.A.; Soomro, N.; Sinclair, P.J.; Pappas, E.; Sanders, R.H. Effect of Injury Prevention Programs That Include the Nordic Hamstring Exercise on Hamstring Injury Rates in Soccer Players: A Systematic Review and Meta-Analysis. *Sports Med.* **2017**. [CrossRef]
58. Tyler, T.F.; Schmitt, B.M.; Nicholas, S.J.; McHugh, M.P. Rehabilitation after Hamstring-Strain Injury Emphasizing Eccentric Strengthening at Long Muscle Lengths: Results of Long-Term Follow-Up. *J. Sport Rehabil.* **2017**. [CrossRef]
59. Croisier, J.L.; Forthomme, B.; Namurois, M.H.; Vanderthommen, M.; Crielaard, J.M. Hamstring muscle strain recurrence and strength performance disorders. *Am. J. Sports Med.* **2002**, *30*, 199–203. [CrossRef]
60. Proske, U.; Morgan, D.L. Muscle Damage from Eccentric Exercise: Mechanism, Mechanical Signs, Adaptation and Clinical Applications. *J. Physiol.* **2001**. [CrossRef]
61. Dueweke, J.J.; Awan, T.M.; Mendias, C.L. Regeneration of skeletal muscle after eccentric injury. *J. Sport Rehabil.* **2017**, *26*, 171–179. [CrossRef] [PubMed]
62. Suchomel, T.J.; Wagle, J.P.; Douglas, J.; Taber, C.B.; Harden, M.; Haff, G.G.; Stone, M.H. Implementing Eccentric Resistance Training—Part 1: A Brief Review of Existing Methods. *J. Funct. Morphol. Kinesiol.* **2019**, *4*, 38. [CrossRef]
63. Granacher, U.; Lesinski, M.; Büsch, D.; Muehlbauer, T.; Prieske, O.; Puta, C.; Gollhofer, A.; Behm, D.G. Effects of Resistance Training in Youth Athletes on Muscular Fitness and Athletic Performance: A Conceptual Model for Long-Term Athlete Development. *Front. Physiol.* **2016**. [CrossRef] [PubMed]
64. Hatzikotoulas, K.; Patikas, D.; Ratel, S.; Bassa, E.; Kotzamanidis, C. Central and Peripheral Fatigability in Boys and Men during Maximal Action. *Med. Sci. Sports Exerc.* **2014**. [CrossRef]
65. Armatas, V.; Bassa, E.; Patikas, D.; Kitsas, I.; Zangelidis, G.; Kotzamanidis, C. Neuromuscular Differences between Men and Prepubescent Boys during a Peak Isometric Knee Extension Intermittent Fatigue Test. *Pediatr. Exerc. Sci.* **2010**. [CrossRef]
66. Dotan, R.; Mitchell, C.J.; Cohen, R.; Gabriel, D.; Klentrou, P.; Falk, B. Explosive Sport Training and Torque Kinetics in Children. *Appl. Physiol. Nutr. Metab.* **2013**. [CrossRef]
67. Zafeiridis, A.; Dalamitros, A.; Dipla, K.; Manou, V.; Galanis, N.; Kellis, S. Recovery during High-Intensity Intermittent Anaerobic Exercise in Boys, Teens, and Men. *Med. Sci. Sports Exerc.* **2005**. [CrossRef]
68. Halin, R.; Germain, P.; Bercier, S.; Kapitaniak, B.; Buttelli, O. Neuromuscular Response of Young Boys versus Men during Sustained Maximal Action. *Med. Sci. Sports Exerc.* **2003**. [CrossRef]

69. Lloyd, R.S.; Radnor, J.M.; De Ste Croix, M.B.A.; Cronin, J.B.; Oliver, J.L. Changes in Sprint and Jump Performances after Traditional, Plyometric, and Combined Resistance Training in Male Youth Pre- and Post-Peak Height Velocity. *J. Strength Cond. Res.* **2016**. [CrossRef]
70. Dotan, R.; Mitchell, C.; Cohen, R.; Klentrou, P.; Gabriel, D.; Falk, B. Child—Adult Differences in Muscle Activation—A Review. *Pediatr. Exerc. Sci.* **2012**. [CrossRef]
71. Falk, B.; Dotan, R. Child-Adult Differences in the Recovery from High-Intensity Exercise. *Exerc. Sport Sci. Rev.* **2006**, 107–112. [CrossRef] [PubMed]
72. Patikas, D.A.; Williams, C.A.; Ratel, S. Exercise-Induced Fatigue in Young People: Advances and Future Perspectives. *Eur. J. Appl. Physiol.* **2018**. [CrossRef] [PubMed]
73. Murphy, J.R.; Button, D.C.; Chaouachi, A.; Behm, D.G. Prepubescent Males Are Less Susceptible to Neuromuscular Fatigue Following Resistance Exercise. *Eur. J. Appl. Physiol.* **2014**. [CrossRef] [PubMed]
74. Paraschos, I.; Hassani, A.; Bassa, E.; Hatzikotoulas, K.; Patikas, D.; Kotzamanidis, C. Fatigue Differences between Adults and Prepubertal Males. *Int. J. Sports Med.* **2007**. [CrossRef] [PubMed]
75. Dipla, K.; Tsirini, T.; Zafeiridis, A.; Manou, V.; Dalamitros, A.; Kellis, E.; Kellis, S. Fatigue Resistance during High-Intensity Intermittent Exercise from Childhood to Adulthood in Males and Females. *Eur. J. Appl. Physiol.* **2009**. [CrossRef] [PubMed]
76. Croix, M.B.A.D.S.; Deighan, M.A.; Ratel, S.; Armstrong, N. Age-and Sex-Associated Differences in Isokinetic Knee Muscle Endurance between Young Children and Adults. *Appl. Physiol. Nutr. Metab.* **2009**. [CrossRef]
77. Kotzamanidou, M.; Michailidis, I.; Hatzikotoulas, K.; Hasani, A.; Bassa, E.; Kotzamanidis, C. Differences in Recovery Process between Adult and Prepubertal Males after a Maximal Isokinetic Fatigue Task. *Isokinet. Exerc. Sci.* **2005**, *13*, 261–266. [CrossRef]
78. Piponnier, E.; Martin, V.; Bontemps, B.; Chalchat, E.; Julian, V.; Bocock, O.; Duclos, M.; Ratel, S. Child-Adult Differences in Neuromuscular Fatigue Are Muscle Dependent. *J. Appl. Physiol.* **2018**. [CrossRef]
79. Streckis, V.; Skurvydas, A.; Ratkevicius, A. Children Are More Susceptible to Central Fatigue than Adults. *Muscle Nerve Off. J. Am. Assoc. Electrodiagn. Med.* **2007**, *36*, 357–363. [CrossRef]
80. Piponnier, E.; Martin, V.; Chalchat, E.; Bontemps, B.; Julian, V.; Bocock, O.; Duclos, M.; Ratel, S. Effect of MTU Length on Child–Adult Difference in Neuromuscular Fatigue. *Med. Sci. Sport. Exerc.* **2019**. [CrossRef]
81. Tanina, H.; Nishimura, Y.; Tsuboi, H.; Sakata, T.; Nakamura, T.; Murata, K.Y.; Arakawa, H.; Umezu, Y.; Tajima, F. Fatigue-Related Differences in Erector Spinae between Prepubertal Children and Young Adults Using Surface Electromyographic Power Spectral Analysis. *J. Back Musculoskelet. Rehabil.* **2017**. [CrossRef] [PubMed]
82. Hatzikotoulas, K.; Patikas, D.; Bassa, E.; Hadjileontiadis, L.; Koutedakis, Y.; Kotzamanidis, C. Submaximal Fatigue and Recovery in Boys and Men. *Int. J. Sports Med.* **2009**. [CrossRef] [PubMed]
83. Patikas, D.; Kansizoglou, A.; Koutlianos, N.; Williams, C.A.; Hatzikotoulas, K.; Bassa, E.; Kotzamanidis, C. Fatigue and Recovery in Children and Adults during Sustained Actions at 2 Different Submaximal Intensities. *Appl. Physiol. Nutr. Metab.* **2013**. [CrossRef] [PubMed]
84. Mendell, L.M. The Size Principle: A Rule Describing the Recruitment of Motoneurons. *J. Neurophysiol.* **2005**. [CrossRef] [PubMed]
85. Bottaro, M.; Brown, L.E.; Celes, R.; Martorelli, S.; Carregaro, R.; De Brito Vidal, J.C. Effect of Rest Interval on Neuromuscular and Metabolic Responses between Children and Adolescents. *Pediatr. Exerc. Sci.* **2011**. [CrossRef] [PubMed]
86. Vidal Filho, J.C.D.B.; Ferreira, C.E.S.; Sales, M.P.M.D.; Almeida, J.A.D.; Bottaro, M. Effects of different rest intervals on muscular performance in children. *Rev. Educ. Física UEM* **2011**, *22*, 613–622.
87. Faigenbaum, A.D.; Ratamess, N.A.; McFarland, J.; Kaczmarek, J.; Coraggio, M.J.; Kang, J.; Hoffman, J.R. Effect of Rest Interval Length on Bench Press Performance in Boys, Teens, and Men. *Pediatr. Exerc. Sci.* **2008**, *20*, 457–469. [CrossRef]
88. Tibana, R.A.; Prestes, J.; Da Cunha Nascimento, D.; Martins, O.V.; De Santana, F.S.; Balsamo, S. Higher Muscle Performance in Adolescents Compared with Adults after a Resistance Training Session with Different Rest Intervals. *J. Strength Cond. Res.* **2012**. [CrossRef]
89. Martin, V.; Kluka, V.; Garcia Vicencio, S.; Maso, F.; Ratel, S. Children Have a Reduced Maximal Voluntary Activation Level of the Adductor Pollicis Muscle Compared to Adults. *Eur. J. Appl. Physiol.* **2015**, *115*, 1485–1491. [CrossRef]

90. Kluka, V.; Martin, V.; Vicencio, S.G.; Jegu, A.G.; Cardenoux, C.; Morio, C.; Coudeyre, E.; Ratel, S. Effect of Muscle Length on Voluntary Activation Level in Children and Adults. *Med. Sci. Sports Exerc.* **2015**, *47*, 718–724. [CrossRef]
91. O'Brien, T.D.; Reeves, N.D.; Baltzopoulos, V.; Jones, D.A.; Maganaris, C.N. In Vivo Measurements of Muscle Specific Tension in Adults and Children. *Exp. Physiol.* **2010**. [CrossRef] [PubMed]
92. Grosset, J.F.; Mora, I.; Lambertz, D.; Pérot, C. Voluntary Activation of the Triceps Surae in Prepubertal Children. *J. Electromyogr. Kinesiol.* **2008**, *18*, 455–465. [CrossRef] [PubMed]
93. Kluka, V.; Martin, V.; Vicencio, S.G.; Giustiniani, M.; Morel, C.; Morio, C.; Coudeyre, E.; Ratel, S. Effect of Muscle Length on Voluntary Activation of the Plantar Flexors in Boys and Men. *Eur. J. Appl. Physiol.* **2016**, *116*, 1043–1051. [CrossRef] [PubMed]
94. Belanger, A.Y.; McComas, A.J. Contractile Properties of Human Skeletal Muscle in Childhood and Adolescence. *Eur. J. Appl. Physiol. Occup. Physiol.* **1989**. [CrossRef]
95. Koh, T.H.H.G.; Eyre, J.A. Maturation of Corticospinal Tracts Assessed by Electromagnetic Stimulation of the Motor Cortex. *Arch. Dis. Child.* **1988**. [CrossRef]
96. Lexell, J.; Sjöström, M.; Nordlund, A.-S.; Taylor, C.C. Growth and Development of Human Muscle: A Quantitative Morphological Study of Whole Vastus Lateralis from Childhood to Adult Age. *Muscle Nerve Off. J. Am. Assoc. Electrodiagn. Med.* **1992**, *15*, 404–409. [CrossRef]
97. Pitt, B.; Dotan, R.; Millar, J.; Long, D.; Tokuno, C.; O'Brien, T.; Falk, B. The Electromyographic Threshold in Boys and Men. *Eur. J. Appl. Physiol.* **2015**, *115*, 1273–1281. [CrossRef]
98. Long, D.; Dotan, R.; Pitt, B.; McKinlay, B.; O'Brien, T.D.; Tokuno, C.; Falk, B. The Electromyographic Threshold in Girls and Women. *Pediatr. Exerc. Sci.* **2017**. [CrossRef]
99. Dotan, R. Children's Neuromotor and Muscle-Functional Attributes—Outstanding Issues. *Pediatr. Exerc. Sci.* **2016**, *28*, 202–209. [CrossRef]
100. Lichtwark, G.A.; Barclay, C.J. A Compliant Tendon Increases Fatigue Resistance and Net Efficiency during Fatiguing Cyclic Actions of Mouse Soleus Muscle. *Acta Physiol.* **2012**. [CrossRef]
101. Ratel, S.; Kluka, V.; Vicencio, S.G.; Jegu, A.G.; Cardenoux, C.; Morio, C.; Coudeyre, E.; Martin, V. Insights into the Mechanisms of Neuromuscular Fatigue in Boys and Men. *Med. Sci. Sports Exerc.* **2015**. [CrossRef] [PubMed]
102. Armstrong, N.; Barker, A.R.; McManus, A.M. Muscle Metabolism Changes with Age and Maturation: How Do They Relate to Youth Sport Performance? *Br. J. Sports Med.* **2015**, *49*, 860–864. [CrossRef] [PubMed]
103. Weinstein, Y.; Inbar, O.; Mor-Unikovski, R.; Luder, A.; Dubnov-Raz, G. Recovery of Upper-Body Muscle Power after Short Intensive Exercise: Comparing Boys and Men. *Eur. J. Appl. Physiol.* **2018**. [CrossRef] [PubMed]
104. Engel, F.A.; Sperlich, B.; Stockinger, C.; Hartel, S.; Bos, K.; Holmberg, H.C. The Kinetics of Blood Lactate in Boys during and Following a Single and Repeated All-out Sprints of Cycling Are Different than in Men. *Appl. Physiol. Nutr. Metab.* **2015**. [CrossRef]
105. Dotan, R.; Ohana, S.; Bediz, C.; Falk, B. Blood Lactate Disappearance Dynamics in Boys and Men Following Exercise of Similar and Dissimilar Peak-Lactate Concentrations. *J. Pediatr. Endocrinol. Metab.* **2003**, *16*, 419–429. [CrossRef]
106. Ratel, S.; Bedu, M.; Hennegrave, A.; Doré, E.; Duché, P. Effects of Age and Recovery Duration on Peak Power Output during Repeated Cycling Sprints. *Int. J. Sports Med.* **2002**, *23*, 397–402. [CrossRef]
107. Kappenstein, J.; Fernández-Fernández, J.; Engel, F.; Ferrauti, A. Effects of Active and Passive Recovery on Blood Lactate and Blood PH after a Repeated Sprint Protocol in Children and Adults. *Pediatr. Exerc. Sci.* **2015**, *27*, 77–84. [CrossRef]
108. Buchheit, M.; Duché, P.; Laursen, P.B.; Ratel, S. Postexercise Heart Rate Recovery in Children: Relationship with Power Output, Blood PH, and Lactate. *Appl. Physiol. Nutr. Metab.* **2010**. [CrossRef]
109. Beneke, R.; Hütler, M.; Jung, M.; Leithäuser, R.M. Modeling the Blood Lactate Kinetics at Maximal Short-Term Exercise Conditions in Children, Adolescents, and Adults. *J. Appl. Physiol.* **2005**. [CrossRef]
110. Ratel, S.; Duche, P.; Hennegrave, A.; Van Praagh, E.; Bedu, M. Acid-Base Balance during Repeated Cycling Sprints in Boys and Men. *J. Appl. Physiol.* **2002**, *92*, 479–485. [CrossRef]
111. McCormack, S.E.; McCarthy, M.A.; Farilla, L.; Hrovat, M.I.; Systrom, D.M.; Grinspoon, S.K.; Fleischman, A. Skeletal Muscle Mitochondrial Function Is Associated with Longitudinal Growth Velocity in Children and Adolescents. *J. Clin. Endocrinol. Metab.* **2011**. [CrossRef] [PubMed]

112. Ratel, S.; Tonson, A.; Le Fur, Y.; Cozzone, P.; Bendahan, D. Comparative Analysis of Skeletal Muscle Oxidative Capacity in Children and Adults: A 31P-MRS Study. *Appl. Physiol. Nutr. Metab.* **2008**. [CrossRef] [PubMed]
113. Taylor, D.J.; Kemp, G.J.; Thompson, C.H.; Radda, G.K. Ageing: Effects on Oxidative Function of Skeletal Muscle in Vivo. *Mol. Cell. Biochem.* **1997**. [CrossRef]
114. Kappenstein, J.; Ferrauti, A.; Runkel, B.; Fernandez-Fernandez, J.; Müller, K.; Zange, J. Changes in Phosphocreatine Concentration of Skeletal Muscle during High-Intensity Intermittent Exercise in Children and Adults. *Eur. J. Appl. Physiol.* **2013**, *113*, 2769–2779. [CrossRef] [PubMed]
115. Birat, A.; Bourdier, P.; Piponnier, E.; Blazevich, A.J.; Maciejewski, H.; Duché, P.; Ratel, S. Metabolic and Fatigue Profiles Are Comparable between Prepubertal Children and Well-Trained Adult Endurance Athletes. *Front. Physiol.* **2018**. [CrossRef]
116. Boisseau, N.; Delamarche, P. Metabolic and Hormonal Responses to Exercise in Children and Adolescents. *Sports Med.* **2000**. [CrossRef] [PubMed]
117. Fleischman, A.; Makimura, H.; Stanley, T.L.; McCarthy, M.A.; Kron, M.; Sun, N.; Chuzi, S.; Hrovat, M.I.; Systrom, D.M.; Grinspoon, S.K. Skeletal Muscle Phosphocreatine Recovery after Submaximal Exercise in Children and Young and Middle-Aged Adults. *J. Clin. Endocrinol. Metab.* **2010**, *95*, E69–E74. [CrossRef]
118. Berg, A.; Kim, S.S.; Keul, J. Skeletal Muscle Enzyme Activities in Healthy Young Subjects. *Int. J. Sports Med.* **1986**. [CrossRef]
119. Berg, A.; Keul, J. Biochemical changes during exercise in children. In *Young Athletes/Biological, Psychological and Educational Perspectives*; Malina, R., Ed.; Human Kinetics: Champaign, IL, USA, 1988; pp. 61–77.
120. Eriksson, B.O.; Gollnick, P.D.; Saltin, B. Muscle Metabolism and Enzyme Activities after Training in Boys 11–13 Years Old. *Acta Physiol. Scand.* **1973**. [CrossRef]
121. Haralambie, G. Enzyme Activities in Skeletal Muscle of 13-15 Years Old Adolescents. *Clin. Respir. Physiol.* **1982**, *18*, 65–74.
122. Hoppeler, H.; Lüthi, P.; Claassen, H.; Weibel, E.R.; Howald, H. The Ultrastructure of the Normal Human Skeletal Muscle—A Morphometric Analysis on Untrained Men, Women and Well-Trained Orienteers. Pflügers Arch. *Eur. J. Physiol.* **1973**. [CrossRef]
123. Ratel, S.; Blazevich, A.J. Are Prepubertal Children Metabolically Comparable to Well-Trained Adult Endurance Athletes? *Sports Med.* **2017**. [CrossRef] [PubMed]
124. Eston, R.; Byrne, C.; Twist, C. Muscle function after exercise-induced muscle damage: Considerations for athletic performance in children and adults. *J. Exerc. Sci. Fit.* **2003**, *1*, 85–96.
125. Ratel, S.; Martin, V. Is There a Progressive Withdrawal of Physiological Protections against High-Intensity Exercise-Induced Fatigue during Puberty? *Sports* **2015**, *3*, 346–357. [CrossRef]
126. Kanda, K.; Sugama, K.; Hayashida, H.; Sakuma, J.; Kawakami, Y.; Miura, S.; Yoshioka, H.; Mori, Y.; Suzuki, K. Eccentric Exercise-Induced Delayed-Onset Muscle Soreness and Changes in Markers of Muscle Damage and Inflammation. *Exerc. Immunol. Rev.* **2013**, *19*, 72–85.
127. Hyldahl, R.D.; Hubal, M.J. Lengthening Our Perspective: Morphological, Cellular, and Molecular Responses to Eccentric Exercise. *Muscle Nerve* **2014**. [CrossRef]
128. Goodall, S.; Thomas, K.; Barwood, M.; Keane, K.; Gonzalez, J.T.; St Clair Gibson, A.; Howatson, G. Neuromuscular Changes and the Rapid Adaptation Following a Bout of Damaging Eccentric Exercise. *Acta Physiol.* **2017**. [CrossRef]
129. Cleak, M.J.; Eston, R.G. Muscle Soreness, Swelling, Stiffness and Strength Loss after Intense Eccentric Exercise. *Br. J. Sports Med.* **1992**. [CrossRef]
130. Hill, J.; Howatson, G.; van Someren, K.; Leeder, J.; Pedlar, C. Compression Garments and Recovery from Exercise-Induced Muscle Damage: A Meta-Analysis. *Br. J. Sports Med.* **2014**. [CrossRef]
131. Cross, R.; Siegler, J.; Marshall, P.; Lovell, R. Scheduling of Training and Recovery during the In-Season Weekly Micro-Cycle: Insights from Team Sport Practitioners. *Eur. J. Sport Sci.* **2019**. [CrossRef]
132. Winwood, P.W.; Buckley, J.J. Short-Term Effects of Resistance Training Modalities on Performance Measures in Male Adolescents. *J. Strength Cond. Res.* **2019**. [CrossRef] [PubMed]
133. Pichardo, A.W.; Oliver, J.L.; Harrison, C.B.; Maulder, P.S.; Lloyd, R.S. Integrating Resistance Training into High School Curriculum. *Strength Cond. J.* **2019**. [CrossRef]
134. Fort-Vanmeerhaeghe, A.; Romero-Rodriguez, D.; Montalvo, A.M.; Kiefer, A.W.; Lloyd, R.S.; Myer, G.D. Integrative Neuromuscular Training and Injury Prevention in Youth Athletes. Part I: Identifying Risk Factors. *Strength Cond. J.* **2016**. [CrossRef]

135. Fort-Vanmeerhaeghe, A.; Romero-Rodriguez, D.; Lloyd, R.S.; Kushner, A.; Myer, G.D. Integrative Neuromuscular Training in Youth Athletes. Part II: Strategies to Prevent Injuries and Improve Performance. *Strength Cond. J.* **2016**. [CrossRef]
136. Murray, A. Managing the Training Load in Adolescent Athletes. *Int. J. Sports Physiol. Perform.* **2017**. [CrossRef]
137. Lin, M.J.; Nosaka, K.; Ho, C.C.; Chen, H.L.; Tseng, K.W.; Ratel, S.; Chen, T.C.C. Influence of Maturation Status on Eccentric Exercise-Induced Muscle Damage and the Repeated Bout Effect in Females. *Front. Physiol.* **2018**. [CrossRef]
138. Chen, T.C.; Chen, H.L.; Liu, Y.C.; Nosaka, K. Eccentric Exercise-Induced Muscle Damage of Pre-Adolescent and Adolescent Boys in Comparison to Young Men. *Eur. J. Appl. Physiol.* **2014**. [CrossRef]
139. Deli, C.K.; Fatouros, I.G.; Paschalis, V.; Georgakouli, K.; Zalavras, A.; Avloniti, A.; Koutedakis, Y.; Jamurtas, A.Z. A Comparison of Exercise-Induced Muscle Damage Following Maximal Eccentric Actions in Men and Boys. *Pediatr. Exerc. Sci.* **2017**. [CrossRef]
140. Dos Santos, R.R.C.; Rossi, R.R.; Rosa, E.C.C.C. Perception of Delayed Onset Muscle Soreness in Children and Adults Trained, Submitted to a Training Session of Force Eccentric. *Int. J. Sports Sci.* **2016**, *6*, 23–26. [CrossRef]
141. Arnett, M.G.; Hyslop, R.; Dennehy, C.A.; Schneider, C.M. Age-Related Variations of Serum CK and CK MB Response in Females. *Can. J. Appl. Physiol.* **2000**. [CrossRef]
142. Moir, G.; Snyder, B.; Connaboy, C.; Lamont, H.; Davis, S. Using Drop Jumps and Jump Squats to Assess Eccentric and Concentric Force-Velocity Characteristics. *Sports* **2018**, *6*, 125. [CrossRef] [PubMed]
143. Lazaridis, S.; Patikas, D.A.; Bassa, E.; Tsatalas, T.; Hatzikotoulas, K.; Ftikas, C.; Kotzamanidis, C. The Acute Effects of an Intense Stretch-Shortening Cycle Fatigue Protocol on the Neuromechanical Parameters of Lower Limbs in Men and Prepubescent Boys. *J. Sports Sci.* **2018**. [CrossRef] [PubMed]
144. Gorianovas, G.; Skurvydas, A.; Streckis, V.; Brazaitis, M.; Kamandulis, S.; McHugh, M.P. Repeated Bout Effect Was More Expressed in Young Adult Males than in Elderly Males and Boys. *Biomed Res. Int.* **2013**. [CrossRef] [PubMed]
145. Marginson, V.; Rowlands, A.V.; Gleeson, N.P.; Eston, R.G. Comparison of the Symptoms of Exercise-Induced Muscle Damage after an Initial and Repeated Bout of Plyometric Exercise in Men and Boys. *J. Appl. Physiol.* **2005**. [CrossRef] [PubMed]
146. Pullinen, T.; Mero, A.; Huttunen, P.; Pakarinen, A.; Komi, P.V. Resistance Exercise-Induced Hormonal Response under the Influence of Delayed Onset Muscle Soreness in Men and Boys. *Scand. J. Med. Sci. Sport.* **2011**. [CrossRef] [PubMed]
147. Soares, J.M.C.; Mota, P.; Duarte, J.A.; Appell, H.J. Children Are Less Susceptible to Exercise-Induced Muscle Damage than Adults: A Preliminary Investigation. *Pediatr. Exerc. Sci.* **1996**. [CrossRef]
148. Duarte, J.A.; Magalhães, J.F.; Monteiro, L.; Almeida-Dias, A.; Soares, J.M.C.; Appell, H.J. Exercise-Induced Signs of Muscle Overuse in Children. *Int. J. Sports Med.* **1999**. [CrossRef]
149. Webber, L.M.; Byrnes, W.C.; Rowland, T.W.; Foster, V.L. Serum Creatine Kinase Activity and Delayed Onset Muscle Soreness in Prepubescent Children: A Preliminary Study. *Pediatr. Exerc. Sci.* **2016**. [CrossRef]
150. Hyldahl, R.D.; Chen, T.C.; Nosaka, K. Mechanisms and Mediators of the Skeletal Muscle Repeated Bout Effect. *Exerc. Sport Sci. Rev.* **2017**. [CrossRef]
151. Nosaka, K.; Aoki, M.S. Repeated bout effect: Research update and future perspective. *Braz. J. Biomotricity* **2011**, *5*, 5–15.
152. McHugh, M.P.; Connolly, D.A.J.; Eston, R.G.; Gleim, G.W. Exercise-Induced Muscle Damage and Potential Mechanisms for the Repeated Bout Effect. *Sports Med.* **1999**. [CrossRef] [PubMed]
153. Bridgeman, L.A.; Gill, N.D.; Dulson, D.K.; Mcguigan, M.R. The Effect of Exercise-Induced Muscle Damage after a Bout of Accentuated Eccentric Load Drop Jumps and the Repeated Bout Effect. *J. Strength Cond. Res.* **2017**. [CrossRef] [PubMed]
154. Pincheira, P.A.; Hoffman, B.W.; Cresswell, A.G.; Carroll, T.J.; Brown, N.A.T.; Lichtwark, G.A. The Repeated Bout Effect Can Occur without Mechanical and Neuromuscular Changes after a Bout of Eccentric Exercise. *Scand. J. Med. Sci. Sport.* **2018**. [CrossRef] [PubMed]
155. Clarkson, P.M.; Nosaka, K.; Braun, B. Muscle Function after Exercise-Induced Muscle Damage and Rapid Adaptation. *Med. Sci. Sports Exerc.* **1992**. [CrossRef]

156. Chen, T.C.; Nosaka, K.; Sacco, P. Intensity of Eccentric Exercise, Shift of Optimum Angle, and the Magnitude of Repeated-Bout Effect. *J. Appl. Physiol.* **2007**. [CrossRef] [PubMed]
157. Kawczyński, A. Force and Electromyographic Responses of the Biceps Brachii after Eccentric Exercise in Athletes and Non-Athletes. *J. Hum. Kinet.* **2019**. [CrossRef]
158. Croix, M.D.S.; Deighan, M.; Armstrong, N. Functional Eccentric-Concentric Ratio of Knee Extensors and Flexors in Pre-Pubertal Children, Teenagers and Adult Males and Females. *Int. J. Sports Med.* **2007**. [CrossRef]
159. Philippaerts, R.M.; Vaeyens, R.; Janssens, M.; Van Renterghem, B.; Matthys, D.; Craen, R.; Bourgois, J.; Vrijens, J.; Beunen, G.; Malina, R.M. The Relationship between Peak Height Velocity and Physical Performance in Youth Soccer Players. *J. Sports Sci.* **2006**. [CrossRef]
160. Van Der Sluis, A.; Elferink-Gemser, M.T.; Brink, M.S.; Visscher, C. Importance of Peak Height Velocity Timing in Terms of Injuries in Talented Soccer Players. *Int. J. Sports Med.* **2015**. [CrossRef]
161. Rejeb, A.; Johnson, A.; Farooq, A.; Verrelst, R.; Pullinger, S.; Vaeyens, R.; Witvrouw, E. Sports Injuries Aligned to Predicted Mature Height in Highly Trained Middle-Eastern Youth Athletes: A Cohort Study. *BMJ Open* **2019**. [CrossRef]
162. Johnson, D.M.; Williams, S.; Bradley, B.; Sayer, S.; Murray Fisher, J.; Cumming, S. Growing Pains: Maturity Associated Variation in Injury Risk in Academy Football. *Eur. J. Sport Sci.* **2019**. [CrossRef] [PubMed]
163. Petushek, E.J.; Sugimoto, D.; Stoolmiller, M.; Smith, G.; Myer, G.D. Evidence-Based Best-Practice Guidelines for Preventing Anterior Cruciate Ligament Injuries in Young Female Athletes: A Systematic Review and Meta-Analysis. *Am. J. Sports Med.* **2019**. [CrossRef] [PubMed]
164. Lubans, D.R.; Morgan, P.J.; Cliff, D.P.; Barnett, L.M.; Okely, A.D. Fundamental Movement Skills in Children and Adolescents. *Sport. Med.* **2010**, *40*, 1019–1035. [CrossRef] [PubMed]
165. Collins, H.; Booth, J.N.; Duncan, A.; Fawkner, S. The Effect of Resistance Training Interventions on Fundamental Movement Skills in Youth: A Meta-Analysis. *Sport. Med. Open.* **2019**. [CrossRef] [PubMed]
166. McKeown, I.; Taylor-McKeown, K.; Woods, C.; Ball, N. Athletic Ability Assessment: A Movement Assessment Protocol for Athletes. *Int. J. Sports Phys. Ther.* **2014**, *9*, 862–873. [PubMed]
167. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; Van Den Bogert, A.J.; Paterno, M.V.; Succop, P. Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study. *Am. J. Sports Med.* **2005**. [CrossRef] [PubMed]
168. Santello, M. Review of Motor Control Mechanisms Underlying Impact Absorption from Falls. *Gait Posture* **2005**. [CrossRef]
169. Hewett, T.E.; Myer, G.D.; Ford, K.R. Anterior Cruciate Ligament Injuries in Female Athletes: Part 1, Mechanisms and Risk Factors. *Am. J. Sports Med.* **2006**. [CrossRef]
170. Dierks, T.A.; Manal, K.T.; Hamill, J.; Davis, I.S. Proximal and Distal Influences on Hip and Knee Kinematics in Runners with Patellofemoral Pain during a Prolonged Run. *J. Orthop. Sports Phys. Ther.* **2008**. [CrossRef]
171. Sigward, S.M.; Pollard, C.D.; Powers, C.M. The Influence of Sex and Maturation on Landing Biomechanics: Implications for Anterior Cruciate Ligament Injury. *Scand. J. Med. Sci. Sport.* **2012**. [CrossRef]
172. Hass, C.J.; Schick, E.A.; Tillman, M.D.; Chow, J.W.; Brunt, D.; Cauraugh, J.H. Knee Biomechanics during Landings: Comparison of Pre- and Postpubescent Females. *Med. Sci. Sports Exerc.* **2005**. [CrossRef] [PubMed]
173. Swartz, E.E.; Decoster, L.C.; Russell, P.J.; Croce, R.V. Effects of Developmental Stage and Sex on Lower Extremity Kinematics and Vertical Ground Reaction Forces during Landing. *J. Athl. Train.* **2005**, *40*, 9. [PubMed]
174. Boden, B.P.; Dean, C.S.; Feagin, J.A.; Garrett, W.E. Mechanisms of Anterior Cruciate Ligament Injury. *Orthopedics* **2000**, *23*, 573–578. [CrossRef] [PubMed]
175. Ireland, M.L. Anterior Cruciate Ligament Injury in Female Athletes: Epidemiology. *J. Athl. Train.* **1999**. [CrossRef]
176. Ford, K.R.; Shapiro, R.; Myer, G.D.; Van Den Bogert, A.J.; Hewett, T.E. Longitudinal Sex Differences during Landing in Knee Abduction in Young Athletes. *Med. Sci. Sports Exerc.* **2010**. [CrossRef]
177. Hewett, T.E.; Myer, G.D.; Kiefer, A.W.; Ford, K.R. Longitudinal Increases in Knee Abduction Moments in Females during Adolescent Growth. *Med. Sci. Sports Exerc.* **2015**. [CrossRef]
178. Fort-Vanmeerhaeghe, A.; Benet, A.; Mirada, S.; Montalvo, A.M.; Myer, G.D. Sex and Maturation Differences in Performance of Functional Jumping and Landing Deficits in Youth Athletes. *J. Sport Rehabil.* **2019**. [CrossRef]

179. Caine, D.; Purcell, L.; Maffulli, N. The Child and Adolescent Athlete: A Review of Three Potentially Serious Injuries. *BMC Sports Sci. Med. Rehabil.* **2014**. [CrossRef]
180. Pollard, C.D.; Sigward, S.M.; Powers, C.M. Limited Hip and Knee Flexion during Landing Is Associated with Increased Frontal Plane Knee Motion and Moments. *Clin. Biomech.* **2010**. [CrossRef]
181. Hewett, T.E.; Myer, G.D.; Ford, K.R. Decrease in Neuromuscular Control about the Knee with Maturation in Female Athletes. *J. Bone Jt. Surg. Ser. A* **2004**. [CrossRef]
182. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Heidt, R.S.; Colosimo, A.J.; McLean, S.G.; van den Bogert, A.J.; Paterno, M.V.; Succop, P. Neuromuscular Control and Valgus Loading of the Knee Predict ACL Injury Risk in Female Athletes. *Med. Sci. Sport. Exerc.* **2004**. [CrossRef]
183. Schmitz, R.J.; Shultz, S.J.; Nguyen, A.D. Dynamic Valgus Alignment and Functional Strength in Males and Females during Maturation. *J. Athl. Train.* **2009**. [CrossRef] [PubMed]
184. Otsuki, R.; Kuramochi, R.; Fukubayashi, T. Effect of Injury Prevention Training on Knee Mechanics in Female Adolescents during Puberty. *Br. J. Sports Med.* **2014**. [CrossRef]
185. Holden, S.; Doherty, C.; Boreham, C.; Delahunt, E. Sex Differences in Sagittal Plane Control Emerge during Adolescent Growth: A Prospective Investigation. *Knee Surg. Sport. Traumatol. Arthrosc.* **2019**. [CrossRef]
186. Ford, K.R.; Myer, G.D.; Hewett, T.E. Valgus Knee Motion during Landing in High School Female and Male Basketball Players. *Med. Sci. Sports Exerc.* **2003**. [CrossRef]
187. Yu, B.; McClure, S.B.; Onate, J.A.; Guskiewicz, K.M.; Kirkendall, D.T.; Garrett, W.E. Age and Gender Effects on Lower Extremity Kinematics of Youth Soccer Players in a Stop-Jump Task. *Am. J. Sports Med.* **2005**. [CrossRef]
188. Read, P.J.; Oliver, J.L.; De Ste Croix, M.B.A.; Myer, G.D.; Lloyd, R.S. Landing Kinematics in Elite Male Youth Soccer Players of Different Chronologic Ages and Stages of Maturation. *J. Athl. Train.* **2018**. [CrossRef]
189. Read, P.J.; Oliver, J.L.; Myer, G.D.; De Ste Croix, M.B.A.; Belshaw, A.; Lloyd, R.S. Altered Landing Mechanics Are Shown by Male Youth Soccer Players at Different Stages of Maturation. *Phys. Ther. Sport* **2018**. [CrossRef]
190. Barber-Westin, S.D.; Noyes, F.R.; Galloway, M. Jump-Land Characteristics and Muscle Strength Development in Young Athletes: A Gender Comparison of 1140 Athletes 9 to 17 Years of Age. *Am. J. Sports Med.* **2006**. [CrossRef]
191. Quatman, C.E.; Ford, K.R.; Myer, G.D.; Hewett, T.E. Maturation Leads to Gender Differences in Landing Force and Vertical Jump Performance: A Longitudinal Study. *Am. J. Sports Med.* **2006**. [CrossRef]
192. Di Stefano, L.J.; Martinez, J.C.; Crowley, E.; Matteau, E.; Kerner, M.S.; Boling, M.C.; Nguyen, A.D.; Trojian, T.H. Maturation and Sex Differences in Neuromuscular Characteristics of Youth Athletes. *J. Strength Cond. Res.* **2015**. [CrossRef] [PubMed]
193. Lloyd, R.S.; Oliver, J.L.; Myer, G.D.; De Ste Croix, M.; Wass, J.; Read, P.J. Comparison of Drop Jump and Tuck Jump Knee Joint Kinematics in Elite Male Youth Soccer Players: Implications for Injury Risk Screening. *J. Sport Rehabil.* **2019**. [CrossRef] [PubMed]
194. Birat, A.; Sebillaud, D.; Bourdier, P.; Doré, E.; Duché, P.; Blazevich, A.J.; Patikas, D.; Ratel, S. Effect of Drop Height on Vertical Jumping Performance in Pre-, Circa-, and Post-Pubertal Boys and Girls. *Pediatr. Exerc. Sci.* **2019**. [CrossRef] [PubMed]
195. Read, P.J.; Oliver, J.L.; De Ste Croix, M.B.A.; Myer, G.D.; Lloyd, R.S. A Prospective Investigation to Evaluate Risk Factors for Lower Extremity Injury Risk in Male Youth Soccer Players. *Scand. J. Med. Sci. Sport* **2018**. [CrossRef] [PubMed]
196. Irmischer, B.S.; Harris, C.; Pfeiffer, R.P.; DeBeliso, M.A.; Adams, K.J.; Shea, K.G. Effects of a Knee Ligament Injury Prevention Exercise Program on Impact Forces in Women. *J. Strength Cond. Res.* **2004**. [CrossRef]
197. Hass, C.J.; Schick, E.A.; Chow, J.W.; Tillman, M.D.; Brunt, D.; Cauraugh, J.H. Lower Extremity Biomechanics Differ in Prepubescent and Postpubescent Female Athletes during Stride Jump Landings. *J. Appl. Biomech.* **2003**. [CrossRef]
198. Leppänen, M.; Pasanen, K.; Kujala, U.M.; Vasankari, T.; Kannus, P.; Äyrämö, S.; Krosshaug, T.; Bahr, R.; Avela, J.; Perttunen, J.; et al. Stiff Landings Are Associated with Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *Am. J. Sports Med.* **2017**. [CrossRef]
199. Hewett, T.E.; Myer, G.D.; Ford, K.R.; Slauterbeck, J.R. Preparticipation Physical Examination Using a Box Drop Vertical Jump Test in Young Athletes: The Effects of Puberty and Sex. *Clin. J. Sport Med.* **2006**. [CrossRef]

200. Paz, G.A.; de Freitas Maia, M.; Santana, H.G.; Miranda, H.; Lima, V.; Willson, J.D. Knee Frontal Plane Projection Angle: A Comparison Study between Drop Vertical Jump and Step-down Tests with Young Volleyball Athletes. *J. Sport Rehabil.* **2019**. [CrossRef]
201. Ali, N.; Robertson, D.G.E.; Rouhi, G. Sagittal Plane Body Kinematics and Kinetics during Single-Leg Landing from Increasing Vertical Heights and Horizontal Distances: Implications for Risk of Non-Contact ACL Injury. *Knee* **2014**. [CrossRef]
202. Bobbert, M.F.; Huijing, P.A.; Schenau, G.J.V.I. Drop Jumping. II. The Influence of Dropping Height on the Biomechanics of Drop Jumping. *Med. Sci. Sports Exerc.* **1987**, *19*, 339–346. [CrossRef] [PubMed]
203. Makaruk, H.; Sacewicz, T. The Effect of Drop Height and Body Mass on Drop Jump Intensity. *Biol. Sport* **2011**. [CrossRef]
204. Zhang, S.N.; Bates, B.T.; Dufek, J.S. Contributions of Lower Extremity Joints to Energy Dissipation during Landings. *Med. Sci. Sports Exerc.* **2000**. [CrossRef] [PubMed]
205. Herrington, L.; Munro, A.; Comfort, P. A Preliminary Study into the Effect of Jumping-Landing Training and Strength Training on Frontal Plane Projection Angle. *Man. Ther.* **2015**. [CrossRef]
206. Montgomery, M.M.; Shultz, S.J.; Schmitz, R.J.; Wideman, L.; Henson, R.A. Influence of Lean Body Mass and Strength on Landing Energetics. *Med. Sci. Sports Exerc.* **2012**. [CrossRef]
207. Jacobs, C.; Mattacola, C. Sex Differences in Eccentric Hip-Abductor Strength and Knee-Joint Kinematics When Landing from a Jump. *J. Sport Rehabil.* **2005**. [CrossRef]
208. Boling, M.; Padua, D. Relationship between Hip Strength and Trunk, Hip, and Knee Kinematics during a Jump-Landing Task in Individuals with Patellofemoral Pain. *Int. J. Sports Phys. Ther.* **2013**, *8*, 661.
209. Baldon, R.D.M.; Lobato, D.F.M.; Carvalho, L.P.; Santiago, P.R.P.; Benze, B.G.; Serrão, F.V. Relationship between Eccentric Hip Torque and Lower-Limb Kinematics: Gender Differences. *J. Appl. Biomech.* **2011**. [CrossRef]
210. Baldon, R.D.M.; Nakagawa, T.H.; Muniz, T.B.; Amorim, C.F.; Maciel, C.D.; Serrão, F.V. Eccentric Hip Muscle Function in Females with and without Patellofemoral Pain Syndrome. *J. Athl. Train.* **2009**. [CrossRef]
211. Ramskov, D.; Barton, C.; Nielsen, R.O.; Rasmussen, S. High Eccentric Hip Abduction Strength Reduces the Risk of Developing Patellofemoral Pain among Novice Runners Initiating a Self-Structured Running Program: A 1-Year Observational Study. *J. Orthop. Sports Phys. Ther.* **2015**. [CrossRef]
212. Wu, X.; Zhang, S.; Liu, Y.; Zhang, D.; Xie, B. Do Knee Concentric and Eccentric Strength and Sagittal-Plane Knee Joint Biomechanics Differ between Jumpers and Non-Jumpers in Landing? *Hum. Mov. Sci.* **2013**. [CrossRef] [PubMed]
213. Strafford, B.W.; van der Steen, P.; Davids, K.; Stone, J.A. Parkour as a Donor Sport for Athletic Development in Youth Team Sports: Insights Through an Ecological Dynamics Lens. *Sport. Med. Open* **2018**. [CrossRef] [PubMed]
214. Maldonado, G.; Soueres, P.; Watier, B. Strategies of Parkour Practitioners for Executing Soft Precision Landings. *J. Sports Sci.* **2018**. [CrossRef] [PubMed]
215. DiStefano, L.J.; Beltz, E.M.; Root, H.J.; Martinez, J.C.; Houghton, A.; Taranto, N.; Pearce, K.; McConnell, E.; Muscat, C.; Boyle, S.; et al. Sport Sampling Is Associated with Improved Landing Technique in Youth Athletes. *Sports Health* **2018**. [CrossRef]
216. Standing, R.J.; Maulder, P.S. A Comparison of the Habitual Landing Strategies from Differing Drop Heights of Parkour Practitioners (Traceurs) and Recreationally Trained Individuals. *J. Sport. Sci. Med.* **2015**, *14*, 723.
217. DiCesare, C.A.; Montalvo, A.; Barber Foss, K.D.; Thomas, S.M.; Ford, K.R.; Hewett, T.E.; Jayanthi, N.A.; Stracciolini, A.; Bell, D.R.; Myer, G.D. Lower Extremity Biomechanics Are Altered across Maturation in Sport-Specialized Female Adolescent Athletes. *Front. Pediatr.* **2019**. [CrossRef]
218. Hall, R.; Foss, K.B.; Hewett, T.E.; Myer, G.D. Sport Specialization's Association with an Increased Risk of Developing Anterior Knee Pain in Adolescent Female Athletes. *J. Sport Rehabil.* **2015**. [CrossRef]
219. Madruga-Parera, M.; Romero-Rodríguez, D.; Bishop, C.; Beltran-Valls, M.R.; Latinjak, A.T.; Beato, M.; Fort-Vanmeerhaeghe, A. Effects of Maturation on Lower Limb Neuromuscular Asymmetries in Elite Youth Tennis Players. *Sports* **2019**, *7*, 106. [CrossRef]
220. Atkins, S.J.; Bentley, I.; Hurst, H.T.; Sinclair, J.K.; Hesketh, C. The Presence of Bilateral Imbalance of the Lower Limbs in Elite Youth Soccer Players of Different Ages. *J. Strength Cond. Res.* **2016**. [CrossRef]
221. Dai, B.; Garrett, W.E.; Gross, M.T.; Padua, D.A.; Queen, R.M.; Yu, B. The Effect of Performance Demands on Lower Extremity Biomechanics during Landing and Cutting Tasks. *J. Sport Heal. Sci.* **2019**. [CrossRef]

222. Pichardo, A.W.; Oliver, J.L.; Harrison, C.B.; Maulder, P.S.; Lloyd, R.S.; Kandoi, R. Effects of Combined Resistance Training and Weightlifting on Motor Skill Performance of Adolescent Male Athletes. *J. Strength Cond. Res.* **2019**. [CrossRef] [PubMed]
223. Chaouachi, A.; Hammami, R.; Kaabi, S.; Chamari, K.; Drinkwater, E.J.; Behm, D.G. Olympic Weightlifting and Plyometric Training with Children Provides Similar or Greater Performance Improvements than Traditional Resistance Training. *J. Strength Cond. Res.* **2014**. [CrossRef] [PubMed]
224. Suchomel, T.J.; Lake, J.P.; Comfort, P. Load Absorption Force-Time Characteristics Following the Second Pull of Weightlifting Derivatives. *J. Strength Cond. Res.* **2017**. [CrossRef] [PubMed]
225. Suchomel, T.J.; Giordanelli, M.D.; Geiser, C.F.; Kipp, K. Comparison of Joint Work During Load Absorption Between Weightlifting Derivatives. *J. Strength Cond. Res.* **2018**. [CrossRef]
226. Sugimoto, D.; Myer, G.D.; Barber Foss, K.D.; Pepin, M.J.; Micheli, L.J.; Hewett, T.E. Critical Components of Neuromuscular Training to Reduce ACL Injury Risk in Female Athletes: Meta-Regression Analysis. *Br. J. Sports Med.* **2016**. [CrossRef] [PubMed]
227. Ericksen, H.M.; Thomas, A.C.; Gribble, P.A.; Armstrong, C.; Rice, M.; Pietrosimone, B. Jump-Landing Biomechanics Following a 4-Week Real-Time Feedback Intervention and Retention. *Clin. Biomech.* **2016**. [CrossRef]
228. Moran, J.; Sandercock, G.R.H.; Ramírez-Campillo, R.; Meylan, C.; Collison, J.; Parry, D.A. Age-Related Variation in Male Youth Athletes' Countermovement Jump Following Plyometric Training. *J. Strength Cond. Res.* **2016**. [CrossRef]
229. Van Dyk, N.; Behan, F.P.; Whiteley, R. Including the Nordic Hamstring Exercise in Injury Prevention Programmes Halves the Rate of Hamstring Injuries: A Systematic Review and Meta-Analysis of 8459 Athletes. *Br. J. Sports Med.* **2019**. [CrossRef]
230. Kenneally-Dabrowski, C.J.B.; Brown, N.A.T.; Lai, A.K.M.; Perriman, D.; Spratford, W.; Serpell, B.G. Late Swing or Early Stance? A Narrative Review of Hamstring Injury Mechanisms during High-Speed Running. *Scand. J. Med. Sci. Sports* **2019**. [CrossRef]
231. Higashihara, A.; Nagano, Y.; Ono, T.; Fukubayashi, T. Differences in Hamstring Activation Characteristics between the Acceleration and Maximum-Speed Phases of Sprinting. *J. Sports Sci.* **2018**. [CrossRef]
232. Higashihara, A.; Nagano, Y.; Ono, T.; Fukubayashi, T. Differences in Activation Properties of the Hamstring Muscles during Overground Sprinting. *Gait Posture* **2015**. [CrossRef] [PubMed]
233. Schache, A.G.; Dorn, T.W.; Wrigley, T.V.; Brown, N.A.T.; Pandy, M.G. Stretch and Activation of the Human Biarticular Hamstrings across a Range of Running Speeds. *Eur. J. Appl. Physiol.* **2013**. [CrossRef] [PubMed]
234. Guex, K.; Millet, G.P. Conceptual Framework for Strengthening Exercises to Prevent Hamstring Strains. *Sports Med.* **2013**. [CrossRef] [PubMed]
235. Chaabene, H.; Negra, Y.; Moran, J.; Prieske, O.; Sammoud, S.; Ramirez-Campillo, R.; Granacher, U. Effects of an Eccentric Hamstrings Training on Components of Physical Performance in Young Female Handball Players. *Int. J. Sports Physiol. Perform.* **2019**, *1*, 1–22. [CrossRef]
236. Markovic, G.; Sarabon, N.; Boban, F.; Zoric, I.; Jelcic, M.; Sos, K.; Scappaticci, M. Nordic Hamstring Strength of Highly Trained Youth Football Players and Its Relation to Sprint Performance. *J. Strength Cond. Res.* **2018**. [CrossRef]
237. Kilding, A.E.; Tunstall, H.; Kuzmic, D. Suitability of FIFA's "The 11" Training Programme for Young Football Players—Impact on Physical Performance. *J. Sport. Sci. Med.* **2008**, *7*, 320.
238. Hegyi, A.; Csala, D.; Péter, A.; Finni, T.; Cronin, N.J. High-Density Electromyography Activity in Various Hamstring Exercises. *Scand. J. Med. Sci. Sport.* **2019**. [CrossRef]
239. Bourne, M.N.; Williams, M.D.; Opar, D.A.; Al Najjar, A.; Kerr, G.K.; Shield, A.J. Impact of Exercise Selection on Hamstring Muscle Activation. *Br. J. Sports Med.* **2017**. [CrossRef]
240. Tsaklis, P.; Malliaropoulos, N.; Mendiguchia, J.; Korakakis, V.; Tsapralis, K.; Pyne, D.; Malliaras, P. Muscle and Intensity Based Hamstring Exercise Classification in Elite Female Track and Field Athletes: Implications for Exercise Selection during Rehabilitation. *Open Access J. Sport. Med.* **2015**. [CrossRef]
241. Valle, X.; Malliaropoulos, N.; Párraga Botero, J.D.; Bikos, G.; Pruna, R.; Mónaco, M.; Maffulli, N. Hamstring and Other Thigh Injuries in Children and Young Athletes. *Scand. J. Med. Sci. Sport.* **2018**. [CrossRef]
242. Drury, B.; Green, T.; Ramírez-Campillo, R.; Moran, J. Influence of Maturation Status on Eccentric Hamstring Strength Improvements in Youth Male Soccer Players following the Nordic Hamstring Exercise. *IJSPP* **2019**, in press.

243. Owoeye, O.B.A.; Akinbo, S.R.A.; Tella, B.A.; Olawale, O.A. Efficacy of the FIFA 11+ Warm-up Programme in Male Youth Football: A Cluster Randomised Controlled Trial. *J. Sport. Sci. Med.* **2014**, *13*, 321.
244. Hislop, M.D.; Stokes, K.A.; Williams, S.; McKay, C.D.; England, M.; Kemp, S.P.T.; Trewartha, G. The Efficacy of a Movement Control Exercise Programme to Reduce Injuries in Youth Rugby: A Cluster Randomised Controlled Trial. *BMJ Open Sport Exerc. Med.* **2016**. [CrossRef] [PubMed]
245. Achenbach, L.; Krutsch, V.; Weber, J.; Nerlich, M.; Luig, P.; Loose, O.; Angele, P.; Krutsch, W. Neuromuscular Exercises Prevent Severe Knee Injury in Adolescent Team Handball Players. *Knee Surg. Sport. Traumatol. Arthrosc.* **2018**. [CrossRef]
246. Forrest, M.R.L.; Scott, B.R.; Hebert, J.J.; Dempsey, A.R. Injury Prevention Strategies for Adolescent Cricket Pace Bowlers. *Sports Med.* **2018**. [CrossRef]
247. Reis, I.; Rebelo, A.; Krustrup, P.; Brito, J. Performance Enhancement Effects of Fédération Internationale de Football Association's "the 11+" Injury Prevention Training Program in Youth Futsal Players. *Clin. J. Sport Med.* **2013**. [CrossRef]
248. Peek, K.; Gatherer, D.; Bennett, K.J.M.; Fransen, J.; Watsford, M. Muscle Strength Characteristics of the Hamstrings and Quadriceps in Players from a High-Level Youth Football (Soccer) Academy. *Res. Sport. Med.* **2018**. [CrossRef]
249. Franchi, M.V.; Ellenberger, L.; Javet, M.; Bruhin, B.; Romann, M.; Frey, W.O.; Spörri, J. Maximal Eccentric Hamstrings Strength in Competitive Alpine Skiers: Cross-Sectional Observations from Youth to Elite Level. *Front. Physiol.* **2019**. [CrossRef]
250. Roe, M.; Malone, S.; Delahunt, E.; Collins, K.; Gissane, C.; Persson, U.M.C.; Murphy, J.C.; Blake, C. Eccentric Knee Flexor Strength Profiles of 341 Elite Male Academy and Senior Gaelic Football Players: Do Body Mass and Previous Hamstring Injury Impact Performance? *Phys. Ther. Sport.* **2018**. [CrossRef]
251. Ellenbecker, T.S.; Roetert, E.P.; Sueyoshi, T.; Riewald, S. A Descriptive Profile of Age-Specific Knee Extension Flexion Strength in Elite Junior Tennis Players. *Br. J. Sports Med.* **2007**. [CrossRef]
252. Gerodimos, V.; Mandou, V.; Zafeiridis, A.; Ioakimidis, P. Isokinetic peak torque and hamstring/quadriceps ratios in young basketball players: Effects of age, velocity, and action mode. *J. Sports Med. Phys. Fit.* **2003**, *43*, 444.
253. Sugimoto, D.; Borg, D.R.; Brilliant, A.N.; Meehan, W.P.; Micheli, L.J.; Geminiani, E.T. Effect of Sports and Growth on Hamstrings and Quadriceps Development in Young Female Athletes: Cross-Sectional Study. *Sports* **2019**, *7*, 158. [CrossRef] [PubMed]
254. Forbes, H.; Bullers, A.; Lovell, A.; McNaughton, L.R.; Polman, R.C.; Siegler, J.C. Relative Torque Profiles of Elite Male Youth Footballers: Effects of Age and Pubertal Development. *Int. J. Sports Med.* **2009**. [CrossRef] [PubMed]
255. Holm, I.; Steen, H.; Olstad, M. Isokinetic Muscle Performance in Growing Boys from Pre-Teen to Maturity. An Eleven-Year Longitudinal Study. *Isokinet. Exerc. Sci.* **2005**, *13*, 153–158. [CrossRef]
256. Buchanan, P.A.; Vardaxis, V.G. Sex-Related and Age-Related Differences in Knee Strength of Basketball Players Ages 11–17 Years. *J. Athl. Train.* **2003**, *38*, 231.
257. Kellis, S.; Gerodimos, V.; Kellis, E.; Manou, V. Bilateral Isokinetic Concentric and Eccentric Strength Profiles of the Knee Extensors and Flexors in Young Soccer Players. *Isokinet. Exerc. Sci.* **2001**, *9*, 31–39. [CrossRef]
258. Holm, I.; Vøllestad, N. Significant Effect of Gender on Hamstring-to-Quadriceps Strength Ratio and Static Balance in Prepubescent Children from 7 to 12 Years of Age. *Am. J. Sports Med.* **2008**. [CrossRef]
259. Wild, C.Y.; Steele, J.R.; Munro, B.J. Insufficient Hamstring Strength Compromises Landing Technique in Adolescent Girls. *Med. Sci. Sports Exerc.* **2013**. [CrossRef]
260. Bencke, J.; Curtis, D.; Krogshede, C.; Jensen, L.K.; Bandholm, T.; Zebis, M.K. Biomechanical Evaluation of the Side-Cutting Manoeuvre Associated with ACL Injury in Young Female Handball Players. *Knee Surg. Sport. Traumatol. Arthrosc.* **2013**. [CrossRef]
261. Salci, Y.; Yildirim, A.; Celik, O.; Ak, E.; Kocak, S.; Korkusuz, F. The Effects of Eccentric Hamstring Training on Lower Extremity Strength and Landing Kinetics in Recreational Female Athletes. *Isokinet. Exerc. Sci.* **2013**. [CrossRef]
262. Anastasi, S.M.; Hamzeh, M.A. Does the Eccentric Nordic Hamstring Exercise Have an Effect on Isokinetic Muscle Strength Imbalance and Dynamic Jumping Performance in Female Rugby Union Players? *Isokinet. Exerc. Sci.* **2011**. [CrossRef]

263. Read, P.J.; Jimenez, P.; Oliver, J.L.; Lloyd, R.S. Injury Prevention in Male Youth Soccer: Current Practices and Perceptions of Practitioners Working at Elite English Academies. *J. Sports Sci.* **2018**. [CrossRef] [PubMed]
264. Forbes, H.; Sutcliffe, S.; Lovell, A.; McNaughton, L.R.; Siegler, J.C. Isokinetic Thigh Muscle Ratios in Youth Football: Effect of Age and Dominance. *Int. J. Sports Med.* **2009**. [CrossRef] [PubMed]
265. Goode, A.P.; Reiman, M.P.; Harris, L.; DeLisa, L.; Kauffman, A.; Beltramo, D.; Poole, C.; Ledbetter, L.; Taylor, A.B. Eccentric Training for Prevention of Hamstring Injuries May Depend on Intervention Compliance: A Systematic Review and Meta-Analysis. *Br. J. Sports Med.* **2015**. [CrossRef]
266. Tansel, R.B.; Salci, Y.; Yildirim, A.; Kocak, S.; Korkusuz, F. Effects of eccentric hamstring strength training on lower extremity strength of 10–12-year-old male basketball players. *Isokinet. Exerc. Sci.* **2008**, *16*, 81–85. [CrossRef]
267. Oakley, A.J.; Jennings, J.; Bishop, C.J. Holistic Hamstring Health: Not Just the Nordic Hamstring Exercise. *Br. J. Sports Med.* **2018**. [CrossRef]
268. Śliwowski, R.; Jadczak, Ł.; Hejna, R.; Wieczorek, A. The Effects of Individualized Resistance Strength Programs on Knee Muscular Imbalances in Junior Elite Soccer Players. *PLoS ONE* **2015**. [CrossRef]
269. Duarte, J.P.; Valente-Dos-Santos, J.; Coelho-e-Silva, M.J.; Malina, R.M.; Deprez, D.; Philippaerts, R.; Lenoir, M.; Vaeyens, R. Developmental Changes in Isometric Strength: Longitudinal Study in Adolescent Soccer Players. *Int. J. Sports Med.* **2018**. [CrossRef]
270. Freeman, B.W.; Young, W.B.; Talpey, S.W.; Smyth, A.M.; Pane, C.L.; Carlon, T.A. The Effects of Sprint Training and the Nordic Hamstring Exercise on Eccentric Hamstring Strength and Sprint Performance in Adolescent Athletes. *J. Sports Med. Phys. Fit.* **2019**. [CrossRef]
271. Guex, K.; Degache, F.; Morisod, C.; Sailly, M.; Millet, G.P. Hamstring Architectural and Functional Adaptations Following Long vs. Short Muscle Length Eccentric Training. *Front. Physiol.* **2016**. [CrossRef]
272. Eustace, S.J.; Page, R.M.; Greig, M. Angle-Specific Isokinetic Metrics Highlight Strength Training Needs of Elite Youth Soccer Players. *J. Strength Cond. Res.* **2018**. [CrossRef] [PubMed]
273. Eustace, S.J.; Page, R.M.; Greig, M. Isokinetic Strength Differences between Elite Senior and Youth Female Soccer Players Identifies Training Requirements. *Phys. Ther. Sport* **2019**. [CrossRef] [PubMed]
274. Timmins, R.G.; Bourne, M.N.; Shield, A.J.; Williams, M.D.; Lorenzen, C.; Opar, D.A. Short Biceps Femoris Fascicles and Eccentric Knee Flexor Weakness Increase the Risk of Hamstring Injury in Elite Football (Soccer): A Prospective Cohort Study. *Br. J. Sports Med.* **2016**. [CrossRef] [PubMed]
275. Potier, T.G.; Alexander, C.M.; Seynnes, O.R. Effects of Eccentric Strength Training on Biceps Femoris Muscle Architecture and Knee Joint Range of Movement. *Eur. J. Appl. Physiol.* **2009**. [CrossRef]
276. Baroni, B.M.; Geremia, J.M.; Rodrigues, R.; De Azevedo Franke, R.; Karamanidis, K.; Vaz, M.A. Muscle Architecture Adaptations to Knee Extensor Eccentric Training: Rectus Femoris vs. Vastus Lateralis. *Muscle Nerve* **2013**. [CrossRef]
277. Duclay, J.; Martin, A.; Duclay, A.; Cometti, G.; Pousson, M. Behavior of Fascicles and the Myotendinous Junction of Human Medial Gastrocnemius Following Eccentric Strength Training. *Muscle Nerve Off. J. Am. Assoc. Electrodiagn. Med.* **2009**, *39*, 819–827. [CrossRef]
278. Presland, J.D.; Timmins, R.G.; Bourne, M.N.; Williams, M.D.; Opar, D.A. The Effect of Nordic Hamstring Exercise Training Volume on Biceps Femoris Long Head Architectural Adaptation. *Scand. J. Med. Sci. Sport.* **2018**. [CrossRef]
279. Timmins, R.G.; Ruddy, J.D.; Presland, J.; Maniar, N.; Shield, A.J.; Williams, M.D.; Opar, D.A. Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training. *Med. Sci. Sports Exerc.* **2016**. [CrossRef]
280. Alonso-Fernandez, D.; Docampo-Blanco, P.; Martinez-Fernandez, J. Changes in Muscle Architecture of Biceps Femoris Induced by Eccentric Strength Training with Nordic Hamstring Exercise. *Scand. J. Med. Sci. Sport* **2018**. [CrossRef]
281. Lacome, M.; Avrillon, S.; Cholley, Y.; Simpson, B.M.; Guilhem, G.; Buchheit, M. Hamstring Eccentric Strengthening Program: Does Training Volume Matter? *Int. J. Sports Physiol. Perform.* **2019**. [CrossRef]
282. Ribeiro-Alvares, J.B.; Marques, V.B.; Vaz, M.A.; Baroni, B.M. Four Weeks of Nordic Hamstring Exercise Reduce Muscle Injury Risk Factors in Young Adults. *J. Strength Cond. Res.* **2018**. [CrossRef] [PubMed]
283. Morse, C.I.; Tolfrey, K.; Thom, J.M.; Vassilopoulos, V.; Maganaris, C.N.; Narici, M.V. Gastrocnemius Muscle Specific Force in Boys and Men. *J. Appl. Physiol.* **2008**. [CrossRef] [PubMed]

284. Kubo, K.; Kanehisa, H.; Kawakami, Y.; Fukanaga, T. Growth Changes in the Elastic Properties of Human Tendon Structures. *Int. J. Sports Med.* **2001**. [CrossRef] [PubMed]
285. Buchheit, M.; Cholley, Y.; Nagel, M.; Poulos, N. The Effect of Body Mass on Eccentric Knee-Flexor Strength Assessed with an Instrumented Nordic Hamstring Device (Nordbord) in Football Players. *Int. J. Sports Physiol. Perform.* **2016**, *11*, 721–726. [CrossRef] [PubMed]
286. Pollard, C.W.; Opar, D.A.; Williams, M.D.; Bourne, M.N.; Timmins, R.G. Razor Hamstring Curl and Nordic Hamstring Exercise Architectural Adaptations: Impact of Exercise Selection and Intensity. *Scand. J. Med. Sci. Sport* **2019**. [CrossRef] [PubMed]
287. Lovell, R.; Knox, M.; Weston, M.; Siegler, J.C.; Brennan, S.; Marshall, P.W.M. Hamstring Injury Prevention in Soccer: Before or after Training? *Scand. J. Med. Sci. Sport* **2018**. [CrossRef]
288. Moir, G.L.; Erny, K.F.; Davis, S.E.; Guers, J.J.; Witmer, C.A. The Development of a Repetition-Load Scheme for the Eccentric-Only Bench Press Exercise. *J. Hum. Kinet.* **2013**. [CrossRef]
289. Hahn, D. Stretching the Limits of Maximal Voluntary Eccentric Force Production in Vivo. *J. Sport Heal. Sci.* **2018**. [CrossRef]
290. Westing, S.H.; Seger, J.Y.; Karlson, E.; Ekblom, B. Eccentric and Concentric Torque-Velocity Characteristics of the Quadriceps Femoris in Man. *Eur. J. Appl. Physiol. Occup. Physiol.* **1988**. [CrossRef]
291. Wagle, J.P.; Cunanan, A.J.; Carroll, K.M.; Sams, M.L.; Wetmore, A.; Bingham, G.E.; Taber, C.B.; DeWeese, B.H.; Sato, K.; Stuart, C.A.; et al. Accentuated Eccentric Loading and Cluster Set Configurations in the Back Squat. *J. Strength Cond. Res.* **2018**. [CrossRef]
292. Martinez-Aranda, L.M.; Fernandez-Gonzalo, R. Effects of Inertial Setting on Power, Force, Work, and Eccentric Overload during Flywheel Resistance Exercise in Women and Men. *J. Strength Cond. Res.* **2017**. [CrossRef]
293. Festa, L.; Tarperi, C.; Skroce, K.; Boccia, G.; Lippi, G.; La Torre, A.; Schena, F. Effects of Flywheel Strength Training on the Running Economy of Recreational Endurance Runners. *J. Strength Cond. Res.* **2019**. [CrossRef]
294. Suarez-Arrones, L.; Lara-Lopez, P.; Torreno, N.; Saez de Villarreal, E.; Di Salvo, V.; Mendez-Villanueva, A. Effects of Strength Training on Body Composition in Young Male Professional Soccer Players. *Sports* **2019**, *7*, 104. [CrossRef]
295. Norrbrand, L.; Pozzo, M.; Tesch, P.A. Flywheel Resistance Training Calls for Greater Eccentric Muscle Activation than Weight Training. *Eur. J. Appl. Physiol.* **2010**. [CrossRef]
296. Norrbrand, L.; Tous-Fajardo, J.; Vargas, R.; Tesch, P.A. Quadriceps Muscle Use in the Flywheel and Barbell Squat. *Aviat. Sp. Environ. Med.* **2011**. [CrossRef]
297. Cuenca-Fernández, F.; López-Contreras, G.; Mourão, L.; de Jesus, K.; de Jesus, K.; Zacca, R.; Vilas-Boas, J.P.; Fernandes, R.J.; Arellano, R. Eccentric Flywheel Post-Activation Potentiation Influences Swimming Start Performance Kinetics. *J. Sports Sci.* **2019**. [CrossRef]
298. Cuenca-Fernández, F.; López-Contreras, G.; Arellano, R. Effect on Swimming Start Performance of Two Types of Activation Protocols: Lunge and YoYo Squat. *J. Strength Cond. Res.* **2015**. [CrossRef]
299. Beato, M.; Stiff, A.; Coratella, G. Effects of Postactivation Potentiation After an Eccentric Overload Bout on Countermovement Jump and Lower-Limb Muscle Strength. *J. Strength Cond. Res.* **2019**. [CrossRef]
300. Beato, M.; De Keijzer, K.L.; Leskauskas, Z.; Allen, W.J.; Dello Iacono, A.; McErlain-Naylor, S.A. Effect of Postactivation Potentiation After Medium vs. High Inertia Eccentric Overload Exercise on Standing Long Jump, Countermovement Jump, and Change of Direction Performance. *J. Strength Cond. Res.* **2019**. [CrossRef]
301. Lundberg, T.R.; García-Gutiérrez, M.T.; Mandić, M.; Lilja, M.; Fernandez-Gonzalo, R. Regional and Muscle-Specific Adaptations in Knee Extensor Hypertrophy Using Flywheel versus Conventional Weight-Stack Resistance Exercise. *Appl. Physiol. Nutr. Metab.* **2019**. [CrossRef]
302. Illera-Domínguez, V.; Nuell, S.; Carmona, G.; Padullés, J.M.; Padullés, X.; Lloret, M.; Cussó, R.; Alomar, X.; Cadefau, J.A. Early Functional and Morphological Muscle Adaptations during Short-Term Inertial-Squat Training. *Front. Physiol.* **2018**. [CrossRef]
303. Seynnes, O.R.; De Boer, M.; Narici, M.V. Early Skeletal Muscle Hypertrophy and Architectural Changes in Response to High-Intensity Resistance Training. *J. Appl. Physiol.* **2007**. [CrossRef]
304. Tesch, P.A.; Ekberg, A.; Lindquist, D.M.; Trieschmann, J.T. Muscle Hypertrophy Following 5-Week Resistance Training Using a Non-Gravity-Dependent Exercise System. *Acta Physiol. Scand.* **2004**. [CrossRef]

305. Maroto-Izquierdo, S.; García-López, D.; De Paz, J.A. Functional and Muscle-Size Effects of Flywheel Resistance Training with Eccentric-Overload in Professional Handball Players. *J. Hum. Kinet.* **2017**. [CrossRef]
306. Naczk, M.; Naczk, A.; Brzenczek-Owczarzak, W.; Arlet, J.; Adach, Z. Impact of Inertial Training on Strength and Power Performance in Young Active Men. *J. Strength Cond. Res.* **2016**. [CrossRef]
307. Sabido, R.; Pombero, L.; Hernández-Davó, J.L. Differential effects of low vs high inertial loads during an eccentric-overload training intervention in rugby union players: A preliminary study. *J. Sports Med. Phys. Fit.* **2019**. [CrossRef]
308. Fernandez-Gonzalo, R.; Lundberg, T.R.; Alvarez-Alvarez, L.; De Paz, J.A. Muscle Damage Responses and Adaptations to Eccentric-Overload Resistance Exercise in Men and Women. *Eur. J. Appl. Physiol.* **2014**. [CrossRef]
309. De Hoyo, M.; De La Torre, A.; Pradas, F.; Sañudo, B.; Carrasco, L.; Mateo-Cortes, J.; Domínguez-Cobo, S.; Fernandes, O.; Gonzalo-Skok, O. Effects of Eccentric Overload Bout on Change of Direction and Performance in Soccer Players. *Int. J. Sports Med.* **2015**. [CrossRef]
310. Horwath, O.; Paulsen, G.; Esping, T.; Seynnes, O.; Olsson, M.C. Isokinetic resistance training combined with eccentric overload improves athletic performance and induces muscle hypertrophy in young ice hockey players. *J. Sci. Med. Sport* **2019**, *22*, 821–826. [CrossRef]
311. Harper, D.J.; Jordan, A.R.; Kiely, J. Relationships Between Eccentric and Concentric Knee Strength Capacities and Maximal Linear Deceleration Ability in Male Academy Soccer Players. *J. Strength Cond. Res.* **2018**. [CrossRef]
312. Dos'Santos, T.; Thomas, C.; Jones, P.A.; Comfort, P. Mechanical Determinants of Faster Change of Direction Speed Performance in Male Athletes. *J. Strength Cond. Res.* **2017**. [CrossRef] [PubMed]
313. Spiteri, T.; Newton, R.U.; Binetti, M.; Hart, N.H.; Sheppard, J.M.; Nimphius, S. Mechanical Determinants of Faster Change of Direction and Agility Performance in Female Basketball Athletes. *J. Strength Cond. Res.* **2015**. [CrossRef] [PubMed]
314. Meyers, R.W.; Oliver, J.L.; Hughes, M.G.; Cronin, J.B.; Lloyd, R.S. Maximal Sprint Speed in Boys of Increasing Maturity. *Pediatr. Exerc. Sci.* **2015**. [CrossRef]
315. McCunn, R.; Weston, M.; Hill, J.K.A.; Johnston, R.D.; Gibson, N.V. Influence of Physical Maturity Status on Sprinting Speed among Youth Soccer Players. *J. Strength Cond. Res.* **2017**. [CrossRef]
316. Rumpf, M.C.; Cronin, J.B.; Oliver, J.; Hughes, M. Kinematics and Kinetics of Maximum Running Speed in Youth across Maturity. *Pediatr. Exerc. Sci.* **2015**. [CrossRef]
317. Emmonds, S.; Morris, R.; Murray, E.; Robinson, C.; Turner, L.; Jones, B. The Influence of Age and Maturity Status on the Maximum and Explosive Strength Characteristics of Elite Youth Female Soccer Players. *Sci. Med. Footb.* **2017**. [CrossRef]
318. Meylan, C.M.P.; Cronin, J.B.; Oliver, J.L.; Hopkins, W.G.; Contreras, B. The Effect of Maturation on Adaptations to Strength Training and Detraining in 11–15-Year-Olds. *Scand. J. Med. Sci. Sport* **2014**, *24*. [CrossRef]
319. Murtagh, C.F.; Brownlee, T.E.; O'Boyle, A.; Morgans, R.; Drust, B.; Erskine, R.M. Importance of Speed and Power in Elite Youth Soccer Depends on Maturation Status. *J. Strength Cond. Res.* **2018**. [CrossRef]
320. Brownlee, T.E.; Murtagh, C.F.; Naughton, R.J.; Whitworth-Turner, C.M.; O'Boyle, A.; Morgans, R.; Morton, J.P.; Erskine, R.M.; Drust, B. Isometric Maximal Voluntary Force Evaluated Using an Isometric Mid-Thigh Pull Differentiates English Premier League Youth Soccer Players from a Maturity-Matched Control Group. *Sci. Med. Footb.* **2018**. [CrossRef]
321. Morris, R.O.; Jones, B.; Myers, T.; Lake, J.; Emmonds, S.; Clarke, N.D.; Singleton, D.; Ellis, M.; Till, K. Isometric Midthigh Pull Characteristics in Elite Youth Male Soccer Players: Comparisons by Age and Maturity Offset. *J. Strength Cond. Res.* **2018**. [CrossRef]
322. Vanrenterghem, J.; Venables, E.; Pataky, T.; Robinson, M.A. The Effect of Running Speed on Knee Mechanical Loading in Females during Side Cutting. *J. Biomech.* **2012**. [CrossRef]
323. Mirwald, R.L.; Baxter-Jones, A.D.G.; Bailey, D.A.; Beunen, G.P. An Assessment of Maturity from Anthropometric Measurements. *Med. Sci. Sports Exerc.* **2002**, *34*, 689–694.
324. Howard, S.M.A.; Cumming, S.P.; Atkinson, M.; Malina, R.M. Biological Maturity-Associated Variance in Peak Power Output and Momentum in Academy Rugby Union Players. *Eur. J. Sport Sci.* **2016**. [CrossRef]
325. Petré, H.; Wernstål, F.; Mattsson, C.M. Effects of Flywheel Training on Strength-Related Variables: A Meta-Analysis. *Sport. Med. Open* **2018**. [CrossRef]

326. Seger, J.Y.; Thorstensson, A. Muscle Strength and Myoelectric Activity in Prepubertal and Adult Males and Females. *Eur. J. Appl. Physiol. Occup. Physiol.* **1994**. [CrossRef]
327. Carroll, K.M.; Wagle, J.P.; Sato, K.; Taber, C.B.; Yoshida, N.; Bingham, G.E.; Stone, M.H. Characterising Overload in Inertial Flywheel Devices for Use in Exercise Training. *Sport. Biomech.* **2019**. [CrossRef]
328. Sabido, R.; Hernández-Davó, J.L.; Pereyra-Gerber, G.T. Influence of Different Inertial Loads on Basic Training Variables during the Flywheel Squat Exercise. *Int. J. Sports Physiol. Perform.* **2018**. [CrossRef]
329. Piqueras-Sanchiz, F.; Martín-Rodríguez, S.; Martínez-Aranda, L.M.; Lopes, T.R.; Raya-González, J.; García-García, Ó.; Nakamura, F.Y. Effects of Moderate vs. High Iso-Inertial Loads on Power, Velocity, Work and Hamstring Contractile Function after Flywheel Resistance Exercise. *PLoS ONE* **2019**. [CrossRef]
330. Simpson, M.; Rio, E.; Cook, J. At What Age Do Children and Adolescents Develop Lower Limb Tendon Pathology or Tendinopathy? A Systematic Review and Meta-Analysis. *Sports Med.* **2016**. [CrossRef]
331. Hagglund, M.; Walden, M.; Zwerver, J.; Ekstrand, J. Epidemiology of Patellar Tendon Injury in Elite Male Soccer Players. *Br. J. Sports Med.* **2011**. [CrossRef]
332. Le Gall, F.; Carling, C.; Reilly, T.; Vandewalle, H.; Church, J.; Rochcongar, P. Incidence of Injuries in Elite French Youth Soccer Players: A 10-Season Study. *Am. J. Sports Med.* **2006**. [CrossRef] [PubMed]
333. Patel, D.R.; Villalobos, A. Evaluation and Management of Knee Pain in Young Athletes: Overuse Injuries of the Knee. *Transl. Pediatr.* **2017**. [CrossRef] [PubMed]
334. Cassel, M.; Intziegianni, K.; Risch, L.; Müller, S.; Engel, T.; Mayer, F. Physiological tendon thickness adaptation in adolescent elite athletes: A longitudinal study. *Front. Physiol.* **2017**, *8*, 795. [CrossRef] [PubMed]
335. Cassel, M.; Carlsohn, A.; Fröhlich, K.; John, M.; Riegels, N.; Mayer, F. Tendon Adaptation to Sport-Specific Loading in Adolescent Athletes. *Int. J. Sports Med.* **2015**. [CrossRef] [PubMed]
336. Cassel, M.; Baur, H.; Hirschmüller, A.; Carlsohn, A.; Fröhlich, K.; Mayer, F. Prevalence of Achilles and Patellar Tendinopathy and Their Association to Intratendinous Changes in Adolescent Athletes. *Scand. J. Med. Sci. Sport* **2015**. [CrossRef]
337. Cassel, M.; Risch, L.; Intziegianni, K.; Mueller, J.; Stoll, J.; Brecht, P.; Mayer, F. Incidence of Achilles and patellar tendinopathy in adolescent elite athletes. *Int. J. Sports Med.* **2018**, *39*, 726–732. [CrossRef]
338. O'Brien, T.D.; Reeves, N.D.; Baltzopoulos, V.; Jones, D.A.; Maganaris, C.N. Mechanical Properties of the Patellar Tendon in Adults and Children. *J. Biomech.* **2010**. [CrossRef]
339. Rudavsky, A.; Cook, J.L.; Docking, S. Proximal Patellar Tendon Pathology Can Develop during Adolescence in Young Ballet Dancers—A 2-Year Longitudinal Study. *Scand. J. Med. Sci. Sport* **2018**. [CrossRef]
340. Mersmann, F.; Bohm, S.; Schroll, A.; Boeth, H.; Duda, G.N.; Arampatzis, A. Muscle and Tendon Adaptation in Adolescent Athletes: A Longitudinal Study. *Scand. J. Med. Sci. Sport* **2017**. [CrossRef]
341. Mersmann, F.; Bohm, S.; Schroll, A.; Boeth, H.; Duda, G.; Arampatzis, A. Evidence of Imbalanced Adaptation between Muscle and Tendon in Adolescent Athletes. *Scand. J. Med. Sci. Sport* **2014**. [CrossRef]
342. Pentidis, N.; Mersmann, F.; Bohm, S.; Giannakou, E.; Aggelousis, N.; Arampatzis, A. Triceps Surae Muscle-Tendon Unit Properties in Preadolescent Children: A Comparison of Artistic Gymnastic Athletes and Non-Athletes. *Front. Physiol.* **2019**. [CrossRef] [PubMed]
343. Kubo, K.; Ikebukuro, T.; Yata, H.; Tsunoda, N.; Kanehisa, H. Time Course of Changes in Muscle and Tendon Properties during Strength Training and Detraining. *J. Strength Cond. Res.* **2010**. [CrossRef] [PubMed]
344. Kubo, K.; Ikebukuro, T.; Maki, A.; Yata, H.; Tsunoda, N. Time course of changes in the human Achilles tendon properties and metabolism during training and detraining in vivo. *Eur. J. Appl. Physiol.* **2012**, *112*, 2679–2691. [CrossRef] [PubMed]
345. Mersmann, F.; Bohm, S.; Arampatzis, A. Imbalances in the Development of Muscle and Tendon as Risk Factor for Tendinopathies in Youth Athletes: A Review of Current Evidence and Concepts of Prevention. *Front. Physiol.* **2017**. [CrossRef] [PubMed]
346. Mersmann, F.; Pentidis, N.; Tsai, M.-S.; Schroll, A.; Arampatzis, A. Patellar Tendon Strain Associates to Tendon Structural Abnormalities in Adolescent Athletes. *Front. Physiol.* **2019**. [CrossRef]
347. Charcharis, G.; Mersmann, F.; Bohm, S.; Arampatzis, A. Morphological and Mechanical Properties of the Quadriceps Femoris Muscle-Tendon Unit from Adolescence to Adulthood: Effects of Age and Athletic Training. *Front. Physiol.* **2019**. [CrossRef]
348. Waugh, C.M.; Blazevich, A.J.; Fath, F.; Korff, T. Age-Related Changes in Mechanical Properties of the Achilles Tendon. *J. Anat.* **2012**. [CrossRef]

349. Waugh, C.M.; Korff, T.; Fath, F.; Blazevich, A.J. Effects of Resistance Training on Tendon Mechanical Properties and Rapid Force Production in Prepubertal Children. *J. Appl. Physiol.* **2014**. [CrossRef]
350. Lee, W.-C.; Ng, G.Y.-F.; Zhang, Z.-J.; Malliaras, P.; Masci, L.; Fu, S.-N. Changes on Tendon Stiffness and Clinical Outcomes in Athletes Are Associated with Patellar Tendinopathy After Eccentric Exercise. *Clin. J. Sport Med.* **2017**. [CrossRef]
351. Geremia, J.M.; Baroni, B.M.; Bobbert, M.F.; Bini, R.R.; Lanferdini, F.J.; Vaz, M.A. Effects of High Loading by Eccentric Triceps Surae Training on Achilles Tendon Properties in Humans. *Eur. J. Appl. Physiol.* **2018**. [CrossRef]
352. Malliaras, P.; Kamal, B.; Nowell, A.; Farley, T.; Dhamu, H.; Simpson, V.; Morrissey, D.; Langberg, H.; Maffulli, N.; Reeves, N.D. Patellar Tendon Adaptation in Relation to Load-Intensity and Action Type. *J. Biomech.* **2013**. [CrossRef] [PubMed]
353. Frizziero, A.; Vittadini, F.; Fusco, A.; Giombini, A.; Masiero, S. Efficacy of Eccentric Exercise in Lower Limb Tendinopathies in Athletes. *J. Sports Med. Phys. Fit.* **2016**, *56*, 1352–1358.
354. O'Neill, S.; Watson, P.J.; Barry, S. Why are eccentric exercises effective for achilles tendinopathy? *Int. J. Sports Phys. Ther.* **2015**, *10*, 552. [PubMed]
355. Arampatzis, A.; Peper, A.; Bierbaum, S.; Albracht, K. Plasticity of Human Achilles Tendon Mechanical and Morphological Properties in Response to Cyclic Strain. *J. Biomech.* **2010**. [CrossRef] [PubMed]
356. Bohm, S.; Mersmann, F.; Tettke, M.; Kraft, M.; Arampatzis, A. Human Achilles Tendon Plasticity in Response to Cyclic Strain: Effect of Rate and Duration. *J. Exp. Biol.* **2014**. [CrossRef]
357. Kongsgaard, M.; Qvortrup, K.; Larsen, J.; Aagaard, P.; Doessing, S.; Hansen, P.; Kjaer, M.; Magnusson, S.P. Fibril Morphology and Tendon Mechanical Properties in Patellar Tendinopathy. *Am. J. Sports Med.* **2010**. [CrossRef]
358. Sanz-López, F.; Berzosa, C.; Hita-Contreras, F.; Martínez-Amat, A. Effects of Eccentric Overload Training on Patellar Tendon and Vastus Lateralis in Three Days of Consecutive Running. *Knee* **2017**. [CrossRef]
359. Sanz-López, F.; Martínez-Amat, A.; Hita-Contreras, F.; Valero-Campo, C.; Berzosa, C. Thermographic Assessment of Eccentric Overload Training Within Three Days of a Running Session. *J. Strength Cond. Res.* **2016**. [CrossRef]
360. Romero-Rodriguez, D.; Gual, G.; Tesch, P.A. Efficacy of an Inertial Resistance Training Paradigm in the Treatment of Patellar Tendinopathy in Athletes: A Case-Series Study. *Phys. Ther. Sport* **2011**. [CrossRef]
361. Gual, G.; Fort-Vanmeerhaeghe, A.; Romero-Rodríguez, D.; Tesch, P.A. Effects of In-Season Inertial Resistance Training with Eccentric Overload in a Sports Population at Risk for Patellar Tendinopathy. *J. Strength Cond. Res.* **2016**. [CrossRef]
362. Suchomel, T.J.; Wagle, J.P.; Douglas, J.; Taber, C.B.; Harden, M.; Haff, G.G.; Stone, M.H. Implementing Eccentric Resistance Training—Part 2: Practical Recommendations. *J. Funct. Morphol. Kinesiol.* **2019**, *4*, 55. [CrossRef]

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Eccentric Resistance Training in Youth: A Survey of Perceptions and Current Practices by Strength and Conditioning Coaches

Benjamin Drury [1,*], Hannah Clarke [1], Jason Moran [2], John F. T. Fernandes [1], Greg Henry [1] and David G. Behm [3]

[1] Department of Applied Sport Sciences, Hartpury University, Gloucestershire GL19 3BE, UK; hannah.clarke@hartpury.ac.uk (H.C.); john.fernandes@hartpury.ac.uk (J.F.T.F.); greg.henry@hartpury.ac.uk (G.H.)
[2] School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester CO4 3SQ, UK; jmorana@essex.ac.uk
[3] School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, NL A1C 5S7, Canada; dbehm@mun.ca
* Correspondence: ben.drury@hartpury.ac.uk

Abstract: Background: Eccentric resistance training (ERT) in youth is advocated for aiding performance and injury risk. However, research investigating the applied practices of ERT in youth is in its infancy. In this study, we surveyed the perceptions and practices of practitioners utilizing ERT in youth to provide an understanding of its current application in practice. Methods: Sixty-four strength and conditioning coaches completed an online survey reporting their current use of ERT in youth using both open and closed questions. Results: Coaches deemed the inclusion of ERT important in youth with its inclusion based upon factors such as maturation status, training age and strength levels. Coaches also displayed an awareness of the physiological responses to eccentric exercise in youth compared to adults. ERT was primarily used for injury prevention, with the majority of coaches using body-weight and tempo exercises. Furthermore, utilizing eccentric hamstrings exercises was reported as highly important. The frequency of ERT tended to increase in older age groups and coaches mainly prescribed self-selected rest intervals. Finally, the need for further research into the training guidelines of ERT in youth was highlighted, in which coaches require more information on how maturation influences training adaptations and the fatigue–recovery responses. Conclusion: Coaches emphasized the importance of including ERT for both performance and injury prevention factors in youth although further research is required to generate practical guidelines for coaches in order to support its inclusion within practice.

Keywords: long-term athletic development; training prescription; injury prevention; strength training; youth athletes

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1. Introduction

Improving youth athletic performance can be achieved using resistance training (RT) throughout childhood and adolescence [1]. Furthermore, to support long-term athletic development (LTAD), position statements exists pertaining to the safe and effective training prescription of RT [2]. These frameworks provide coaches, working with youth athletes, guidance on how factors such as growth and maturation can influence adaptations to training stimuli as well as how the training process can be structured. Such an approach is necessary considering that performance and adaptive responses in youth are influenced by an individual's maturity status [3]. This is particularly important with reference to the youth physical development model (YPD) in which the development of muscular strength and power is key [4]. Prior research in youth athletes has reported that higher levels of muscular strength improves performance in tasks such as jumping [5], sprinting [6] and change of direction movements [7] as well as reducing injury risk [8]. Therefore, knowledge of RT methods that can be utilized to enhance physical qualities in youth athletes is important to understand.

One RT method that is commonly utilized to improve athletic performance is eccentric resistance training (ERT). Indeed, the use of ERT has been reported to improve physical qualities such as strength and power [9]. Importantly, improvements following ERT are not necessarily exclusive to the muscle action type with increases in both eccentric, concentric and isometric strength previously shown [10]. Such changes can be explained by neuromuscular [10], morphological [11] and molecular [12] adaptations. Despite this, greater levels of muscle damage and a longer time for neuromuscular function to recover are observed following eccentric exercise due to both central and peripheral factors [13]. Consequently, the incorporation of ERT for athletes has been noted as a challenge by strength and conditioning (S&C) coaches [14]. To support this, practical guidelines have been generated to provide coaches with a framework of how to prescribe ERT for athletes [15]. However, muscular and neural differences exist between youth and adults which influence the response and adaptations to resistance training (RT) [16]. Therefore, the training prescription of ERT for youth athletes is likely to require a more tailored approach.

A breadth of literature currently exists pertaining to the prescription of RT to support LTAD [17–19]. Comparatively, little of this information specifically addresses the use of ERT. Although the reasons for this are unclear, previous research has commented that the inclusion of eccentric exercises could be too intense for young and inexperienced athletes [20]. However, the inclusion of RT in youth has been reported to be effective provided that it is age appropriate, safe and supervised [21]. Moreover, potential concerns of male and female youths being at greater risk of fatigue and muscle damage compared to adults following eccentric exercise is not supported by current literature [22,23]. From a performance perspective, ERT in youth has also been shown to lead to improvements in strength and power, change of direction, sprint performance and injury prevention [24–33]. Additionally, tasks which include high levels of eccentric forces such as jumping, landing, hopping, and deceleration are all considered key athletic motor skills competencies that should be developed in youth [34]. Therefore, whilst the practical application of ERT in youth athletes is still in its infancy, it would appear that its implementation throughout youth has potentially important implications.

To date, conceptual recommendations have been provided with regards to the training prescription of ERT methods in youth [1,35]. However, little is known about its actual implementation within practice for youth athletes. Conversely, the practices of ERT in in elite athletes have been reported [14,36]. Since aspects such as growth and maturation [37] as well as training age [38] influence adaptations to RT it is likely that current practices of ERT in youth will, and should, differ. However, the lack of specific training guidelines available to S&C coaches in this area makes it is unclear what evidence-based approach is currently being undertaken. Consequently, it is important to understand S&C coach's current knowledge of the area as well as barriers and concerns regarding its inclusion. Such an approach is recommended to allow research to guide practice, but also for practice to guide research [39]. Indeed, the reporting of perceptions and practices of injury prevention strategies by practitioners working with youth athletes has previously highlighted important areas for consideration [40]. Therefore, the purpose of this study was to survey S&C coaches in order to understand their perceptions and current practices of ERT in youth as well as perceived barriers they may face with regards to its inclusion.

2. Materials and Methods

2.1. Subjects

Coaches were recruited through the use of online platforms (Twitter, LinkedIn and email networks). Inclusion criteria required the strength and conditioning coaches to currently be with youth athletes under the age of 18 y. Informed consent was sought from all coaches prior to completing the questionnaire in which their responses were anonymous. The study was conducted in accordance with the Declaration of Helsinki and by the University Ethics Committee.

2.2. Experimental Design

This study used a web-based questionnaire (British Online Surveys, Bristol, UK) to survey the perceptions and current practices of ERT in youth athletes by S&C coaches. The questionnaire included a mixture of open and closed questions which took approximately 15–20 minutes to complete (Supplementary Materials). A total of twelve questions, which included ten closed questions and two open questions, were used from the full completed survey. Questions were framed around four areas including (1) perceptions of ERT in youth; (2) implementation of ERT in youth; (3) training prescription of ERT in youth; and (4) barriers and future directions for the use of ERT in youth. Quantitative responses for closed question responses were primarily provided on a five-point Likert scales to determine perceived importance and extent of agreement. Additionally, several multiple-choice questions were also included requiring either single or multi-response answers. Open questions were used to further understand the coaches concerns and future directions to the inclusion of ERT in youth. ERT was defined as using a load during the eccentric phase that is in excess of the concentric phase [9], whilst traditional resistance training (TRT) was defined as an emphasis on loading the upward concentric phase of an exercise using resistance or body mass [41].

2.3. Procedures

An initial survey was designed by a panel of three experts that had both practical and research experience in the topic area. The survey was reviewed for face and content validity [42] via a panel of four experienced S&C coaches currently working with youth athletes. Subsequently, a pilot survey was sent out ($n = 4$) to gain feedback and recommendations on areas of the survey that they believed could be improved. This approach is similar to previous studies that have completed surveys of practitioners within topic areas of eccentric training and youth athletes [36,40]. The panel and pilot survey subjects were from a range of different sports and employment settings within youth to ensure that the questions were appropriate for a wide range of potential subjects that may complete the survey. Once the survey was finalized it was sent out to the target population. Subjects were provided a maximum of six weeks to complete the survey and the lead researcher's contact details were provided in case any queries or clarity was required regarding the answers to the questions. Subsequently, a total of 64 responses were received for the survey and were included for the analyses.

2.4. Statistical Analysis

All data were collected using an online questionnaire (https://www.onlinesurveys.ac.uk/ (accessed on 18 February 2021)). Data were then transferred to Microsoft Excel for further analysis. This observational study followed a descriptive, cross-sectional design, therefore quantitative data presentation is mostly descriptive in nature with frequency counts and percentages calculated. For questions incorporating unipolar Likert scales, responses were coded (e.g., 1 = "least important" or "strongly disagree", 5 = "most important" or "strongly agree"). Points for each response were then summed to facilitate ranking of highest to lowest in importance [43]. Where possible, for between-group differences in TRT compared to ERT responses a proportion ratio (PR) was calculated in accordance with previous research [44]. The PR magnitudes were calculated and assessed against the following magnitude scale: 1.00, 1.11, 1.43, 2.0, 3.3 and 10 for trivial, small, moderate, large, very large and extremely large, respectively, and their inverses 0.9, 0.7, 0.5, 0.3 and 0.1 [45]. Responses to open questions were sorted into categories for a frequency count by the lead researcher and then discussed with members of the research team to ensure agreement. Areas for future research of ERT in youth were visualized to display the generated themes in accordance with previous research investigating practitioner's perceptions [46] using WordArt (https://wordart.com/ (accessed on 18 February 2021)).

3. Results

3.1. Demographic Characteristics of the Coaches

Coaches worked in a variety of youth team sports including rugby union, soccer, Gaelic football, cricket, basketball, swimming, triathlon and weightlifting. Coaches were from the United Kingdom (86%, *n* = 55), United States of America (3%, *n* = 2), Portugal (3% *n* = 2), Sweden (1.5%, *n* = 1), France (1.5%, *n* = 1) and Canada (1.5%, *n* = 1) with the remaining coaches not reporting this information (3%, *n* = 2). Overall, 76% (*n* = 49) of coaches worked in professional sport, 14% (*n* = 9) in schools/colleges and 10% (*n* = 6) in semi-professional sport. With regard to the sexes that the coaches coached, 78% (*n* = 50) worked with male youth athletes exclusively, 2% (*n* = 1) worked with female youth athletes exclusively and 20% (*n* = 13) worked with both male and females.

3.2. Perceptions of ERT in Youth

The majority of coaches reported that they perceived both TRT and ERT to be important for youth athletes (Table 1). Whilst *trivial* differences were found in the combined agreement scores (TRT = 98% vs. ERT = 96%) a *small* difference existed between groups for the "strongly agree" category in which a greater number of coaches perceived TRT to be more important (PR = 1.13). Movement competency (68%, *n* = 44) was perceived as the most important pre-requisite prior to beginning TRT (Figure 1A) followed by the training age (20%, *n* = 13), maturation status (19%, *n* = 12), chronological age (13%, *n* = 8) and strength level (9%, *n* = 6). A similar order was reported for ERT (Figure 1B) in which movement competency (53%, *n* = 34) was followed by training age (34%, *n* = 22) and maturation status (27%, *n* = 17). However, strength level (16%, *n* = 10) and chronological age (8%, *n* = 5) were then subsequently noted. When "most-high" categories were combined, *small* differences were found between TRT compared to ERT for movement competency (79 vs. 70%, PR = 1.13) and maturation status (54 vs. 47%, PR = 1.15). Alternatively, a *small* difference was found between TRT compared to ERT for training age (53 vs. 61%, PR = 0.87). Additionally, a *moderate* difference was found between TRT compared to ERT for strength level (29 vs. 50%, PR = 0.58). The majority of coaches disagreed with all statements regarding the training responses to ERT in youth compared to adults (Table 2) for higher risk of injury (80%, *n* = 51), recovery time (78%, *n* = 50), muscle damage (69%, *n* = 44) and fatigue (67%, *n* = 43).

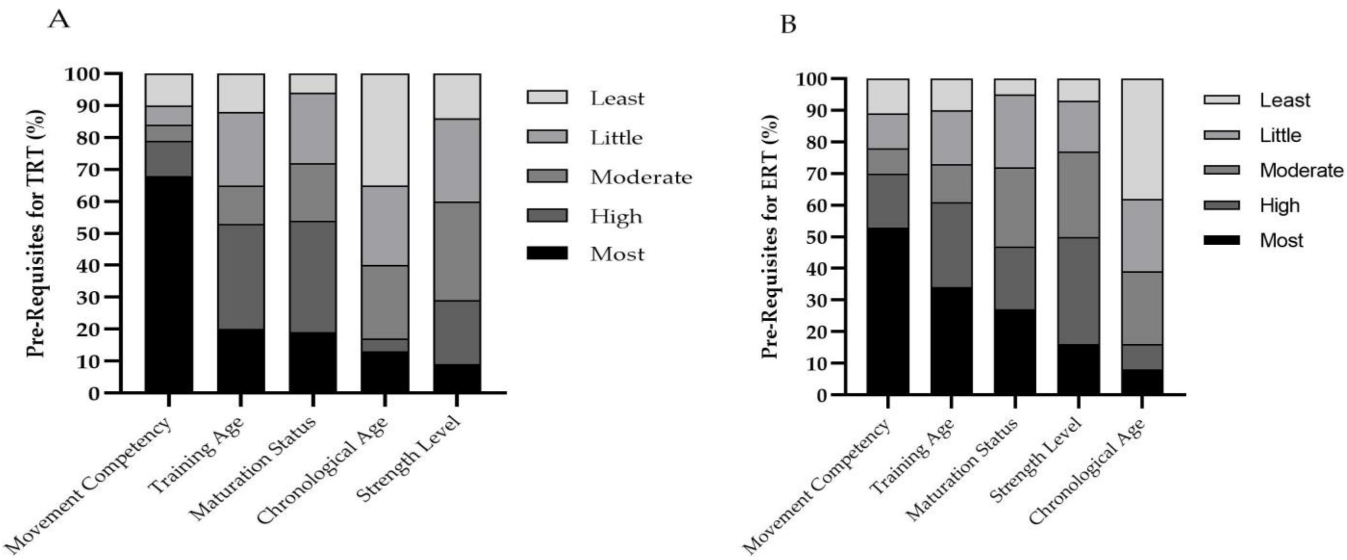

Figure 1. Coaches' perceived importance of pre-requisites for (**A**) traditional (TRT) and (**B**) eccentric (ERT) resistance training in youth athletes.

Table 1. Coaches' perceived importance of traditional (TRT) and eccentric (ERT) resistance training in youth athletes.

Training Type	Strongly Agree % (No.)	Agree % (No.)	Unsure % (No.)	Disagree % (No.)	Strongly Disagree % (No.)
TRT	76 (49)	22 (14)	0 (0)	2 (1)	0 (0)
ERT	67 (43)	29 (19)	2 (1)	2 (1)	0 (0)

Table 2. Coaches' perceptions of responses to eccentric resistance training in youth compared to adults.

Training Response	Strongly Disagree % (No.)	Disagree % (No.)	Unsure % (No.)	Agree % (No.)	Strongly Agree % (No.)
Risk of Injury	22 (14)	58 (37)	17 (11)	3 (2)	0 (0)
Recovery Time	20 (13)	58 (37)	13 (8)	9 (6)	0 (0)
Muscle Damage	17 (11)	52 (33)	23 (15)	8 (5)	0 (0)
Fatigue	17 (11)	50 (32)	19 (12)	14 (9)	0 (0)

3.3. Implementation of ERT in Youth

A *moderate* difference (PR = 1.85) was found between the number of coaches which included TRT during pre-peak height velocity (PHV) compared to ERT (Figure 2). Consequently, *very large* differences were found between TRT compared to ERT in which a greater number of coaches included ERT during PHV (PR = 0.25) and post-PHV (PR = 0.24). Coaches' primary reason for utilizing ERT in youth (Figure 3) was for injury prevention purposes (61%, n = 39). This was then followed by change of direction (30%, n = 19), strength and power (28%, n = 18), injury rehabilitation (19%, n = 12) and muscle hypertrophy (14%, n = 9). Coaches reported that eccentric hamstrings training was the most important for youth athletes followed by isometric and concentric training (Table 3). Furthermore, ninety-one percent (91%) of coaches also stated that they prescribed the Nordic hamstrings exercise (NHE) to their youth athletes.

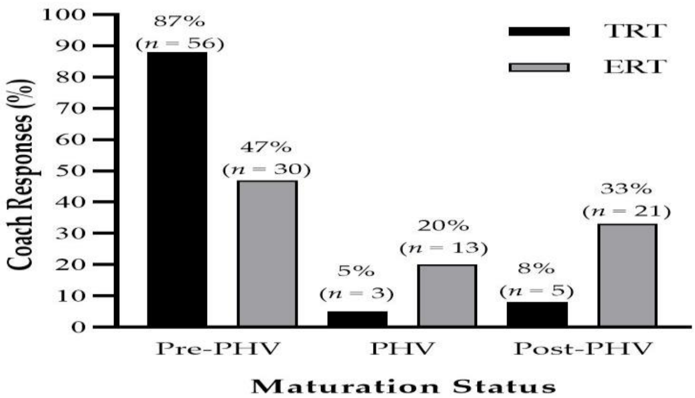

Figure 2. Maturation status at which coaches implement traditional (TRT) and eccentric (ERT) resistance training. PHV = peak height velocity.

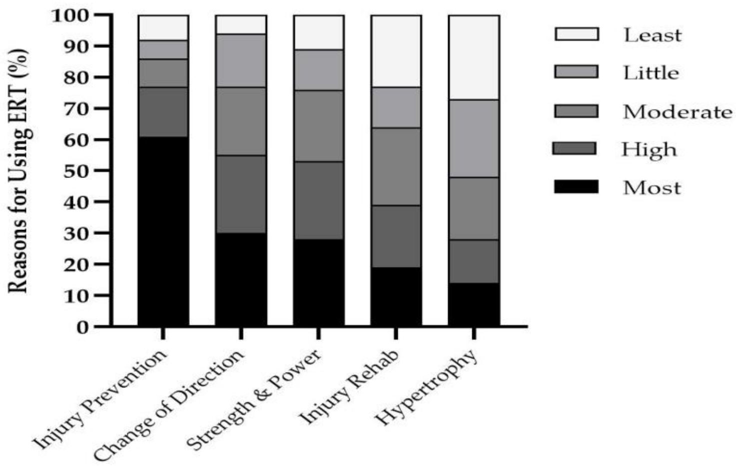

Figure 3. Reasons for utilizing eccentric resistance training (ERT) for youth athletes by coaches.

Table 3. Coaches' perceived importance of muscle action type for hamstrings training in youth.

Muscle Action Type	High Importance % (No.)	Important % (No.)	Moderate % (No.)	Low Importance % (No.)	Not Important % (No.)
Eccentric	79 (51)	21 (13)	0 (0)	0 (0)	0 (0)
Isometric	27 (17)	52 (33)	19 (12)	2 (2)	0 (0)
Concentric	19 (12)	55 (35)	19 (12)	7 (5)	0 (0)

3.4. Training Prescription of ERT in Youth

Coaches reported that body weight, tempo (e.g., greater emphasis on duration during the descent phase) and free weights training modalities were primarily used for ERT in youth (Figure 4). The weekly frequency of both TRT and ERT increased concurrently as age groups increased (Figure 5). However, a greater frequency of coaches prescribed TRT at all age groups compared to ERT with *large* differences between the groups found at U10 (6 vs. 3%, PR = 2.0), U12 (18 vs. 7%, PR = 2.57) and U14 (45 vs. 15%, PR = 3.0) age groups for two sessions per week. Additionally, *very large* to *large* differences were found at U14 (5 vs. 1%, PR = 5.0), U16 (27 vs. 5%, PR = 5.4) and U18 (60 vs. 20%, PR = 3.0) age groups for three sessions per week. With regards to the inter-set rest period (ISRP), the coaches reported that they mainly prescribed a self-selected ISRP for both RT methods at U10 (TRT = 32%, ERT = 46%), U12 (TRT = 31%, ERT = 33%) and U14 (TRT = 28%, ERT = 29%) age groups (Figure 6). However, a three-minute ISRP became more prevalent for both TRT or ERT at U16 (TRT = 31%, ERT = 42%) and U18 (TRT = 52%, ERT = 44%) age groups.

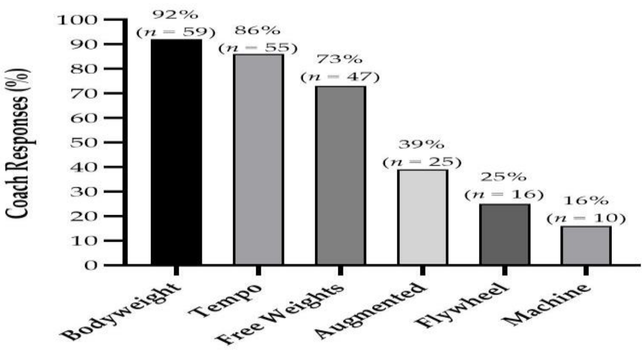

Figure 4. Reported eccentric resistance training modalities used by coaches for youth athletes.

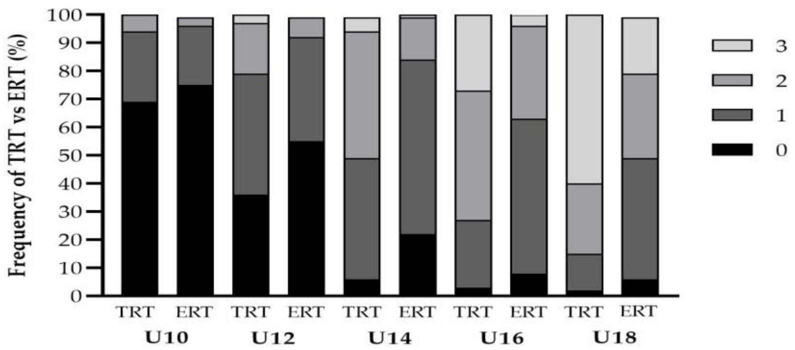

Figure 5. Weekly training frequency of traditional (TRT) and eccentric (ERT) resistance training across youth age groups.

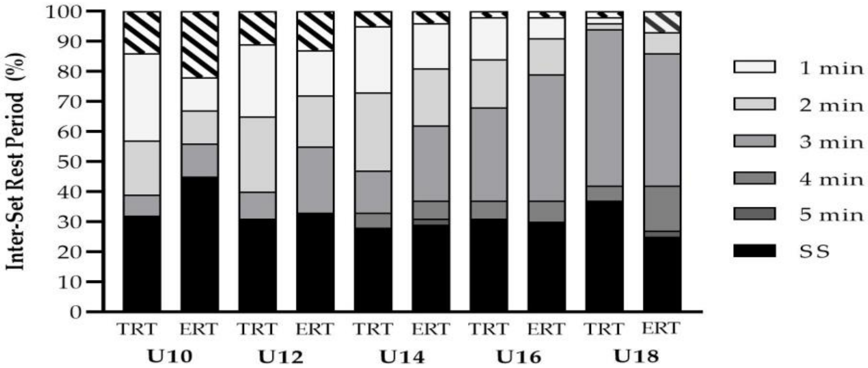

Figure 6. Inter-set rest period prescribed for traditional (TRT) and eccentric (ERT) resistance training across youth age groups. min = minute. SS = self-selected.

3.5. Barriers and Concerns for Utilizing ERT in Youth

Figure 7 shows the perceived barriers for the use of ERT in youth athletes. These main barriers were focused around logistical aspects such as training and match schedules as well as equipment required to perform ERT. With regards to future directions within ERT for youth, an array of areas was reported that practitioners felt required further information (Figure 8). These areas mainly included developing a better understanding of the training prescription for ERT in youth and how the maturation status may influence training adaptations, along with the fatigue and recovery responses to ERT too.

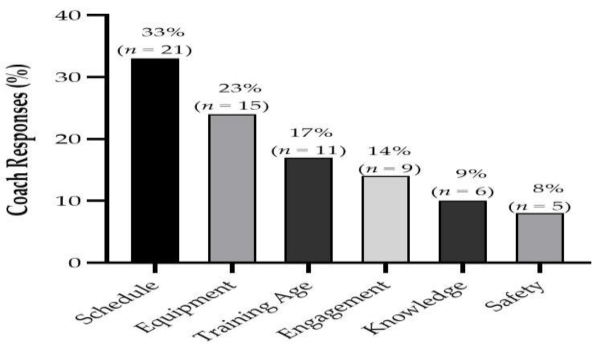

Figure 7. Coaches' perceived barriers to the implementation of eccentric resistance training in youth athletes.

Figure 8. Word cloud presenting coaches' perceived importance of areas for future research within ERT in youth athletes. This word cloud is based on the frequency of responses to the open questions. The more times a word is used the larger it appears.

4. Discussion

The aim of this study was to investigate the perceptions and current practices of ERT for youth athletes by S&C coaches. To the authors' knowledge, this is the first study to survey ERT in youth athletes, and to identify the current practices, perceptions and barriers that S&C coaches have regarding its use. Overall, coaches believed that ERT is important for youth athletes with training age, strength levels and the maturation status of the individual influencing its inclusion. There appeared to be a good understanding of the responses to eccentric exercise in youth with injury prevention the primary reason for the inclusion of ERT. Barriers for the implementation of ERT in youth were largely based around logistical factors with coaches also highlighting the need for further research into the different ERT methods for youth in order to provide further information on training guidelines.

Coaches agreed that the inclusion of both TRT and ERT is important for youth athletes. Although coaches believed that movement competency is the most important pre-requisite to begin either TRT or ERT, a greater proportion of responses for ERT highlighted the necessity of training age and strength levels. Evidence for why ERT requires a greater emphasis on these latter factors in youth is unclear. In adult athletes, previous research has found moderate to very high positive relationships between concentric and eccentric strength capabilities [47]. It is thus reasonable to presume that the consistent inclusion of dynamic RT exercises throughout youth will result in increases in eccentric as well as concentric force capabilities. However, responses to RT have been shown to be specific to the muscle action type trained [48]. Furthermore, greater levels of force are produced during maximal eccentric vs. concentric muscle actions [49]. Therefore, the delay of integrating ERT during youth may limit the development of eccentric strength. For instance, adolescent soccer players have been shown to have difficulty in reaching eccentric-overload during flywheel exercises [50]. The result of not developing eccentric strength qualities early on in youth may potentially impact the performance of sporting tasks. Indeed, eccentric knee extensor strength has been associated with greater deceleration ability in youth male soccer players [51]. Consequently, whilst future research should ascertain if a threshold of strength should exist prior to beginning ERT in youth, coaches should be mindful of the potential limitations in delaying its inclusion for tasks which require eccentric strength that are fundamental to athletic motor skill competencies (e.g., landing, change of direction).

Coaches demonstrated an awareness of the physiological responses to eccentric exercise in youth. For example, coaches largely disagreed that greater risks of muscle damage, fatigue and recovery would exist in youth compared to adults. Indeed, this is supported by current literature within the area among both males and females [22,23]. However, TRT was reported to mainly begin being prescribed during pre-PHV whilst the inclusion of ERT was more varied across maturation stages. The timing of when it is appropriate to begin ERT in youth is still unclear. Concerns for its inclusion too early in childhood could be due to the reported inefficiencies in male youth athletes (12.1 $\pm$ 1.1 yrs) in utilizing their stretch-shortening cycle (SSC) [52]. Indeed, the efficiency of the utilization of the SSC improves as the athlete matures [53]. However, positive responses to ERT have been shown following training interventions prescribing eccentric hamstrings training and flywheel inertia training (FIT) in pre-PHV athletes [24,30–32]. Additionally, post-PHV athletes have shown improvements in performance after completing such methods as well [25–28,33,54]. However, it should be acknowledged that further research is required to better understand how maturation may influence the responses to these methods in youth and the subsequent differences in training stimuli required as the athlete matures. Nevertheless, whilst some coaches may potentially favour a lower use of ERT during childhood and early adolescence, current literature suggests its inclusion can be considered an appropriate stimulus.

The primary reason for including ERT for youth athletes was for injury prevention purposes. Practitioners working with youth athletes have previously highlighted the requirement of lower-limb strength and eccentric hamstrings strength to prevent injuries [40]. Accordingly, nearly all coaches reported the importance of using eccentric muscle actions to develop hamstrings strength compared to concentric and isometric. Furthermore, 91% of our subjects reported that they prescribed the NHE. Whilst the reduction in hamstrings injuries in youth athletes via using the NHE is yet to be fully established, its use in adult athletes has been shown to reduce hamstrings injury risk by up to 51% [55]. The efficacy of such an approach during youth is becoming more salient with longitudinal analysis investigating injuries in youth practicing soccer and sprinting reporting hamstrings strains to be common during youth [56,57]. Furthermore, the use of ERT in youth may be beneficial for reducing the risk of injuries such as patella tendinopathy which is known to be impacted due to growth [58]. Indeed, following six weeks of flywheel training, an improved patella tendon condition was found in female youth athletes [59]. Moving forward, it is necessary to further investigate the impact of ERT on injury risk factors and the corresponding training guidelines that optimize this.

Coaches primarily used bodyweight and tempo training for ERT. Previously, the use of tempo training in youth male rugby union players (15.0 ± 0.9 yrs) was shown to enhance change of direction (COD) performance [7]. However, further research for its inclusion in youth is currently limited. Coaches increased both TRT and ERT frequencies in accordance with increases in age, although the frequency was consistently lower for ERT than TRT. The increase in RT frequency is in accordance with current RT guidelines in youth which suggest increases in weekly frequency in accordance with maturity status [60]. The lower frequency of ERT is likely expected considering that eccentric exercise has been shown to result in greater levels of muscle damage, fatigue, and time to recover than concentric training [12]. This approach is likely relevant for youth as well, since children and adolescents exhibit muscle damage after eccentric exercise, albeit to a lesser extent than their adult counterparts [22,23]. However, it should be noted that the aforementioned studies did not use well-trained youth athletes. Additionally, there was a tendency for self-selected rest periods to be preferred throughout U10 to U14 age groups. Such an approach is contrary to current evidence as previous research has reported the inability of less mature youth athletes to regulate their performance when using self-selected rest periods [61]. However, once athletes entered the U16 and U18 age groups, rest periods of three minutes were mainly prescribed, which may reflect a more specific training prescription approach once the athlete reaches post-PHV status. Indeed, as maturation increases, a longer recovery time is required to replenish energy resources [62].

The most frequently reported barriers for the inclusion of ERT in youth were focused around logistical aspects such as the training schedule and equipment. Previously, factors such as available time and equipment (e.g., budgetary constraints, minimal equipment and facilities available) have been reported to be important factors for the inclusion of injury prevention programme in youth [40]. Indeed, "cost effective" methods for ERT in youth were highlighted by coaches as an area for future research within ERT for youth in our study. Therefore, it is important for future research to identify ways in which ERT can be successfully integrated into training. Furthermore, coaches noted the need for further information on the practical methods of ERT in youth. Specifically, coaches commented that further information for aspects such as training guidelines for ERT is required as well as a better understanding of how maturation influences training adaptations. Accordingly, coaches also highlighted the need to understand the fatigue and recovery responses to ERT in youth as this is likely to affect how the micro-cycle is scheduled as well as the management of the training load. Subsequently, researchers can further investigate the areas highlighted here by S&C coaches in order to better inform their applied practices.

Despite our novel findings, our study is not without its limitations. For instance, the survey was potentially biased toward those coaches that actually currently use ERT with their youth athletes. Understanding the reasons for those coaches not using ERT among youth athletes could provide further clarification for this practice. Furthermore, most of the coaches were from the United Kingdom and therefore current practices presented in this study may not reflect those from other countries or regions which may not have access to the same extent of sport science literature. Unfortunately, our findings are mainly representative of the practices of youth male athletes. As previously noted, 2% of coaches worked only with female youth athletes and a further 20% worked with both male and females. It has been previously highlighted that the body of research relating to RT in female youth is substantially smaller than that in male youth and therefore requires further investigation [63]. The use of ERT in youth female athletes may be particularly necessary to understand, considering that low eccentric hamstrings strength is associated with landing mechanics that place the individual at greater risk of anterior cruciate ligament injury [64]. Therefore, further knowledge of how eccentric strength can be developed in female youth athletes and its relation to performance tasks and injury prevention is also necessary.

5. Conclusions

To the authors' knowledge, this is the first study to survey the perceptions and practices of ERT in youth athletes. The findings from this study demonstrate that coaches agree that the use of ERT in youth is important and that they display a good awareness of the physiological responses to eccentric exercise in youth. Furthermore, it was apparent that injury prevention is the primary reason for the inclusion of ERT and that a focus on improving eccentric hamstrings strength is deemed necessary. Despite this, a large proportion of coaches reported to not begin ERT during pre-PHV. In light of the available research in this area, we would recommend that practitioners consider the adoption of ERT earlier on in youth. With regards to training prescription factors such as exercise selection, rest periods and training frequency appear to be operating on anecdotal information, beliefs or ERT research conducted in other populations. It is for this reason that the practices reported here should be interpreted with caution. Overall, based upon the received responses, it is evident that further research is required in order to provide coaches with ERT guidelines that enhance both performance and injury prevention aspects.

Supplementary Materials: Full questionnaire originally provided to all coaches. The following are available online at https://www.mdpi.com/2411-5142/6/1/21/s1.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Ethics Committee of Hartpury University (Protocol: ETHICS2019-66, Approval Date: 28 May 2020).

Informed Consent Statement: Informed consent was obtained from all coaches involved in the study. Written informed consent has been obtained from the coaches to publish this paper.

Data Availability Statement: All data is available within the manuscript.

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References

1. Granacher, U.; Lesinski, M.; Büsch, D.; Muehlbauer, T.; Prieske, O.; Puta, C.; Gollhofer, A.; Behm, D.G. Effects of resistance training in youth athletes on muscular fitness and athletic performance: A conceptual model for long-term athlete devel-opment. *Front. Physiol.* **2016**, *7*, 164. [CrossRef] [PubMed]
2. Lloyd, R.S.; Cronin, J.B.; Faigenbaum, A.D.; Haff, G.G.; Howard, R.; Kraemer, W.J.; Micheli, L.J.; Myer, G.D.; Oliver, J.L. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. *J. Strength Cond. Res.* **2016**, *30*, 1491–1509. [CrossRef] [PubMed]
3. Pearson, D.; Naughton, G.; Torode, M. Predictability of physiological testing and the role of maturation in talent identification for adolescent team sports. *J. Sci. Med. Sport* **2006**, *9*, 277–287. [CrossRef]
4. Lloyd, R.S.; Oliver, J.L. The Youth Physical Development Model: A New Approach to Long-Term Athletic Development. *Strength Cond. J.* **2012**, *34*, 61–72. [CrossRef]
5. Śliwowski, R.; Grygorowicz, M.; Wieczorek, A.; Jadczak, Ł. The relationship between jumping performance, isokinetic strength and dynamic postural control in elite youth soccer players. *J. Sports Med. Phys. Fit.* **2017**, *58*, 1226–1233.
6. Markovic, G.; Sarabon, N.; Boban, F.; Zoric, I.; Jelcic, M.; Sos, K.; Scappaticci, M. Nordic Hamstring Strength of Highly Trained Youth Football Players and Its Relation to Sprint Performance. *J. Strength Cond. Res.* **2020**, *34*, 800–807. [CrossRef] [PubMed]
7. Bourgeois, F.A.; Gamble, P.; Gill, N.D.; McGuigan, M.R. Effects of a Six-Week Strength Training Programme on Change of Direction Performance in Youth Team Sport Athletes. *Sports* **2017**, *5*, 83. [CrossRef] [PubMed]
8. Lehance, C.; Binet, J.; Bury, T.; Croisier, J.L. Muscular strength, functional performances and injury risk in professional and junior elite soccer players. *Scand. J. Med. Sci. Sports* **2008**, *19*, 243–251. [CrossRef]
9. Wagle, J.P.; Taber, C.B.; Cunanan, A.J.; Bingham, G.E.; Carroll, K.M.; Deweese, B.H.; Sato, K.; Stone, M.H. Accentuated Eccentric Loading for Training and Performance: A Review. *Sports Med.* **2017**, *47*, 2473–2495. [CrossRef] [PubMed]
10. Walker, S.; Blazevich, A.J.; Haff, G.G.; Tufano, J.J.; Newton, R.U.; Häkkinen, K. Greater Strength Gains after Training with Accentuated Eccentric than Traditional Isoinertial Loads in Already Strength-Trained Men. *Front. Physiol.* **2016**, *7*, 149. [CrossRef] [PubMed]
11. Maeo, S.; Shan, X.; Otsuka, S.; Kanehisa, H.; Kawakami, Y. Neuromuscular Adaptations to Work-matched Maximal Eccentric versus Concentric Training. *Med. Sci. Sports Exerc.* **2018**, *50*, 1629–1640. [CrossRef]
12. Franchi, M.V.; Atherton, P.J.; Reeves, N.D.; Flück, M.; Williams, J.; Mitchell, W.K.; Selby, A.; Valls, R.M.B.; Narici, M.V. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol.* **2014**, *210*, 642–654. [CrossRef] [PubMed]
13. Souron, R.; Nosaka, K.; Jubeau, M. Changes in central and peripheral neuromuscular fatigue indices after concentric versus eccentric contractions of the knee extensors. *Graefe's Arch. Clin. Exp. Ophthalmol.* **2018**, *118*, 805–816. [CrossRef]
14. Harden, M.; Bruce, C.; Wolf, A.; Hicks, K.M.; Howatson, G. Exploring the practical knowledge of eccentric resistance training in high-performance strength and conditioning practitioners. *Int. J. Sports Sci. Coach.* **2019**, *15*, 41–52. [CrossRef]
15. Suchomel, T.J.; Wagle, J.P.; Douglas, J.; Taber, C.B.; Harden, M.; Haff, G.G.; Stone, M.H. Implementing Eccentric Resistance Training—Part 2: Practical Recommendations. *J. Funct. Morphol. Kinesiol.* **2019**, *4*, 55. [CrossRef]
16. Patikas, D.A.; Williams, C.A.; Ratel, S. Exercise-induced fatigue in young people: Advances and future perspectives. *Graefe's Arch. Clin. Exp. Ophthalmol.* **2018**, *118*, 899–910. [CrossRef] [PubMed]
17. Zwolski, C.; Quatman-Yates, C.; Paterno, M.V. Resistance Training in Youth: Laying the Foundation for Injury Prevention and Physical Literacy. *Sports Health Multidiscip. Approach* **2017**, *9*, 436–443. [CrossRef] [PubMed]
18. Faigenbaum, A.D.; Lloyd, R.S.; Myer, G.D. Youth Resistance Training: Past Practices, New Perspectives, and Future Directions. *Pediatr. Exerc. Sci.* **2013**, *25*, 591–604. [CrossRef] [PubMed]
19. Faigenbaum, A.D.; Lloyd, R.S.; Macdonald, J.; Myer, G.D. Citius, Altius, Fortius: Beneficial effects of resistance training for young athletes: Narrative review. *Br. J. Sports Med.* **2015**, *50*, 3–7. [CrossRef] [PubMed]
20. Kilding, A.E.; Tunstall, H.; Kuzmic, D. Suitability of FIFA's "The 11" training programme for young football players–impact on physical performance. *J. Sports Sci. Med.* **2008**, *7*, 320. [PubMed]
21. Faigenbaum, A.D.; Myer, G.D. Resistance training among young athletes: Safety, efficacy and injury prevention effects. *Br. J. Sports Med.* **2009**, *44*, 56–63. [CrossRef]
22. Lin, M.-J.; Nosaka, K.; Ho, C.-C.; Chen, H.-L.; Tseng, K.-W.; Ratel, S.; Chen, T.C.-C. Influence of Maturation Status on Eccentric Exercise-Induced Muscle Damage and the Repeated Bout Effect in Females. *Front. Physiol.* **2018**, *8*, 1118. [CrossRef]
23. Deli, C.K.; Fatouros, I.G.; Paschalis, V.; Georgakouli, K.; Zalavras, A.; Avloniti, A.; Koutedakis, Y.; Jamurtas, A.Z. A Comparison of Exercise-Induced Muscle Damage Following Maximal Eccentric Actions in Men and Boys. *Pediatr. Exerc. Sci.* **2017**, *29*, 316–325. [CrossRef]

24. Fiorilli, G.; Mariano, I.; Iuliano, E.; Giombini, A.; Ciccarelli, A.; Buonsenso, A.; Calcagno, G.; di Cagno, A. Isoinertial Eccentric-Overload Training in Young Soccer Players: Effects on Strength, Sprint, Change of Direction, Agility and Soccer Shooting Precision. *J. Sports Sci. Med.* **2020**, *19*, 213. [PubMed]
25. De Hoyo, M.; Pozzo, M.; Sañudo, B.; Carrasco, L.; Gonzalo-Skok, O.; Domínguez-Cobo, S.; Morán-Camacho, E. Effects of a 10-Week In-Season Eccentric-Overload Training Program on Muscle-Injury Prevention and Performance in Junior Elite Soccer Players. *Int. J. Sports Physiol. Perform.* **2015**, *10*, 46–52. [CrossRef]
26. Suarez-Arrones, L.; Saez de Villarreal, E.; Núñez, F.J.; Di Salvo, V.; Petri, C.; Buccolini, A.; Maldonado, R.A.; Torreno, N.; Mendez-Villanueva, A. In-season eccentric-overload training in elite soccer players: Effects on body composition, strength and sprint performance. *PLoS ONE* **2018**, *13*, e0205332. [CrossRef] [PubMed]
27. di Cagno, A.; Iuliano, E.; Buonsenso, A.; Giombinim, A.; Di Martinom, G.; Parisim, A.; Calcagnom, G.; Fiorillim, G. Effects of Accentuated Eccentric Training vs. Plyometric Training on Performance of Young Elite Fencers. *J. Sports Sci. Med.* **2020**, *19*, 703. [PubMed]
28. Raya-González, J.; Castillo, D.; De Keijzer, K.L.; Beato, M. The effect of a weekly flywheel resistance training session on elite U-16 soccer players' physical performance during the competitive season. A randomized controlled trial. *Res. Sports Med.* **2021**, *7*, 1–15. [CrossRef]
29. Bittencourt, N.F.; Vaz, R.V.; Oliveira, R.R.; Scattone-Silva, R.; Leite, M.M.A.G.; Mendonça, L.D. Preventive effect of tailored exercises on patellar tendinopathy in youth athletes. *Int. J. Sports Phys. Ther.* **2019**, *14*.
30. Drury, B.; Green, T.; Ramirez-Campillo, R.; Moran, J. Influence of Maturation Status on Eccentric Hamstring Strength Improvements in Youth Male Soccer Players After the Nordic Hamstring Exercise. *Int. J. Sports Physiol. Perform.* **2020**, *15*, 1–7. [CrossRef] [PubMed]
31. Tansel, R.B.; Salci, Y.; Yildirim, A.; Kocak, S.; Korkusuz, F. Effects of eccentric hamstring strength training on lower extremity strength of 10–12 year old male basketball players. *Isokinet. Exerc. Sci.* **2008**, *16*, 81–85. [CrossRef]
32. Hammami, R.; Duncan, M.J.; Nebigh, A.; Werfelli, H.; Rebai, H. The Effects of 6 Weeks Eccentric Training on Speed, Dynamic Balance, Muscle Strength, Power, and Lower Limb Asymmetry in Prepubescent Weightlifters. *J. Strength Cond. Res.* **2020**. [CrossRef] [PubMed]
33. Freeman, B.W.; Young, W.B.; Talpey, S.W.; Smyth, A.M.; Pane, C.L.; Carlon, T.A. The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. *J. Sports Med. Phys. Fit.* **2019**, *59*, 1119–1125. [CrossRef] [PubMed]
34. Lloyd, R.S.; Oliver, J.L.; Faigenbaum, A.D.; Howard, R.; Croix, M.B.; Williams, C.A.; Best, T.M.; Alvar, B.A.; Micheli, L.J.; Thomas, D.P.; et al. Long-term athletic development, part 2: Barriers to success and potential solutions. *J Strength Cond. Res.* **2015**, *29*, 1451–1464. [CrossRef]
35. Drury, B.; Ratel, S.; Clark, C.C.; Fernandes, J.F.; Moran, J.; Behm, D.G. Eccentric Resistance Training in Youth: Perspectives for Long-Term Athletic Development. *J. Funct. Morphol. Kinesiol.* **2019**, *4*, 70. [CrossRef]
36. McNeill, C.; Beaven, C.M.; McMaster, D.T.; Gill, N. Survey of Eccentric-Based Strength and Conditioning Practices in Sport. *J. Strength Cond. Res.* **2020**, *34*, 2769–2775. [CrossRef] [PubMed]
37. Eisenmann, J.C.; Till, K.; Baker, J. Growth, maturation and youth sports: Issues and practical solutions. *Ann. Hum. Biol.* **2020**, *47*, 324–327. [CrossRef]
38. Till, K.; Darrall-Jones, J.; Weakley, J.J.; Roe, G.A.; Jones, B.L. The Influence of Training Age on the Annual Development of Physical Qualities Within Academy Rugby League Players. *J. Strength Cond. Res.* **2017**, *31*, 2110–2118. [CrossRef] [PubMed]
39. Bishop, D. An Applied Research Model for the Sport Sciences. *Sports Med.* **2008**, *38*, 253–263. [CrossRef]
40. Read, P.J.; Jimenez, P.; Oliver, J.L.; Lloyd, R.S. Injury prevention in male youth soccer: Current practices and perceptions of practitioners working at elite English academies. *J. Sports Sci.* **2018**, *36*, 1423–1431. [CrossRef] [PubMed]
41. Behm, D.G.; Young, J.D.; Whitten, J.H.D.; Reid, J.C.; Quigley, P.J.; Low, J.; Li, Y.; Lima, C.D.; Hodgson, D.D.; Chaouachi, A.; et al. Effectiveness of Traditional Strength vs. Power Training on Muscle Strength, Power and Speed with Youth: A Systematic Review and Meta-Analysis. *Front. Physiol.* **2017**, *8*, 423. [CrossRef]
42. Stoszkowski, J.; Collins, D. Sources, topics and use of knowledge by coaches. *J. Sports Sci.* **2016**, *34*, 794–802. [CrossRef]
43. Hills, S.P.; Radcliffe, J.N.; Barwood, M.J.; Arent, S.M.; Cooke, C.B.; Russell, M. Practitioner perceptions regarding the practices of soccer substitutes. *PLoS ONE* **2020**, *15*, e0228790. [CrossRef]
44. Weston, M. Training load monitoring in elite English soccer: A comparison of practices and perceptions between coaches and practitioners. *Sci. Med. Footb.* **2018**, *2*, 216–224. [CrossRef]
45. Hopkins, W.G. Linear models and effect magnitudes for research, clinical and practical applications. *Sportscience* **2010**, *14*, 49–57.
46. Russell, S.; Jenkins, D.; Rynne, S.; Halson, S.L.; Kelly, V. What is mental fatigue in elite sport? Perceptions from athletes and staff. *Eur. J. Sport Sci.* **2019**, *19*, 1367–1376. [CrossRef]
47. Spiteri, T.; Nimphius, S.; Hart, N.H.; Specos, C.; Sheppard, J.M.; Newton, R.U. Contribution of Strength Characteristics to Change of Direction and Agility Performance in Female Basketball Athletes. *J. Strength Cond. Res.* **2014**, *28*, 2415–2423. [CrossRef]
48. Cadore, E.L.; González-Izal, M.; Grazioli, R.; Setuain, I.; Pinto, R.S.; Izquierdo, M. Effects of Concentric and Eccentric Strength Training on Fatigue Induced by Concentric and Eccentric Exercises. *Int. J. Sports Physiol. Perform.* **2019**, *14*, 91–98. [CrossRef]

49. Hollander, D.B.; Kraemer, R.R.; Kilpatrick, M.W.; Ramadan, Z.G.; Reeves, G.V.; Francois, M.; Hebert, E.P.; Tryniecki, J.L. Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise. *J. Strength Cond. Res.* **2007**, *21*, 34–40. [CrossRef]
50. Raya-González, J.; Castillo, D.; Domínguez-Díez, M.; Hernández-Davó, J.L. Eccentric-overload production during the fly-wheel squat exercise in young soccer players: Implications for injury prevention. *Int. J. Environ. Res.* **2020**, *17*, 3671.
51. Harper, D.J.; Jordan, A.R.; Kiely, J. Relationships Between Eccentric and Concentric Knee Strength Capacities and Maximal Linear Deceleration Ability in Male Academy Soccer Players. *J. Strength Cond. Res.* **2021**, *35*, 465–472. [CrossRef] [PubMed]
52. Gillen, Z.M.; Jahn, L.E.; Shoemaker, M.E.; McKay, B.D.; Mendez, A.I.; Bohannon, N.A.; Cramer, J.T. Effects of Eccentric Preloading on Concentric Vertical Jump Performance in Youth Athletes. *J. Appl. Biomech.* **2019**, *35*, 327–335. [CrossRef] [PubMed]
53. Radnor, J.M.; Oliver, J.L.; Waugh, C.M.; Myer, G.D.; Moore, I.S.; Lloyd, R.S. The Influence of Growth and Maturation on Stretch-Shortening Cycle Function in Youth. *Sports Med.* **2018**, *48*, 57–71. [CrossRef]
54. Chaabene, H.; Negra, Y.; Moran, J.; Prieske, O.; Sammoud, S.; Ramirez-Campillo, R.; Granacher, U. Effects of an Eccentric Hamstrings Training on Components of Physical Performance in Young Female Handball Players. *Int. J. Sports Physiol. Perform.* **2020**, *15*, 91–97. [CrossRef] [PubMed]
55. Van Dyk, N.; Behan, F.P.; Whiteley, R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: A systematic review and meta-analysis of 8459 athletes. *Br. J. Sports Med.* **2019**, *53*, 1362–1370. [CrossRef] [PubMed]
56. Raya-González, J.; Croix, M.D.S.; Read, P.; Castillo, D. A Longitudinal Investigation of Muscle Injuries in an Elite Spanish Male Academy Soccer Club: A Hamstring Injuries Approach. *Appl. Sci.* **2020**, *10*, 1610. [CrossRef]
57. Martínez-Silván, D.; Wik, E.H.; Alonso, J.M.; Jeanguyot, E.; Salcinovic, B.; Johnson, A.; Cardinale, M. Injury characteristics in male youth athletics: A five-season prospective study in a full-time sports academy. *Br. J. Sports Med.* **2020**. [CrossRef]
58. Mersmann, F.; Bohm, S.; Arampatzis, A. Imbalances in the Development of Muscle and Tendon as Risk Factor for Tendi-nopathies in Youth Athletes: A Review of Current Evidence and Concepts of Prevention. *Front. Physiol.* **2017**, *8*, 197. [CrossRef]
59. Arede, J.; Gonzalo-Skok, O.; Bishop, C.; Schöllhorn, W.I.; Leite, N. Rotational flywheel training in youth female team sport athletes: Could inter-repetition movement variability be beneficial? *J. Sports Med. Phys. Fit.* **2020**, *60*. [CrossRef]
60. Moran, J.; Sandercock, G.R.H.; Ramírez-Campillo, R.; Meylan, C.; Collison, J.; Parry, D.A. A Meta-Analysis of Matura-tion-Related Variation in Adolescent Boy Athletes' Adaptations to Short-Term Resistance Training. *J. Sports Sci.* **2017**, *35*, 1041–1051. [CrossRef]
61. Brownstein, C.G.; Ball, D.; Micklewright, D.; Gibson, N.V. The Effect of Maturation on Performance During Repeated Sprints With Self-Selected Versus Standardized Recovery Intervals in Youth Footballers. *Pediatr. Exerc. Sci.* **2018**, *30*, 500–505. [CrossRef] [PubMed]
62. Tonson, A.; Ratel, S.; Le Fur, Y.; Vilmen, C.; Cozzone, P.J.; Bendahan, D. Muscle energetics changes throughout maturation: A quantitative 31P-MRS analysis. *J. Appl. Physiol.* **2010**, *109*, 1769–1778. [CrossRef] [PubMed]
63. Moran, J.; Clark, C.C.; Ramirez-Campillo, R.; Davies, M.J.; Drury, B. A meta-analysis of plyometric training in female youth: Its efficacy and shortcomings in the literature. *J. Strength Cond. Res.* **2019**, *33*, 1996–2008. [CrossRef] [PubMed]
64. Wild, C.Y.; Steele, J.R.; Munro, B.J. Insufficient Hamstring Strength Compromises Landing Technique in Adolescent Girls. *Med. Sci. Sports Exerc.* **2013**, *45*, 497–505. [CrossRef]

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ORIGINAL ARTICLE

WILEY

The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers

John F. T. Fernandes[1] | Jason Moran[2] | Hannah Clarke[1] | Benjamin Drury[1]

[1]Higher Education Sport, Hartpury University, Hartpury, UK

[2]School of Sport, Rehabilitation, and Exercise Sciences, University of Essex, Colchester, UK

Correspondence
John F. T. Fernandes, Sport, Health and Well-being Arena, Hartpury University, Hartpury, GL19 3BE, UK.
Email: jfmtfernandes@hotmail.co.uk

Abstract

This study sought to establish the reliability of the Nordic hamstring exercise (NHE) in male youth football players. Sixty-four youth football players completed two x three repetitions of the NHE, separated by 1 week. Eccentric hamstring strength was during the NHE using the NordBord. Participants were categorized via maturity offset (based on peak height velocity [PHV]) and age. For all dependent variables and groups, the typical error (TE) was greater than the smallest worthwhile change. Reliability for left, right, bilateral, and relative peak force for the U11s (TE = 0.26-11.1N, coefficient of variation [CV] = 5.9%-7.4%), U13s (TE = 0.28-17.9N, CVs = 5.6%-7.8%) and U16s (TE = 0.28-24.3, CVs = 6.6%-8.7%) was favorable and demonstrated no clear pattern between groups. According to PHV, those less mature provided smaller TEs (0.22-9.3N) and CVs (4.8%-5.7%) compared with their more mature counterparts (TE = 0.30-22.5N, CVs = 7.2%-8.5%). For all age and maturation groups, imbalances yielded poor reliability (TE = 7.1-10.8N, CVs = 33.1%-38.3%). Eccentric left and right limb, bilateral and relative hamstring peak force can reliably be measured during the NHE across maturation stages. Applied practitioners should exercise caution when assessing muscular imbalances using the NHE.

KEYWORDS

eccentric, eccentric force, imbalance, peak force, relative force, reproducibility

1 | INTRODUCTION

Strength refers to the maximal force or torque that the skeletal muscles can exert [1] and is dependent on the muscle contraction type (eg, concentric, isometric, or eccentric) and velocity. For example, when compared with eccentric contractions, concentric and isometric contractions exhibit lower peak forces.[2] Furthermore, for the youth athlete, strength is an important part of sporting performance.[3] That is, strength is moderately and strongly correlated with sprint ($r \geq -.60$) and jump performance ($r \geq -.76$), respectively, [4] and is integral for the performance of fundamental movement skills.[3]

Strength increases naturally throughout maturation[5] and is underpinned by neural and muscular alterations.[6-9] For those who want to maximize a youth's strength gain, resistance training is a potent method for enhancing strength.[10] However, the magnitude of strength adaptations to resistance training can be dependent on maturation status, among other factors.[10] For example, strength adaptations are greater in boys during, and after, peak height velocity (PHV) than before PHV.[11] When resistance training (eg, traditional high-intensity training, Olympic lifting) youths in the pre-, mid- and post-PHV stages can expect enhancements in strength that range from 3.5% to 36%,[12,13] 1.1%-44.4%,[14,15] and 8.7%-44.5%,[16,17] respectively.

Despite the well-documented strength increases with resistance training in youths, eccentric muscle actions have received little attention in the literature. Although speculative, this might be owing to coach perceptions of eccentric contractions. That is, the high force and lengthening nature of eccentric actions might cause damage to the muscle. However, it has consistently been reported that bouts of eccentric exercise in youths results in similar, and often attenuated, symptoms of exercise-induced muscle damage, as compared with adults.[18-20] When used longitudinally, eccentrically biased training can provide a range of benefits including enhanced concentric and eccentric strength,[21] change of direction ability,[22,23] sprint and jump performance,[23,24] and decreased injury incidence.[24] Moreover, a recent meta-analysis concluded that the Nordic hamstring exercise (NHE) can induce positive changes in muscle architecture and strength.[25] Notwithstanding the performance-related benefits, the NHE has the ability to reduce hamstring injuries by up to 51% in a sample of 8459 athletes[26] and is advocated within youth soccer injury prevention programs.[27] This is particularly important when considering that hamstring strains account for 12% of injuries among 17 top fight European soccer teams[28] and is considered the most important injury risk factor.[29] Though these injury rates are lower in youths compared with adults, injury prevention is still an important issue in youths as its occurrence negatively affects participation in sport and can have medical implications.[30] Before the efficacy of such a training study can be investigated, the reliability of the test must first be determined. Consequently, accurate assessment of eccentric hamstring strength via a field-based measure such as the NHE is warranted. While the reliability of the NHE has been determined in adults,[31] there are no available data in youths. Previous work has established that isokinetic eccentric[32] and isometric hamstring[33] muscle actions can be reproduced within acceptable limits in males youth (~13 and 17 years, respectively). However, these authors did not ascertain if maturation altered the reliability of these exercises. This is a concern in testing the youth athlete as disrupted motor coordination can occur around the interval of maximal growth.[34] Thus, it is plausible that the reliability of a test could change as it is used across the maturational spectrum.[35] A study that determines the reliability of measures of eccentric hamstring strength across maturation stages would help applied practitioners monitor strength adaptations with confidence. Whether for athlete support or inclusion in research, the importance of exercise test reliability is well established.[36,37] Moreover, by establishing the reliability of an exercise test, a practitioner/research can identify if a change has occurred due to a training intervention rather than biological variation or maturation.[37] Consequently, the aim of this study was to establish the reliability of the NHE in male youths using a field-based device (NordBord). A further aim was to establish if maturation stage, determined by both chronological age and maturity offset, influences the reliability of the NHE.

2 | METHODS

2.1 | Subjects

Sixty-four male youth football players aged between 10 and 16 years took part in the study (Table 1). All participants were free from lower-limb musculoskeletal injuries, physically active and participated regularly in association football training. None of the participants were involved in any formalized strength and conditioning programs and had no prior experience of performing the NHE. Parental informed consent was obtained for the study which was approved by the host institutions ethics committee.

2.2 | Study design

This study employed a repeated measures design in which participants performed the NHE on six separate occasions. Before each performance, participants complete a standardized warm-up consisting of low-intensity jogging, change of direction, jumping tasks, and dynamic lower-limb stretching. In the first four sessions, participants were familiarized to the NHE. Participants were deemed "familiarized" when they could perform multiple repetitions with the correct technique (see below). These familiarization trials were not used for analysis. For the testing trials, participants attended on two occasions, separated by 7 days. During each testing trial, participants completed three repetitions of the NHE. Participants did not report any symptoms of exercise-induced muscle damage (eg, reduced muscle function or elevated muscle soreness).

2.3 | Methodology

2.3.1 | Anthropometry

Age, stature, and body mass were obtained prior to testing. Participants' standing and seated height were measured using

TABLE 1 Anthropometric characteristics of the participants

	All (n = 64)	U11 (n = 17)	U13 (n = 29)	U16 (n = 18)	Pre-PHV (n = 29)	Mid-post-PHV (n = 35)
Age (y)	13.2 ± 1.7	10.8 ± 0.3	12.1 ± 0.7	15.4 ± 0.4	11.6 ± 0.9	14.5 ± 0.9
Mass (kg)	52.3 ± 12.8	42.0 ± 3.7	39.6 ± 2.5	63.7 ± 6.6	40.0 ± 3.8	62.3 ± 7.2
Stature (cm)	161.9 ± 13.4	148.6 ± 2.8	149.2 ± 4.7	173.9 ± 6.7	148.4 ± 5.1	172.4 ± 6.7

a stadiometer (Seca Model 213, Birmingham, England). Body mass was measured using a calibrated electronic scale (Seca Model 813). Maturity offset was calculated using age, body mass, standing and seated height.[38] This method provides a practical, non-invasive, and accurate measure of maturation status.[38] Pre-PHV and mid-post-PHV participants were categorized as exceeding −2 years and between −1 and + 2.5 years, respectively, from PHV. In addition, participants were categorized chronologically by age (ie, under 11, 13, and 16 years).

2.3.2 | Eccentric hamstring strength

Eccentric hamstring strength was determined using the NHE on the NordBord (Nordbord, Vald Performance). The NHE is deemed a reliable marker of peak eccentric hamstring force in adult males athletes (coefficient of variation [CV] % = 5.8%-8.5%).[31] Participants were instructed to kneel on the padded part of the NordBord and were positioned with their ankles secured with padded hooks, which were attached to load cells. Participants were positioned so that their ankles were perpendicular to the lower limb and the hooks superior to the lateral malleolus. Participants were instructed to gradually lower their upper body while trying to resistance the movement by contracting the hamstrings. With trunk and hips in a neutral position, participants were encouraged to maintain an upright posture. Coaching cues (ie, "stay as tall as you can," "slowly fall like a tree") were provided. During the movement, participants arms were flexed at the elbow so that their palms were pronated at shoulder level. In the final stages of the movement, participants were allowed to use their hands to buffer their fall. The researchers assisted in returning the participants back to the starting position. Participants performed three repetitions with a self-selected rest that ranged from 10-15 seocnds. The NordBord provides peak forces for each limb, thus bilateral peak force was determined by averaging the three scores from each limb. Bilateral peak force was divided by body mass to established relative peak force. The imbalance in peak force between limbs was calculated as the absolute difference between left and right limbs.

2.4 | Statistical analysis

The average value of peak force (N) across the three repetitions was used for analysis. Data were found to be normally distributed according to the Shapiro-Wilk statistic ($P > .05$). A paired samples t test was used to determine the differences in peak force metrics between trials 1 and 2. The reliability of the NHE was quantified via the typical error (TE; standard deviation of the differences divided by $\sqrt{2}$) and CV (TE divided by the grand mean test-retest score, multiplied by

TABLE 2 Mean ± standard deviations values for left, right and bilateral peak flexor force, relative peak force and peak force imbalances during the Nordic hamstring exercise

	Left limb (N)		Right limb (N)		Bilateral force (N)		Relative force (N· kg)		Imbalance (N)	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
U11	141.7 ± 42.8	159.1 ± 44.7*	165.2 ± 41.8	176.1 ± 40.2*	153.5 ± 40.3	167.6 ± 41.7*	3.9 ± 0.9	4.2 ± 1.0*	29.5 ± 17.7	20.5 ± 10.3
U13	211.8 ± 51.7	221.3 ± 55.7	220.0 ± 52.1	240.4 ± 63.2*	215.9 ± 51.1	230.9 ± 58.6*	4.3 ± 0.7	4.5 ± 0.7*	18.8 ± 15.6	24.3 ± 14.7*
U16	244.5 ± 65.3	264.7 ± 54.6*	260.4 ± 55.5	296.1 ± 59.8*	252.5 ± 58.9	280.4 ± 56.0*	4.0 ± 1.1	4.4 ± 1.1*	25.5 ± 18.9	32.4 ± 22.7
Pre-PHV	157.8 ± 41.8	168.4 ± 37.5*	175.7 ± 39.5	183.5 ± 36.4*	166.7 ± 38.7	176.0 ± 35.9*	4.2 ± 0.9	4.4 ± 0.9*	25.4 ± 17.0	20.3 ± 11.0
Mid-post-PHV	234.9 ± 64.8	252.4 ± 61.5*	247.5 ± 57.8	280.2 ± 66.0*	241.2 ± 60.0	266.3 ± 62.8*	4.0 ± 0.9	4.4 ± 0.9*	22.8 ± 18.3	29.9 ± 19.3*
All	202.4 ± 66.2	217.0 ± 65.0*	216.8 ± 61.2	239.0 ± 71.8*	209.6 ± 62.5	228.0 ± 67.7*	4.1 ± 0.9	4.4 ± 0.9*	23.5 ± 17.5	25.6 ± 16.8

*Denotes significantly different between trials 1 and 2 ($P < .05$).

100) statistics.[39] The smallest worthwhile change (SWC; 0.2 multiplied by the shared standard deviation) was calculated to provide a practical interpretation of the findings. The dependent variables were considered capable of detecting small changes if the TE was less than the SWC.[40]

3 | RESULTS

The descriptive characteristics for the NHE across groups and for the entire sample are presented in Table 2. A paired samples *t* test revealed a significant bias from trial 1 to trial 2 for 25 of the 30 comparisons ($P < .05$). For all dependent variables and for all comparisons, the TE was greater than the SWC (Table 3). Across the age groups, the CVs for left (CV% = 5.6-7.4), right (CV% = 5.9-8.7), and bilateral (CV% = 6.1-7.4) relative peak force (CV% = 6.3-6.6) were generally favorable and revealed no clear trend in agreement. The peak force imbalance between left and right limbs demonstrate poor agreement between trials (CV% = 33.1-38.3) across the age groups. Reliability for those pre-PHV was better than those mid-post-PHV for left (CV% = 5.7 vs 6.9, respectively), right (CV% = 4.8 vs 8.5, respectively), bilateral (CV% = 4.9 vs 7.3, respectively), relative peak force (CV% = 5.0 vs 7.2, respectively), and the imbalance (CV% = 35.3 vs 36.1, respectively).

TABLE 3 Reliability statistics for left, right and bilateral peak flexor force, relative peak force and strength imbalances during the Nordic hamstring exercise

	Left limb	Right limb	Bilateral force	Relative force	Imbalance
All					
TE (N)	14.0	18.9	15.4	0.27	9.1
SWC (N)	4.0	5.3	4.4	0.08	2.6
CV (%)	6.7	8.3	7.0	6.3	36.9
U11					
TE (N)	11.1	10.0	9.8	0.26	9.6
SWC (N)	3.1	2.8	2.8	0.07	2.7
CV (%)	7.4	5.9	6.1	6.3	38.3
U13					
TE (N)	12.1	17.9	14.1	0.28	7.1
SWC (N)	3.4	5.1	4.0	0.08	2.0
CV (%)	5.6	7.8	6.3	6.3	33.1
U16					
TE (N)	18.3	24.3	19.8	0.28	10.8
SWC (N)	5.2	6.9	5.6	0.08	3.1
CV (%)	7.2	8.7	7.4	6.6	37.3
Pre-PHV					
TE (N)	9.3	8.7	8.4	0.22	8.1
SWC (N)	2.6	2.5	2.4	0.06	2.3
CV (%)	5.7	4.8	4.9	5.0	35.5
Mid-post-PHV					
TE (N)	16.7	22.5	18.4	0.30	9.5
SWC (N)	4.7	6.4	5.2	0.09	2.7
CV (%)	6.9	8.5	7.3	7.2	36.1

4 | DISCUSSION

We sought to establish the reliability of the Nordic hamstring exercise using a field-based device in male youth soccer players. We report that certain measures of peak force (ie, individual limits, bilateral and relative force) can be reproduced within acceptable limits for this population. A secondary aim was to investigate if maturation affected the reliability of the NHE. While reliability was not different across chronological age groups, those classified as pre-PHV demonstrated better agreement between trials than those in the mid-post-PHV group.

Atkinson and Nevill[36] propose that the reliability of a measure/test is dependent on the setting that it is applied in. For youths who resistance train, lower-body strength (maximal force, torque, or kilograms) can increase by up to 44.5%[12-17] depending on maturation stage. As such a variation of 10% (ie, a CV of 10%) would allow such improvements to be detected. Importantly, the TE and SWC can be incorporated to facilitate the analysis.[37]

The reliability for the whole sample, for left, right, bilateral, and relative peak force was generally favorable (CV% = 6.3-8.3), albeit none of the TEs were able to detect the SWC. Previous work has also reported good reliability for eccentric hamstring exercise in circumpubertal males (r = .71-0.85) [32] and isometric hamstring dynamometry in male youths (minimal detectable change = 11.8-15.9%).[33] Similarly, during the NHE (in adult males) Opar and colleagues[31] reported low CVs for peak force (5.8-8.5%). However, our study adds to the current body of literature by demonstrating poor reliability of lower-limb strength asymmetry during the NHE (TE and CV of 9.1N and 36.9%, respectively). It is unclear why such poor reliability was observed, especially given the good agreement observed for left and right limbs individually. Irrespective of the mechanism, this data indicates that when assessing muscular imbalances during the NHE across a range of ages, applied practitioners should be cautious.

When categorizing the participants by chronological age, reliability was similar across U11 (CV% = 5.9%-7.4%), U13 (CV% = 5.6-7.8), and U16 (CV% = 6.6-8.7) groups, although none of the TE were lower than the SWC. Conversely, when categorized by maturity offset, those in pre-PHV group demonstrated better reliability (TE = 0.22-9.3N, CV% = 4.8-35.5) than the mid-post-PHV group (TE = 0.30-22.5, CV% = 6.9-36.1). The reliability observed for these maturity groups can comfortably detect the increases in strength that occur in those pre- (~36%) [13] and mid-post-PHV (~44.5%).[15] However, practitioners should adopt caution when establishing muscular imbalances using the NHE across maturation stages given the large random errors (TE ≥8.1 N and CVs >35.5%). That we observed better reliability in those pre-PHV than their more mature counterparts might be due to the well-established disruptions in motor performance that occur during maturation.[34] Moreover, these data reinforce the importance of categorizing youths by maturation rather than chronological age y.[11,41] Nonetheless, the reliability of left and right limb, bilateral and relative peak force for the mid-post-PHV group was still acceptable and thus typical changes in strength can still be detected.

In the present study, we observed a systematic bias for several of the dependent variables. While the reasons for this are not entirely clear, the larger values in trial 2, than trial 1, might be indicative of short-term adaptation to the exercise. That participants were given four familiarization attempts before the testing trials and could competently perform the exercise might support this. Nonetheless, applied practitioners should consider these short-term changes when assessing peak force variables using the NHE.

5 | CONCLUSION

To our knowledge, this is the first study to provide a comprehensive assessment of Nordic hamstring exercise reliability in male youth soccer players. We report that, despite not being able to detect the small changes, the reliability of the exercise is generally favorable. Notably, the reliability in less mature (ie, pre-PHV) participants was generally better than their mid-post-PHV counterparts. Nonetheless, applied practitioners can be confident in assessing changes in eccentric hamstring strength using the NHE. However, when assessing muscular imbalances using the NHE, applied practitioners should exercise caution given the large random errors.

ORCID

John F. T. Fernandes https://orcid.org/0000-0002-0843-508X

REFERENCES

1. Knuttegen HG, Komi PV. Basic considerations for exercise . In: Komi PV, ed. *Strength and power in sport*, 2nd edn. Oxford, UK: Blackwell Publishing Company; 2003:3–11.
2. Duchateau J, Enoka RM. Neural control of lengthening contractions. *J Exp Biol*. 2016;219(2):197-204.
3. Lloyd RS, Faigenbaum AD, Stone MH, et al. Position statement on youth resistance training: the 2014 international consensus. *Br J Sports Med*. 2014;48(7):498-505.
4. Comfort P, Stewart A, Bloom L, Clarkson B. Relationship between strength sprint and jump performance in well-trained youth soccer players. *J Strength Cond Res*. 2014;28(1):173-177.
5. Branta C, Haubenstricker J, Seefeldt V. Age changes in motor skills during childhood and adolescence. *Exerc Sport Sci Rev*. 1984;12(1):467-520.
6. Kraemer WJ, Fry AC, Conroy B, Frykman PN, Hoffman J. Resistance training and youth. *Pediatr Exerc Sci*. 1989;1(4):336-350.
7. Granacher U, Goesele A, Roggo K, et al. Effects and mechanisms of strength training in children. *Int J Sports Med*. 2011;32:357-364.
8. Ramsay JA, Blimkie CJR, Smith K, Garner S, MacDougall JD, Sale DG. Strength training effects in prepubescent boys. *Med Sci Sports Exerc*. 1990;22(5):605-614.
9. Tonson A, Ratel S, Le FY, Cozzone P, Bendahan D. Effect of maturation on the relationship between muscle size and force production. *Med Sci Sports Exerc*. 2008;40(5):918-925.
10. Moran J, Sandercock GRH, Ramírez-Campillo R, Meylan C, Collison J, Parry DA. A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *J Sports Sci*. 2016;35(11):1041-1051.
11. Moran J, Sandercock GRH, Ramirez-Campillo R, et al. Maturation-related differences in adaptations to resistance training in young male swimmers. *J Strength Cond Res*. 2018;32(1):139-149.
12. Meylan CMP, Cronin JB, Oliver JL, Hopkins WG, Contreras B. The effect of maturation on adaptations to strength training and detraining in 11–15-year-olds. *Scand J Med Sci Sport*. 2014;24(3):156-164.
13. Chaouachi A, Othman AB, Hammami R, Drinkwater EJ, Behm DG. The combination of plyometric and balance training improves sprint and shuttle run performances more often than plyometric-only training with children. *J Strength Cond Res*. 2014;28(2):401-412.
14. Channell BTC, Barfield JP. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *J Strength Cond Res*. 2008;22(11):1522-1527.
15. Szymanski DJ, Szymanski JM, Molloy JM, Pascoe DD. Effect of 12 weeks of wrist and forearm training on high school baseball players. *J Strength Cond Res*. 2004;18(3):432-440.
16. Kotzamanidis C, Chatzopoulos D, Michailidis C, Papaiakovou G, Patikas D. The effect of a combined high-intensity strength and speed training program on the running and jumping ability of soccer players. *J Strength Cond Res*. 2005;19(2):369-375.
17. Harries SK, Lubans DR, Callister R. Comparison of resistance training progression models on maximal strength in sub-elite adolescent rugby union players. *J Sci Med Sport*. 2016;19(2):163-169.
18. Gorianovas G, Skurvydas A, Streckis V, Brazaitis M, Kamandulis S, McHugh MP. Repeated bout effect was more expressed in young adult males than in elderly males and boys. *Biomed Res Int*. 2013:1–10.
19. Pullinen T, Mero A, Huttunen P, Pakarinen A, Komi PV. Resistance exercise-induced hormonal response under the influence of delayed onset muscle soreness in men and boys. *Scand J Med Sci Sport*. 2011;21:184-194.
20. Deli CK, Fatouros IG, Paschalis V, Avloniti A. A comparison of exercise-induced muscle damage following maximal eccentric contractions in men and boys. *Pediatr Exerc Sci*. 2017;29:316-326.
21. Walker S, Blazevich AJ, Haff GG, Tufano JJ, Newton RU, Häkkinen K. Greater strength gains after training with accentuated eccentric

than traditional isoinertial loads in already strength-trained men. *Front Physiol*. 2016;7:1-12.
22. de Hoyo M, Sañudo B, Carrasco L, et al. Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players. *J Sports Sci*. 2016;34(14):1380-1387.
23. de Hoyo M, de la Torre A, Pradas F, et al. Effects of eccentric overload bout on change of direction and performance in soccer players. *Int J Sports Med*. 2015;36:308-314.
24. de Hoyo M, Pozzo M, Sañudo B, et al. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int J Sports Physiol Perform*. 2015;10:46-52.
25. Cuthbert M, Ripley N, Mcmahon JJ, Evans M, Haff GG, Comfort P. The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses. *Sport Med*. 2019. https://doi.org/10.1007/s40279-019-01178-7
26. Van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2018;2019:1-10.
27. Owoeye OBA, Akinbo SRA, Tella BA, Olawale OA. Efficacy of the FIFA 11+ warm-up programme in male youth football: a cluste…: EBSCOhost. *J Sport Sci Med*. 2014;13:321–328. http://web.a.ebscohost.com.ezproxy.library.unlv.edu/ehost/pdfviewer/pdfviewer?vxml:id=3&sxml:id=66859ceb-8540-4bf1-a8c3-dc4fb95c5ac6%40sessionmgr4002&hxml:id=4106.
28. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br J Sports Med*. 2011;45(7):553-558.
29. Read PJ, Jimenez P, Oliver JL, Lloyd RS. Injury prevention in male youth soccer: current practices and perceptions of practitioners working at elite English academies. *J Sports Sci*. 2018;36(12):1423-1431.
30. Valle X, Malliaropoulos N, Párraga Botero JD, et al. Hamstring and other thigh injuries in children and young athletes. *Scand J Med Sci Sport*. 2018;28(12):2630-2637.
31. Opar DA, Piatrkowski T, Williams MD, Shield A. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther*. 2013;43(9):636-640.
32. Kellis E, Kellis S, Gerodimos V, Manou V. Reliability of isokinetic concentric and eccentric strength in circumpubertal soccer players. *Pediatr Exerc Sci*. 1999;11:218-228.
33. Wollin M, Purdam C, Drew MK. Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players. *J Sci Med Sport*. 2016;19(1):93-96.
34. Quatman-Yates CC, Quatman CE, Meszaros AJ, Paterno MV, Hewett TE. A systematic review of sensorimotor function during adolescence: a developmental stage of increased motor awkwardness? *Br J Sports Med*. 2012;46(9):649-655.
35. Moeskops S, Oliver JL, Read PJ, et al. Within- and between-session reliability of the isometric midthigh pull in young female athletes. *J Strength Cond Res*. 2018;32(7):1892-1901.
36. Atkinson G, Nevill A. Statistical methods for assssing measurement error (reliability) in variables relevant to sports medicine. *Sport Med*. 1998;26(4):217-238.
37. Fernandes JFT, Lamb KL, Twist C. The intra- and inter-day reproducibility of the FitroDyne as a measure of multi-jointed muscle function. *Isokinet Exerc Sci*. 2016;24(1):39-49.
38. Mirwald RL, Baxter-Jones ADG, Bailey DA, Beunen GP. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc*. 2002;34(4):689-694.
39. Hopkins WG. Measures of reliability in sports medicine and science. *Sport Med*. 2000;30(5):375-381.
40. Pyne DB. Interpreting the results of fitness testing. In: International Science and Football Symposium. 2003:1-6.
41. Moran J, Sandercock G, Clark CCT, Fernandes JFT, Drury B. A meta-analysis of resistance training in female youth: its effect on muscular strength, and shortcomings in the literature. *Sport Med*. 2018;48(7):1661-1671.

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Human Kinetics
ORIGINAL INVESTIGATION

Influence of Maturation Status on Eccentric Hamstring Strength Improvements in Youth Male Soccer Players After the Nordic Hamstring Exercise

Benjamin Drury, Thomas Green, Rodrigo Ramirez-Campillo, and Jason Moran

Purpose: This study examined the effects of a 6-week Nordic hamstring exercise (NHE) program in youth male soccer players of less mature (pre–peak height velocity [PHV]) or more mature (mid/post-PHV) status. ***Methods:*** Forty-eight participants were separated into pre-PHV (11.0 [0.9] y) or mid/post-PHV (13.9 [1.1]) groups and further divided into experimental (EXP) and control groups with eccentric hamstring strength assessed (NordBord) both before and after the training program. Participants in the EXP groups completed a periodized NHE program performed once or twice weekly over a 6-week period. ***Results:*** The NHE program resulted in moderate and small increases in relative eccentric hamstring strength (in newtons per kilogram) in the pre-PHV EXP ($d = 0.83$ [0.03–1.68]) and mid-PHV EXP ($d = 0.53$ [–0.06 to 1.12]) groups, respectively. Moderate increases in the same measure were also seen in the between-groups analyses in the pre-PHV ($d = 1.03$ [0.23–1.84]) and mid-PHV ($d = 0.87$ [0.22–1.51]) groups, with a greater effect observed in the former. ***Conclusion:*** The results from this study demonstrate that a 6-week NHE program can improve eccentric hamstring strength in male youth soccer players, with less-mature players achieving mostly greater benefits. The findings from this study can aid in the training prescription of NHE in youth male soccer players.

Keywords: adolescent, resistance training, physical performance, pediatrics, kinetics

To support the athletic development of youth soccer players and to reduce their injury potential, the safest and most successful training methods should be incorporated to help them compete at the highest level.[1] In addition, it has been suggested that due to the developmental nature of youth soccer players and their desire to achieve professional status, it is important to reduce their occurrence of injury.[2] Indeed, it has recently been reported that injury risk increases with age in young soccer players from as early 7 years old.[3] In particular, to support the aforementioned within soccer, the Fédération Internationale de Football Association (FIFA) 11+ program has been developed to support the prevention of lower extremity injuries for players aged 14 years and older.[4] Furthermore, evidence of the efficacy of using the FIFA 11+ to reduce the incidence of injury in male youth soccer players aged between 14 and 19 years has previously been demonstrated.[5] Therefore, the inclusion of specific injury prevention strategies to mitigate injury risk in youth soccer players is required.

A key component of the FIFA 11+ is the emphasis placed upon the development of eccentric hamstring strength via performing the Nordic hamstring exercise (NHE). Its inclusion as an injury prevention exercise is supported due to its ability to greatly reduce hamstring injuries.[6] For example, in elite soccer players, high levels of eccentric hamstring strength have been shown to reduce the risk of hamstring injury.[5] Furthermore, the specific inclusion of the NHE has been shown to reduce hamstring injury risk in male adult soccer players.[7–9] However, although the inclusion of the NHE is recommended within the FIFA 11+ for all playing levels, direct evidence supporting the beneficial effects of the NHE in increasing eccentric hamstring strength in male youth soccer players younger than 14 years has not been reported. Although eccentric hamstring strength was not directly measured, it has recently been demonstrated that a 5-week training period with 2 sessions per week of the FIFA 11+ warm-up improved body stability in 10-year-old male soccer players.[10] The limited information that exists pertaining to the benefits of the inclusion of the NHE in developing eccentric hamstring strength in youth soccer players is surprising. Indeed, this becomes further apparent when considering that it has been reported that practitioners working in elite English male youth soccer academies have indicated that players aged 13–16 years are at the greatest risk of injury and that a lack of eccentric hamstring strength is among the most important injury risk factors.[11]

Despite the efficacy of the NHE in adult athletes, its inclusion within youth athletes is not commonplace. For example, a previous iteration of FIFA 11+, simply entitled "11," excluded the exercise on the basis that it was considered too intense for young and inexperienced athletes.[12] In contradiction to this, though, a significant increase of 12.6% in eccentric hamstring strength has been reported in male basketball players aged between 10 and 12 years following the performance of a 5-week NHE training program.[13] Therefore, although the inclusion of the NHE in male youth soccer players warm-up protocols may aid in the prevention of injuries, the specific improvements in eccentric hamstring strength within this population are unknown. Moreover, this notion is further confounded by the individual's maturation status, which can influence performance capacities in youth.[14] For instance, in youth soccer, it has been shown that maturity status in male youth soccer players influences the outcomes from training programs such as sprinting[15,16] and

Drury is with the Dept of Applied Sport Sciences, Hartpury University, Hartpury, United Kingdom. Green is with the Dept of Physical Education, St Peter's RC High School, Gloucester, United Kingdom. Ramirez-Campillo is with the Laboratory of Human Performance, Quality of Life and Wellness Research Group, Dept of Physical Activity Sciences, University of Los Lagos, Osorno, Chile. Moran is with the School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, United Kingdom. Drury (ben.drury@hartpury.ac.uk) is corresponding author.

plyometrics,[16,17] with changes attributed to differences such as muscle size, coordination, and hormonal profile.[18] Therefore, this study investigated the effects of a NHE program on improvements in eccentric hamstring strength in youth male soccer players, comparing responses in prepubertal (pre-peak height velocity [PHV]) and mid/postpubertal (mid/post-PHV) male participants. Based on previous findings of strength and power training in youth athletes, we hypothesized that greater improvements in eccentric hamstring strength would be observed in the more mature participants.

Methods

Design

A randomized controlled trial was conducted to compare the effects of 6 weeks of NHE training in male youth soccer players. To calculate the sample size, statistical software (G*Power; University of Düsseldorf, Dusseldorf, Germany) was used. Given the study design (4 groups, 2 repeated measures), the effect size 1.05 based on a previous research investigating the effects of lower limb strength training in pre-PHV and mid/post-PHV young male athletes,[19] alpha error <.05, the nonsphericity correction €= 1, the correlation between the repeated measures = .5, and a desired power (1–β error) = 0.80, the total sample size resulted in a minimum of 8 participants required in each condition. Subsequently, a total of 48 participants were recruited from the soccer team and randomly allocated (www.randomizer.org) into 2 experimental (EXP; n = 8 × pre-PHV and n = 16 × mid/post-PHV) and 2 control (CON; n = 11 × pre-PHV and n = 13 × mid/post-PHV) groups. The experiment took place within the competitive season, and participants continued to participate in their regular soccer training programs performed twice per week for a period of 6 weeks; however, the EXP groups additionally performed a NHE program prior to the beginning of each soccer training session. All participants were tested for eccentric hamstring strength before and after the 6-week program, by the same investigators who were not blinded to the groups. During the previous 2 weeks prior to pretesting occurring, 4 separate familiarization sessions were conducted for all participants to ensure technical proficiency of performing the NHE. A maximum of 3 to 5 repetitions of the NHE were performed in each session, and this was overseen by the lead researcher. Each familiarization session took place at the club's training facility prior to their soccer training session and was separated by a minimum of 48 hours.

Participants

Initially, 76 male youth soccer players volunteered to participate in the study. However, after completion of the experiment, 28 participants had to be removed from the study because they did not follow the targeted adherence rate, were released by the club, or did not present for posttraining tests. No participants were excluded from the study due to injury. Subject characteristics per maturity level and training group are presented in Table 1. All participants were free from lower limb musculoskeletal injuries prior to the start of the study, were physically active, had ≥2 years of soccer experience, and were participating regularly in training at their club. Participants were not involved with any formalized strength and conditioning programs and had no prior experience of performing the NHE. Parental informed consent was obtained for participants as they were younger than 18 years. The Hartpury University research committee provided ethical approval prior to the beginning of testing, and the study was completed in accordance with the Declaration of Helsinki.

Procedures

Eccentric hamstring strength was tested both before and after the training intervention. These tests were performed a minimum of 48 hours after the most recent training session or matched to allow appropriate recovery. Prior to each testing session, the participants completed the same standardized warm-up, which was subsequently completed prior to all training sessions. The warm-up lasted approximately 10 minutes and included low-intensity jogging, change of direction drills, lower limb dynamic stretching, and jumping-based tasks. All participants in the EXP and CON groups performed soccer-specific training with the club, twice per week, on a Monday and Wednesday evening from 6 PM to 9 PM. A weekly competitive match was scheduled on a Saturday.

Anthropometrics

Before testing started, data on age, stature, and body mass were recorded to assert each player's current maturation status. Body mass measurements were also collected following completion of the training program prior to follow-up testing occurring. Participants' standing and seated heights were measured using a stadiometer (model 213; seca, Birmingham, England), to the nearest 0.1 cm. Body mass was measured, using a calibrated electronic scale (model 813; sec, Birmingham, England), to the nearest 0.1 kg. To estimate maturity status, these anthropometric measurements were taken and entered into an equation to predict maturity offset,[20] within an error of ±1 year, 95% of the time. The assessment is a noninvasive and practical method of predicting years from PHV as a measure of maturity offset. Maturation groups were divided in accordance with previous recommendations with pre-PHV participants categorized as below −2 years from PHV, while mid/post-PHV participants were between −1 and +2.5 years from PHV.[21]

Eccentric Hamstring Strength

The NHE was performed on the NordBord apparatus (Vald Performance, Brisbane, Australia), which has been shown to be a reliable device to assess eccentric hamstring strength (ICC = .83–.90 and CV% = 5.8–8.5%).[22] Similarly, we have found values for between-session relative reliability for male youth soccer players from our lab (CV% = 6.1–7.4%). All baseline and follow-up testing occurred at the same location and facility, which

Table 1 Participants' Characteristics

Maturation status	Group	n	Age, y	Standing height, cm	Seated height, cm	Body mass, kg	PHV offset, y
Pre-PHV	EXP	8	11.0 (0.9)	144.2 (4.4)	71.5 (2.0)	37.7 (2.8)	–2.8 (0.3)
	CON	11	10.9 (0.8)	147.2 (4.4)	72.5 (3.0)	40.3 (4.1)	–2.7 (0.5)
Mid/post-PHV	EXP	16	14.0 (1.1)	172.3 (7.0)	84.6 (3.4)	61.8 (6.3)	0.4 (0.9)
	CON	13	13.7 (1.0)	171.9 (8.3)	85.1 (4.3)	59.5 (8.3)	0.1 (0.8)

Abbreviations: CON, control; EXP, experimental; PHV, peak height velocity. Note: Data are presented as mean (SD).

was the team's training center. For the assessment of eccentric hamstring strength, participants were instructed to kneel on the padded part of the NordBord and were positioned with their ankles secured with padded hooks, which were attached to load cells. The participants' positions were altered so that ankles would be perpendicular to the lower leg and the hooks were positioned superior to the lateral malleolus. The NHE was performed using an eccentric muscle action of the knee flexors, and participants were instructed to gradually lower the upper body trying to resist the movement by contracting the hamstrings and keeping the trunk and hips held in a neutral position throughout. Participants were encouraged to maintain an upright posture with their spine and pelvis in a neutral position. Participants' arms were flexed at the elbow joints such that the palms of the hands were facing forward at the level of the shoulder joints. The participants were allowed to use their arms in the final stages of the movement to buffer the fall as they approached the ground. For the ascent, the research personnel assisted the participants back to the starting position. Due to the inherent maturation-related differences in strength that existed between the EXP groups, we elected only to include relative peak force as an outcome measure, instead of absolute peak force, which would have favored the mid-PHV groups in the analyses. Relative peak force normalized to body mass (in newtons per kilogram) for each leg of the 3 trials was recorded in newtons. Subsequently, data were analyzed using a predesigned Excel spreadsheet, with the average of each limb from the 3 trials added together and divided by 2 to provide a bilateral score that was used for data analysis.

Training Programs

The NHE program lasted 6 weeks (Table 2). To be included in the final analyses, participants were required to complete at least 85% of the total training sessions (9 of 11 scheduled sessions). This adherence threshold was chosen to reflect a recent experiment in male youth soccer players that also used a similar training program duration.[23] Furthermore, greater benefits in strength have been reported when compliance over this threshold has been achieved.[24] To monitor the compliance to the NHE protocol, participants' attendance rates at the training sessions were recorded for each individual session by a strength and conditioning coach using a registration form that was subsequently confirmed by the respective age group coach. To ensure the correct execution of the NHE, each training group was allocated a strength and conditioning coach to oversee the training program, which helped provide the participants with instructions regarding their technique where necessary. Each session was separated by a minimum of 48 hours. The NHE program was immediately performed after the warm-up.

Table 2 The 6-Week Nordic Hamstring Exercise Training Program

Week	Frequency	Prescription	Total weekly volume
1	1	2 × 5	10
2	2	2 × 5	20
3	2	2 × 6	24
4	2	3 × 6 (S1), 2 × 6 (S2)	30
5	2	3 × 6	36
6	2	3 × 8 (S1), 3 × 6 (S2)	42

Abbreviations: S1, session 1; S2, session 2.

The structure of the NHE program was adapted from previous recommendations, with the volume of training progressively increasing weekly.[9] Coaching cues and instructions used throughout the training program were the same as those provided throughout the aforementioned NHE testing procedures. Identical weekly increases in NHE training volume were performed for both EXP groups, and participants alternated between performing one set and assisting their partner in doing the same, with approximately 60 to 90 seconds of interset rest provided. While the EXP group completed the NHE program, the CON group participated in low-intensity passing drills until the main training session began, in which both groups completed the same soccer training. No formal sprint training was scheduled within the training sessions throughout the experiment period as it has been recently reported that improvements in eccentric hamstring strength in adolescents can be improved to a similar extent via sprint training or the NHE.[25]

Statistical Analysis

Initial analyses were performed using SPSS (version 23; IBM Corp, Armonk, NY). The Shapiro–Wilk test was conducted to test for normality in each variable, and this condition was satisfied ($P < .05$). Independent samples t tests were used to test for any differences between each maturity group's EXP and CON conditions for anthropometric measures and initial eccentric hamstring strength. Thereafter, magnitude-based inferences were used to quantify within- and between-group differences from baseline to follow-up, and to compare changes in EXP and CON conditions, respectively. Uncertainty in the effect sizes (d) was represented by 90% confidence limits.[26] Effect sizes were interpreted using previously outlined ranges (<0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 = large, 2.0–4.0 = very large, and >4.0 = extremely large).[27] An effect size of 0.2 was considered the "smallest worthwhile difference."[26] The scale for interpreting the probability that the result was significant was as follows: <1% = almost certainly not, 1% to 5% = very unlikely, 5% to 25% = unlikely, 25% to 75% = possibly, 75% to 95% = likely, 95% to 99.5% = very likely, >99.5% = most likely, and was calculated using an online spreadsheet.[28] Differences were considered unclear if the confidence interval overlapped thresholds for substantial positive and negative values. Data are presented as mean (SD).

Results

No significant differences ($P > .05$) between the pre-PHV and mid/post-PHV EXP groups and their respective CON group for anthropometric and initial eccentric hamstring measures were found. Effect sizes and their descriptors and likelihood estimates of beneficial effects for within- and between-group analyses are shown in Tables 3 and 4, respectively.

Within-group analyses showed an increase in relative peak force in both EXP groups, although this was improved to a greater extent in pre-PHV compared with mid/post-PHV ($d = 0.83$ vs 0.53). Both pre-PHV and mid/post-PHV CON groups demonstrated trivial increases.

Between-group analyses revealed moderate increases in both maturity groups with the larger effect size being seen in the pre-PHV group ($d = 1.03$ vs 0.87).

Discussion

The aim of this study was to examine the effects of a NHE program on improving eccentric hamstring strength in youth male soccer

Table 3 Within-Group Analysis for Eccentric Hamstring Strength Normalized to Body Mass (in Newtons per Kilogram)

Group	Prescore, $N \cdot kg^{-1}$	Postscore, $N \cdot kg^{-1}$	ES (90% CI)	ES descriptor	Beneficial	Trivial	Harmful	Odds ratio
Pre-PHV								
EXP (n = 8)	4.27 (0.88)	4.95 (0.76)	0.83 (0.03–1.68)	Moderate	Likely (90.3%)	Unlikely (7.1%)	Very unlikely (2.6%)	357
CON (n = 11)	4.24 (0.83)	4.20 (0.70)	–0.05 (–0.75 to 0.65)	Trivial	Most unlikely (0%)	Most likely (100%)	Most unlikely (0%)	0
Mid/post-PHV								
EXP (n = 16)	4.69 (0.85)	5.17 (0.95)	0.53 (–0.06 to 1.12)	Small	Likely (85.4%)	Unlikely (13.2%)	Very unlikely (1.4%)	397
CON (n = 13)	4.45 (0.69)	4.43 (0.72)	–0.03 (–0.67 to 0.20)	Trivial	Most unlikely (0%)	Most likely (100%)	Most unlikely (0%)	0

Abbreviations: CI, confidence interval; CON, control; ES, effect size; EXP, experimental; PHV, peak height velocity.

Table 4 Between-Groups Analysis for Eccentric Hamstring Strength Normalized to Body Mass (in Newtons per Kilogram)

Variable	Group	ES (90% CI)	ES descriptor	Beneficial	Trivial	Harmful	Odds ratio
Relative peak force, $N \cdot kg^{-1}$	Pre-PHV EXP vs pre-PHV CON	1.03 (0.23–1.84)	Moderate	Likely (91.1%)	Unlikely (6.3%)	Very unlikely (2.6%)	373
	Mid/post-PHV EXP vs mid/post-PHV CON	0.87 (0.22–1.51)	Moderate	Likely (89.9%)	Very unlikely (7.8%)	Very unlikely (2.3%)	384

Abbreviations: CI, confidence interval; CON, control; ES, effect size; EXP, experimental; PHV, peak height velocity.

players of different maturation status, comparing pre-PHV and mid/post-PHV players. The within-group analyses revealed that the inclusion of the NHE increased relative eccentric hamstring strength in both pre-PHV and mid/post-PHV groups, although larger effects were observed in the pre-PHV group. In addition, both CON groups yielded no changes in eccentric hamstring strength values from pretesting to posttesting. To the authors' knowledge, this is the first study to demonstrate the effectiveness of the NHE in developing eccentric hamstring strength in male youth soccer players and to specifically compare the influence of different maturation status on this outcome.

The pre-PHV and mid/post-PHV EXP groups increased relative peak force by ~19% and ~10%, respectively. These findings are similar to those previously reported in studies following a NHE program in which increases of absolute and normalized eccentric hamstring strength have been reported to be ~11% and ~14% in well-trained soccer players following a 10-week (250–286 repetitions) or 4-week (162 repetitions) NHE training program, respectively.[29,30] Similarly, in amateur male soccer players, a 12-week (642 repetitions) NHE program performed either before or after training resulted in increases in eccentric hamstring strength of ~12%.[31] Furthermore, in male adults with no prior experience of performing the NHE, similar to the participants used in this study, increases of ~15% in eccentric hamstring strength have been shown following a 6-week (340 repetitions) NHE program.[32] However, we do acknowledge that such comparisons in the changes in eccentric hamstring strength in our study should be taken with caution due to the differences in the assessment method used. Nonetheless, the current findings suggest that a well-structured NHE program conducted over a 6-week training period is sufficient to elicit beneficial changes in eccentric hamstring strength in male youth soccer players, without causing injury.

To the authors' knowledge, only one previous study has investigated the effects of the NHE in male youth athletes with male youth basketball players, aged 10–12 years, increasing their eccentric hamstring strength.[13] The participants in that study completed 232 to 304 repetitions over a 5-week period, which resulted in a 12.6% increase in eccentric hamstring strength. Although this study resulted in similar increases, these were achieved with a total of 162 repetitions. Therefore, it appears that increases in eccentric hamstring strength via the completion of use of NHE training program in youth male soccer players can be achieved via relatively modest training volumes. However, whether such improvements can be made with lower training volumes within this population remains to be seen, as it has been recently demonstrated that in elite youth soccer players, a low-volume NHE program, including just 10 repetitions per week, is sufficient to elicit benefits in eccentric hamstring strength.[33] In particular, our finding of increased strength in the pre-PHV EXP group is interesting as, to date, some doubt over the appropriateness of this exercise for use in a prepubertal population had been expressed.[12] However, in this study, we demonstrated performance gains that were also achieved without any occurrence of musculoskeletal injuries. Participants who withdrew from the study, due to failing to meet the agreed training adherence rate, did so due to other issues, rather than factors such as muscle soreness that have been thought to be associated with the use of eccentric exercise in younger individuals. Indeed, conceptions such as these would not be supported by current evidence in any case.[34,35]

Our results also showed that although the NHE program resulted in improvements in eccentric hamstring strength in both EXP groups, the magnitude of the effects were greater in pre-PHV than in mid/post-PHV (Table 3). We chose relative strength as an outcome measure, as higher body mass and absolute strength can influence total eccentric hamstring strength scores in the NHE exercise.[36] Relatedly, our finding that prepubertal boys respond more positively to resistance training than postpubertal boys is not entirely in agreement with previous research in which it has been demonstrated that more mature males experience greater improvements in strength and power-related characteristics than less mature males.[19,37,38] However, it may indicate the importance in ingraining relative strength as a base for absolute strength in less mature individuals from an early age. From an exercise prescription standpoint, a potential explanation for the differences in responses between the EXP groups may be due to the possible inadequate stimulus of the NHE program for the mid/post-PHV group. For example, while both groups within this study had no prior experience of the NHE, the greater chronological age of the mid/post-PHV group may have acted as a surrogate of training age, whereby older players have adapted positively from a longer training history.[39] Indeed, in adolescents, it has recently been reported that eccentric hamstring strength can be improved to a similar extent via sprint training or the NHE.[25] Therefore, while high-speed sprint training was avoided during the training program, the mid/post-PHV group players' higher training age and exposure to training stimuli, such as sprinting, may have meant that the NHE program produced a lower adaptation than that seen in the pre-PHV group. Consequently, mid/post-PHV athletes may require an altered training prescription.

In light of the aforementioned, the programming of the NHE during growth and maturation may require further specificity to optimize its effectiveness. For example, due to only bodyweight being used as the loading strategy in this study, it could be speculated that this may have inadvertently provided a lower training stimulus for the mid/post-PHV group. This is because performance of the NHE is largely body mass dependent, and it has been predicted that soccer players should be expected to achieve eccentric hamstring strength scores (in newtons) of 4 × body mass (in kilograms) + 26.1 when assessed with the NordBord.[36] Therefore, considering the initial relative strength scores of the mid/post-PHV (4.69 $N \cdot kg^{-1}$) compared with those of the pre-PHV EXP group (4.27 $N \cdot kg^{-1}$), this may have created a ceiling of adaptation for the more mature individuals, especially with training volume being equated. Indeed, it has been reported that additional loads, such as weighted vests, should be used during the NHE to promote strength increases.[40] Therefore, although unknown, there may be a certain threshold of eccentric hamstring strength that, once achieved, requires further augmentation to provide sufficient overload. Another potential explanation for this may be that the NHE presented an altered motor control strategy for the mid/post-PHV group, which subsequently influenced the performance of the exercise. This is because during the NHE, as the trunk moves forward, the movement becomes progressively uncontrolled due to the shortening of the hamstring moment arm while the body mass moment arm lengthens.[41] Therefore, due to alterations in both upper and lower limb lengths during PHV and accompanying changes in body mass,[20] it could be plausible that this increases the complexity of the NHE during the growth spurt, which subsequently may impact performance of the exercise. However, this requires further investigation.

This study is not without limitations. Due to the age range of the participants available for this study, it was not possible to include separate mid-PHV and post-PHV groups (a combined mid/post group was used). Considering responses to training stimuli can differ between these maturation groups,[17,42] it would be beneficial to examine such effects in the future. In addition, although improvements in eccentric hamstring strength were evident within and between maturation groups, the mechanisms behind such adaptations are unknown. Therefore, future studies could examine the effects of the NHE in youth athletes accounting for changes, such as muscle action and muscle architecture, in addition to effect on physical fitness tests, such as jumping, sprinting, and deceleration.

Practical Applications

While current guidelines, such as the FIFA 11+, provide helpful guidelines for the inclusion of the NHE, the training program used in this study provides a potentially more structured periodized program that can be followed by inexperienced youth athletes. Furthermore, the inclusion of NHE may be utilized with youth male soccer players from the age of 10 years old. Therefore, the inclusion of a low-dosage NHE program, as part of a well-structured warm prior to soccer training, in male youth players is advised. However, we suggest that technical proficiency in the NHE should be taught prior to its inclusion within the athlete's long-term physical development plan and that the NHE forms part of a holistic strength and conditioning program that enhances physical fitness in male youth soccer players.

Conclusion

This is the first study to examine the effects of a NHE program on eccentric hamstring strength in male youth soccer players of different maturation status. Results show the completion of a 6-week NHE provides beneficial increases in eccentric hamstring strength in both pre-PHV and mid/post-PHV players, although larger improvements were observed in less mature players. The training program utilized within this study may help practitioners working with male youth soccer players to implement the NHE into their training programs.

References

1. Johnson A, Doherty P, Freemont A. Investigation of growth, development, and factors associated with injury in elite schoolboy footballers: prospective study. *BMJ*. 2009;338(1):b490. doi:10.1136/bmj.b490
2. Read PJ, Oliver JL, De Ste Croix MB, Myer GD, Lloyd RS. An audit of injuries in six English professional soccer academies. *J Sports Sci*. 2018;36(13):1542–1548. PubMed ID: 29125037 doi:10.1080/02640414.2017.1402535
3. Rössler R, Junge A, Chomiak J, et al. Risk factors for football injuries in young players aged 7 to 12 years. *Scand J Med Sci Sports*. 2018;28(3):1176–1182. doi:10.1111/sms.2018.28.issue-3
4. Bizzini M, Junge A, Dvorak J. Implementation of the FIFA 11+ football warm up program: how to approach and convince the Football associations to invest in prevention. *Br J Sports Med*. 2013;47:803–806. PubMed ID: 23813485 doi:10.1136/bjsports-2012-092124
5. Owoeye OB, Akinbo SR, Tella BA, Olawale OA. Efficacy of the FIFA 11+ warm-up program in male youth football: a cluster randomised controlled trial. *J Sports Sci Med*. 2014;13(2), 321–328. PubMed ID: 24790486
6. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programs halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2019;53:1362–1370. PubMed ID: 30808663 doi:10.1136/bjsports-2018-100045
7. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2016;50(24):1524–1535. PubMed ID: 26675089 doi:10.1136/bjsports-2015-095362
8. Grooms D, Palmer T, Onate J, Myer G, Grindstaff T. Soccer-specific warm-up and lower extremity injury rates in collegiate male soccer players. *J Athl Train*. 2013;48(6):782–789. PubMed ID: 23848519 doi:10.4085/1062-6050-48.4.08
9. van der Horst N, Smits D, Petersen J, Goedhart E, Backx F. The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. *Am J Sports Med*. 2015;43(6):1316–1323. PubMed ID: 25794868 doi:10.1177/0363546515574057
10. Gatterer H, Lorenzi D, Ruedl G, Burtscher M. The" FIFA 11+" injury prevention program improves body stability in child (10 year old) soccer players. *Biol Sport*. 2018;35(2):153–158. PubMed ID: 30455543
11. Read PJ, Jimenez P, Oliver J, Lloyd R. Injury prevention in male youth soccer: current practices and perceptions of practitioners working at elite English academies. *J Sports Sci*. 2018;36(12):1423–1431. PubMed ID: 29019743 doi:10.1080/02640414.2017.1389515
12. Kilding AE, Tunstall H, Kuzmic D. Suitability of FIFA's "The 11" training program for young football players—impact on physical performance. *J Sports Sci Med*. 2008;7(3):320–326. PubMed ID: 24149898
13. Tansel RB, Salci Y, Yildirim A, Kocak S, Korkusuz PF. Effects of eccentric hamstring strength training on lower extremity strength of 10–12 year old male basketball players. *Isokinet Exerc Sci*. 2008;16(2):81–85. doi:10.3233/IES-2008-0300
14. Pearson D, Naughton G, Torode M. Predictability of physiological testing and the role of maturation in talent identification for adolescent team sports. *J Sci Med Sport*. 2006;9(4):277–287. PubMed ID: 16844415 doi:10.1016/j.jsams.2006.05.020
15. Moran J, Parry D, Lewis I, Collison J, Rumpf M, Sandercock G. Maturation-related adaptations in running speed in response to sprint training in youth soccer players. *J Sci Med Sport*. 2018;21(5):538–542. PubMed ID: 28964690 doi:10.1016/j.jsams.2017.09.012
16. Asadi A, Ramirez-Campillo R, Arazi H, Sáez de Villarreal E. Effects of maturation on jumping ability and sprint adaptations to plyometric training in youth soccer players. *J Sports Sci*. 2018;36(21):2405–2411. PubMed ID: 29611771 doi:10.1080/02640414.2018.1459151
17. Vera-Assaoka T, Ramirez-Campillo R, Alvarez C, et al. Effects of maturation on physical fitness adaptations to plyometric drop jump training in male youth soccer players [published online ahead of print April 3, 2019]. *J Strength Cond Res*. doi:10.1519/JSC.0000000000003151
18. Moran J, Sandercock GR, Ramírez-Campillo R, Meylan C, Collison J, Parry DA. A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *J Sports Sci*. 2017;35(11):1041–1051. PubMed ID: 27454545 doi:10.1080/02640414.2016.1209306
19. Moran J, Sandercock G, Ramírez-Campillo R, et al. Maturation-related differences in adaptations to resistance training in young male swimmers. *J Strength Cond Res*. 2018;32(1):139–149. PubMed ID: 28118309 doi:10.1519/JSC.0000000000001780
20. Mirwald RG, Baxter-Jones A, Bailey D, Beunen G. An assessment of maturity from anthropometric measurements. *Med Sci Sports Exerc*. 2002;34(4):689–694. PubMed ID: 11932580
21. Moran J, Sandercock GR, Ramirez-Campillo R, Todd O, Collinson J, Parry DA. Maturation-related effect of low-dose plyometric training

on performance in youth hockey players. *Pediatr Exerc Sci*. 2017;29(2):194–202. PubMed ID: 27834619 doi:10.1123/pes.2016-0151

22. Opar D, Piatkowski T, Williams M, Shield A. A novel device using the Nordic hamstring exercise to assess eccentric hamstring strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther*. 2013;43(9):636–640. PubMed ID: 23886674 doi:10.2519/jospt.2013.4837
23. Ramirez-Campillo R, Alvarer C, García-Pinillos F, et al. Optimal reactive strength index: is it an accurate variable to optimize plyometric training effects on measures of physical fitness in young soccer players? *J Strength Cond Res*. 2018;32(4):885–893. PubMed ID: 29389692 doi:10.1519/JSC.0000000000002467
24. Dai Sugimoto GD, Bush HM, Hewett TE. Effects of compliance on trunk and hip integrative neuromuscular training on hip abductor strength in female athletes. *J Strength Cond Res*. 2014;28(5):1187–1194. doi:10.1097/JSC.0000000000000228
25. Freeman BW, Young WB, Talpey SW, Smyth AM, Pane CL, Carlon TA. The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. *J Sports Med Phys*. 2019;59(7):1119–1125.
26. Hopkins WG, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–13. PubMed ID: 19092709 doi:10.1249/MSS.0b013e31818cb278
27. Spencer M, Fitzsimons M, Dawson B, Bishop D, Goodman C. Reliability of a repeated-sprint test for field-hockey. *J Sci Med Sport*. 2006;9(1–2):181–184. doi:10.1016/j.jsams.2005.05.001
28. Hopkins WG. A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a P value. *Sportscience*. 2007;11:16–20.
29. Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports*. 2004;14(5):311–317. doi:10.1046/j.1600-0838.2003.367.x
30. Iga J, Fruer CS, Deighan M, Croix MD, James DV. 'Nordic' hamstrings exercise—engagement characteristics and training responses. *Int J Sports Med*. 2012;33(12):1000–1004. PubMed ID: 22895870 doi:10.1055/s-00000028
31. Lovell R, Knox M, Weston M, Siegler JC, Brennan S, Marshall PW. Hamstring injury prevention in soccer: before or after training? *Scand J Med Sci Sports*. 2018;28(2):658–666. PubMed ID: 28544170 doi:10.1111/sms.2018.28.issue-2
32. Delahunt E, McGroarty M, De Vito G, Ditroilo M. Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. *Eur J Appl Physiol*. 2016;116(4):663–672. PubMed ID: 26754149 doi:10.1007/s00421-015-3325-3
33. Lacome M, Avrillon S, Cholley Y, Simpson BM, Guilhem G, Buchheit M. Hamstring eccentric strengthening program: does training volume matter? *Int J Sports Physiol Perform*. 2020;15(1):81–90. doi:10.1123/ijspp.2018-0947
34. Deli CK, Fatouros IG, Paschalis V, et al. A comparison of exercise-induced muscle damage following maximal eccentric contractions in men and boys. *Pediatr Exerc Sci*. 2017;29(3):316–325. PubMed ID: 28165870 doi:10.1123/pes.2016-0185
35. Chen TC, Chen HL, Liu YC, Nosaka K. Eccentric exercise-induced muscle damage of pre-adolescent and adolescent boys in comparison to young men. *Eur J Appl Physiol*. 2014;114(6):1183–1195. PubMed ID: 24563093 doi:10.1007/s00421-014-2848-3
36. Buchheit M, Cholley Y, Nagel M, Poulos N. The effect of body mass on eccentric hamstring strength assessed with an instrumented Nordic hamstring device (Nordbord) in football players. *Int J Sports Physiol Perform*. 2016;11(6):721–726. PubMed ID: 26638728 doi:10.1123/ijspp.2015-0513
37. Meylan CM, Cronin JB, Oliver JL, Hopkins WG, Contreras B. The effect of maturation on adaptations to strength training and detraining in 11–15-year-olds. *Scand J Med Sci Sports* 2014;24(3):e156–e164. doi:10.1111/sms.2014.24.issue-3
38. Rumpf MC, Cronin JB, Mohamad IN, Mohamad S, Oliver JL, Hughes MG. The effect of resisted sprint training on maximum sprint kinetics and kinematics in youth. *Eur J Sport Sci*. 2015;15(5):374–381. PubMed ID: 25190489 doi:10.1080/17461391.2014.955125
39. Read P, Oliver JL, De Ste Croix MB, Myer GD, Lloyd RS. Landing kinematics in elite male youth soccer players of different chronologic ages and stages of maturation. *J Athl Train*. 2018;53(4):372–378. PubMed ID: 29693423 doi:10.4085/1062-6050-493-16
40. Pollard CW, Opar DA, Williams MD, Bourne MN, Timmins RG. Razor hamstring curl and Nordic hamstring exercise architectural adaptations: impact of exercise selection and intensity. *Scand J Med Sci Sports*. 2019;29(5):706–715. PubMed ID: 30629773 doi:10.1111/sms.2019.29.issue-5
41. Monajati A, Larumbe-Zabala E, Goss-Sampson M, Naclerio F. Analysis of the hamstring muscle activation during two injury prevention exercises. *J Hum Kinet*. 2017;60(1):29–37. doi:10.1515/hukin-2017-0105
42. Moran J, Sandercock GR, Ramírez-Campillo R, Meylan CM, Collison JA, Parry DA. Age-related variation in male youth athletes' countermovement jump after plyometric training: a meta-analysis of controlled trials. *J Strength Cond Res*. 2017;31(2):552–565. PubMed ID: 28129282 doi:10.1519/JSC.0000000000001444

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Different Interset Rest Intervals During the Nordic Hamstrings Exercise in Young Male Athletes

Benjamin Drury, MSc*; Dan Peacock, BSc†; Jason Moran, PhD‡; Chris Cone, MSc§; Rodrigo Ramirez Campillo, PhD||

*Department of Applied Sport Sciences, Hartpury University, Gloucestershire, United Kingdom; †Sport Science Department, Bristol City Football Club, United Kingdom; ‡School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, United Kingdom; §Sport Science Department, Bristol Rovers Football Club, Gloucestershire, United Kingdom; ||Department of Physical Activity Sciences, Universidad de Los Lagos, Osorno, Chile

Context: The Nordic hamstring exercise (NHE) is known to reduce hamstrings injury risk in athletes. To optimize the NHE, it is important to understand how acute resistance-training variables influence its performance.

Objective: To examine the effects of different interset rest intervals (ISRIs) on force indices during performance of the NHE.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: Ten well-trained, young, male, team-sport athletes (age = 20.7 ± 2.3 years, height = 179.4 ± 5.5 cm, mass = 83.9 ± 12.4 kg).

Intervention(s): Participants performed 2 sets of 6 repetitions of the NHE with either a 1- or 3-minute ISRI. All sets were performed using the NordBord.

Main Outcomes Measure(s): Peak force (newtons), average force (newtons), percentage maintenance, and percentage decline were recorded for both the dominant and nondominant limbs, and interlimb force asymmetries (percentages) were calculated.

Results: No interactions or main effects ($P > .05$) were present between conditions or sets for any variables. However, individual repetitions showed reductions ($P < .05$; effect size range = 0.58–1.28) in peak force from repetition 4 onward.

Conclusions: Our findings suggest that a 1-minute ISRI was sufficient to maintain force-production qualities and interlimb asymmetries between sets during the NHE in well-trained athletes. Nonetheless, practitioners should be aware of the potentially large decrements in peak force production that may occur within the set.

Key Words: youth sports, eccentric, resistance training, injury prevention

Key Points

- Minimal reductions in eccentric hamstrings force indices between sets occurred when well-trained individuals performed the Nordic hamstring exercise (NHE).
- A 1-minute rest interval between NHE sets was adequate to maintain performance, although 3 minutes may provide modest benefits.
- The structure of the NHE set may be enhanced by performing fewer repetitions to ensure that peak force is maintained throughout the set.

To maximize an athlete's adaptation to imposed stimuli during resistance training (RT), an athletic trainer can manipulate several program-related factors, such as the interset rest interval (ISRI), muscle action type, loading and volume, and exercise order and frequency. Of these, the ISRI is critical in underpinning both the acute and chronic responses to RT because its duration influences the development of physical qualities, such as muscle strength and power.[1] This is because an extended ISRI facilitates the restoration of adenosine triphosphate and phosphocreatine by approximately 85% within 3 minutes of exercise cessation,[2] making it reasonable to assume that the longer the ISRI, the greater the acute benefit that is derived from RT performance. Previous research[3] supported this assertion, as greater improvements in muscle strength were reported with a 3-minute (LONG) than a 1-minute (SHORT) ISRI. Accordingly, when targeting increases in muscle strength, practitioners are encouraged to use a longer ISRI. However, whether this approach is applicable to all muscle action types is unknown.

Despite recommendations for prescribing the ISRI during RT, current guidelines are based on exercises that emphasize a predominantly concentric muscle action. Considering the distinctive nature of physiological responses to eccentric muscle actions, the prescription of eccentric RT exercises requires a more targeted approach.[4] For example, the energy cost of eccentric muscle actions is lower than that of concentric muscle actions.[5] Furthermore, during isokinetic exercises of the knee extensors, eccentric muscle actions were more resistant to fatigue than were concentric actions.[6] Because less fatigue is experienced during eccentric muscle actions, it is plausible that, during eccentric RT, longer ISRIs may not be warranted in the same manner as for concentric-dominant exercises. This may be of particular importance to practitioners when implementing an injury-prevention program, considering that time constraints are a perceived barrier.[7] Therefore, information about how the ISRI influences performance during eccentric RT can provide clinicians with further knowledge of how to optimize the training prescription. This is especially necessary because practitioners place a high degree of importance on developing eccentric strength in injury-prevention programs.[7]

An eccentric RT exercise that is known to reduce the risk of hamstrings injuries in athletes is the Nordic hamstrings exercise (NHE), which has been noted to reduce hamstrings injuries by up to 51% in athletes.[8] This was attributed to the benefits it conveys in developing eccentric hamstrings strength and muscle architectural properties, such as increased fascicle length.[9] To date, researchers have shown that the NHE improves both eccentric hamstrings torque and endurance[10] and reduces interlimb asymmetries.[11] This is particularly relevant given that factors such as low eccentric hamstrings strength,[12] high eccentric hamstrings force asymmetries,[13] and hamstrings fatigue[14] have been cited as increasing the risk of hamstrings injuries. However, although several factors related to the effective training prescription of the NHE are known, limited information exists concerning how the ISRI may influence its performance. Consequently, knowledge of how acute training prescription variables such as the ISRI may optimize performance of the NHE could provide clinicians with further guidance on its implementation in an injury-prevention program. Therefore, the purpose of our study was to examine the effects of a SHORT versus LONG ISRI on such measures during the NHE. Based on the lower levels of fatigue associated with eccentric muscle actions, we hypothesized that the length of the ISRI used for the NHE would not result in performance differences between sets.

METHODS

Design

We used a randomized, repeated-measures crossover design to assess the effect of different ISRIs on selected indices including force, asymmetries, and fatigue during the NHE. The randomization was conducted according to a computer-generated sequence (www.randomizer.org). Participants were required to execute 2 sets of 6 repetitions of the NHE with either a SHORT (1-minute) or LONG (3-minutes) ISRI. We divided participants into 2 groups, and they performed 1 condition in their first session before changing to the other condition in the following session (76–96 hours apart). The NHE dosage was chosen for consistency with a previous investigation[15] that demonstrated positive changes in eccentric hamstrings strength in young team-sport athletes when this prescription was included. In addition, this dosage was similar to the protocol in the participants' current training programs. Although all participants had previous exposure to the NHE, a familiarization session was required to fully prepare them for the laboratory procedures and performance of the exercise on the NordBord apparatus (Vald Performance) and to ensure they met the inclusion criteria. Before SHORT and LONG sessions, participants completed the same standardized 10-minute warmup, including low-intensity jogging, change-of-direction drills, lower limb dynamic stretching, and jumping-based tasks. All testing sessions occurred at the same time of day (approximately 8:00 AM).

Participants

An a priori power analysis was conducted (version 3.1.9.4; G*Power, University of Düsseldorf[16]) to determine the minimum sample size needed to find a difference with a desired power level of 0.80, α error of .05, and effect size (ES) of 0.53 based on earlier research[15] on the effects of NHE training in young male soccer athletes. Subsequently, the sample consisted of 10 young male team-sport athletes (age = 20.7 $\pm$ 2.3 years, height = 179.4 $\pm$ 5.5 cm, mass = 83.9 $\pm$ 12.4 kg). Participants were physically active and undertaking 2 to 3 sessions of supervised RT and 3 to 5 sport-specific practices per week. Given that previous hamstrings injuries can influence indices such as force and asymmetries, we required participants to meet the following inclusion criteria: (1) peak force eccentric hamstrings score of $\geq$337 N during the NHE,[12] (2) peak force asymmetry of $<$15% during the NHE,[13] (3) regular (ie, once per week) exposure to the NHE in current training, and (4) no lower limb injury in the 6 months before the study as documented by the team's medical department. Participants were instructed to avoid vigorous exercise and caffeine and alcohol consumption for a minimum of 24 hours before each testing session. The use of nutritional aids was prohibited throughout the testing process. All players provided written informed consent, and the Hartpury University Research Committee approved the study.

Procedures

Anthropometrics. Before testing started, we recorded age, stature, and body mass. Participants' standing height was measured using a stadiometer (model 213; Seca) to the nearest 0.1 cm, and mass was measured using a calibrated electronic scale (model 813; Seca) to the nearest 0.1 kg.

Eccentric Hamstrings Strength. The NHE was performed using the NordBord, which has been shown to be a reliable device (coefficient of variation range = 6.1%–7.4%) for assessing eccentric hamstrings strength in young male athletes.[17] All testing occurred in the university's performance gymnasium. For the assessment of eccentric hamstrings strength, participants knelt on the padded part of the NordBord and their ankles were secured using padded hooks that were attached to load cells. Each person's position was altered so that his ankles were perpendicular to the lower leg, and the hooks were positioned superior to the lateral malleolus. Participants were instructed to gradually lower the upper body while trying to resist the movement by contracting the hamstrings and holding the trunk and hips in a neutral position throughout. Their arms were flexed at the elbow joints such that their palms faced forward at the level of the shoulder joints to help buffer the fall as they approached the ground. For the ascent, participants were assisted back to the starting position. As soon as they reached the starting position, they were required to immediately begin the next repetition. *Peak force* (newtons), determined as the highest force output from a single repetition, and *average force* (newtons), calculated as the mean of the peak force outputs from all 6 repetitions, were recorded for each condition and set using LabChart (version 7.3; ADInstruments). All data were analyzed using a predesigned Excel spreadsheet (Microsoft Corp), with the scores from each limb calculated.

Calculating Asymmetry and Fatigue. Interlimb asymmetries for each set were quantified and calculated in accordance with current recommendations.[18] Specifically, the mean score from the peak force values of each limb across the set was recorded, and the magnitude of the interlimb asymmetries was calculated using the percentage difference method: 100/maximum (right and left)/minimum (right and left) $\times -1 + 100$. The ability to maintain force during all repetitions in each set was assessed using the following equation: percentage maintenance $= 100 - [(\text{mean set} - \text{repetition}_1)/\text{repetition}_1] \times 100$.[19] In addition, the effect of the ISRI length in each condition was determined by a percentage decline from the first to the 12th repetition using the following equation: percentage decline $= [(\text{repetition}_{12} - \text{repetition}_1)/\text{repetition}_1] \times 100$.[19]

Statistical Analyses

All data from each NHE repetition were recorded and entered into Excel (version 16.0.4) to compute means and SDs. The subsequent statistical analysis was performed using SPSS (version 26; IBM Corp) with statistical significance set at $P < .05$. Normality was assessed via the Shapiro-Wilk test. A 2-way repeated-measures analysis of variance was conducted to assess differences in peak force between conditions (SHORT versus LONG) for individual repetitions (repetitions 1 to 6) in sets 1 and 2. Subsequently, we used simple planned contrasts to assess changes in peak force between repetition 1 and subsequent repetitions. A 2-way repeated-measures analysis of variance was also calculated to assess differences in conditions between sets (set 1 versus set 2) for all force index measures (peak force, average force, percentage maintenance, and interlimb asymmetries). When an F ratio was significantly different, post hoc comparisons were performed using a Bonferroni correction. The independent-samples t test was used to assess differences between the dominant and nondominant limbs, as well as the percentage decline between conditions. The ESs were determined using the Cohen d and defined using the following thresholds: <0.20, *trivial*; 0.20 to 0.59, *small*; 0.60 to 1.19, *moderate*; 1.20 to 1.99, *large*; 2.0 to 3.99, *very large*; and >4.0, *extremely large*.[20]

RESULTS

Force Production

All data were normally distributed ($P > .05$). The differences between repetitions in sets 1 and 2 for peak force are shown in Figure 1. In set 1, the dominant limb displayed no condition-by-repetition interaction ($F_{5,45} = 0.570$, $P = .72$) or main condition effect ($F_{1,9} = 0.574$, $P = .47$) for peak force, although a main repetition effect was observed ($F_{5,45} = 7.636$, $P < .001$). Planned contrasts revealed that peak force was lower in repetitions 4 ($t_{45} = -2.852$, $P = .01$, ES = 0.58, –4.86% decline), 5 ($t_{45} = -4.026$, $P < .001$, ES = 0.94, –7.57% decline), and 6 ($t_{45} = -4.385$, $P < .001$, ES = 1.13, –8.25% decline) than in repetition 1. In set 2, the dominant limb demonstrated no condition-by-repetition interaction ($F_{5,45} = 0.128$, $P = .99$) or main condition effect ($F_{1,9} = 0.879$, $P = .37$) for peak force, but a main repetition effect was present ($F_{5,45} = 4.118$, $P = .004$). Planned contrasts indicated that peak force was lower in repetitions 5 ($t_{45} = -2.780$, $P = .008$, ES = 0.82, –4.53% decline) and 6 ($t_{45} = -4.106$, $P < .001$, ES = 0.85, –6.70% decline) than in repetition 1. Set 1 for the nondominant limb showed no condition-by-repetition interaction ($F_{5,45} = 0.704$, $P = .62$) or main condition effect ($F_{1,9} = 1.080$, $P = .33$) for peak force, but a main repetition effect was observed ($F_{5,45} = 8.175$, $P < .001$). Planned contrasts revealed that peak force was lower in repetitions 4 ($t_{45} = -3.334$, $P = .002$, ES = 0.77, –7.94% decline), 5 ($t_{45} = -4.820$, $P < .001$, ES = 1.26, –11.49% decline), and 6 ($t_{45} = -5.290$, $P < .001$, ES = 1.28, –12.61% decline) than in repetition 1. No condition-by-repetition interaction ($F_{5,45} = 0.399$, $P = .74$) or main effects for condition ($F_{1,9} = 1.678$, $P = .23$) or repetitions ($F_{5,45} = 1.517$, $P = .20$) were found for peak force in the

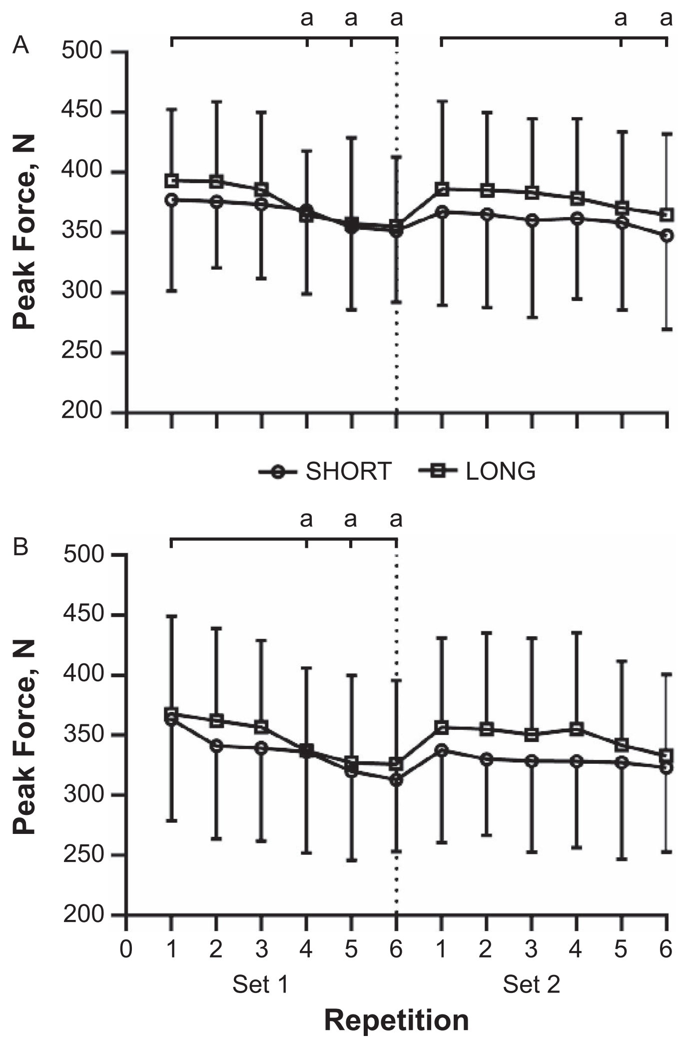

Figure 1. All individual repetitions for eccentric hamstrings peak force during the SHORT (1-min) and LONG (3-min) interset rest interval conditions (Mean ± SD). [a] Indicates a difference ($P < .05$).

Table. Changes in Eccentric Hamstrings Force Index Measures Between Sets During the SHORT and LONG Interset Rest Interval Conditions

Variable	Condition[a]	Set, Mean ± SD 1	Set, Mean ± SD 2	Effect Size (90% CI)	Condition, Value $F_{1,9}$	Condition, Value P	Set, Value $F_{1,9}$	Set, Value P	Condition × Set, Value $F_{1,9}$	Condition × Set, Value P
Peak force, N	Dominant limb				1.079	.33	1.228	.30	0.571	.47
	SHORT	398.60 ± 58.64	388.60 ± 69.35	−0.16 (−0.89, 0.59)						
	LONG	405.70 ± 62.88	406.30 ± 59.89	0.01 (−0.73, 0.74)						
	Nondominant limb				1.641	.23	2.452	.15	0.623	.45
	SHORT	371.00 ± 81.42	354.60 ± 73.50	−0.21 (−0.94, 0.53)						
	LONG	380.80 ± 80.94	374.70 ± 73.37	−0.08 (−0.81, 0.66)						
Average force, N	Dominant limb				0.998	.33	0.103	.76	0.771	.40
	SHORT	366.63 ± 61.17	360.40 ± 70.90	−0.09 (−0.83, 0.65)						
	LONG	374.63 ± 58.63	377.93 ± 62.29	0.05 (−0.68, 0.79)						
	Nondominant limb				1.851	.21	0.402	.54	0.376	.56
	SHORT	335.55 ± 73.38	329.18 ± 71.04	−0.09 (−0.82, 0.65)						
	LONG	346.18 ± 70.28	347.48 ± 73.62	0.02 (−0.72, 0.75)						
Maintenance, %	Dominant limb				0.046	.84	0.148	.71	1.164	.40
	SHORT	98.14 ± 8.15	96.35 ± 8.26	−0.22 (−0.95, 0.53)						
	LONG	95.31 ± 3.18	98.53 ± 5.57	0.71 (−0.08, 1.44)						
	Nondominant limb				0.136	.72	3.492	.09	1.017	.34
	SHORT	93.04 ± 7.00	98.00 ± 7.53	0.68 (−0.10, 1.41)						
	LONG	94.81 ± 6.23	97.43 ± 3.56	0.52 (−0.25, 1.24)						

[a] The SHORT condition was 1 minute, and the LONG condition was 3 minutes.

nondominant limb for set 2. The Table provides the differences between sets in the dominant and nondominant limbs for peak force, average force, and percentage maintenance. No condition-by-set interactions or main effects existed for peak force in the dominant and nondominant limbs (Figure 2). In addition, no differences occurred between the dominant and nondominant limbs for the SHORT ($t_{18} = 0.458$, $P = .65$, ES = 0.21) and LONG ($t_{18} = 0.593$, $P = .56$, ES = 0.27) conditions. No condition-by-set interactions or main effects were noted for average force in the dominant and nondominant limbs (Figure 3). In addition, no differences were demonstrated between the dominant and nondominant limbs for the SHORT ($t_{18} = 0.016$, $P = .988$, ES = 0.007) and LONG ($t_{18} = 0.170$, $P = .867$, ES = 0.08) conditions.

Fatigue

No condition-by-set interactions or main effects were evident for the percentage maintenance values in the dominant and nondominant limbs (Figure 4). In addition, no differences were seen between the dominant and nondominant limbs in the SHORT ($t_{18} = 1.452$, $P = .16$, ES = 0.65) and LONG ($t_{18} = -0.138$, $P = .89$, ES = –0.06) conditions. For the percentage decline values (Figure 5), no differences were present between the dominant SHORT and dominant LONG ($t_{18} = -0.151$, $P = .88$, ES = 0.07), nondominant SHORT and nondominant LONG ($t_{18} = -0.367$, $P = .72$, ES = 0.16), dominant SHORT and nondominant SHORT ($t_{18} = 0.566$, $P = .58$, ES = 0.25), and dominant LONG and nondominant LONG ($t_{18} = 0.138$, $P = .89$, ES = 0.06) conditions.

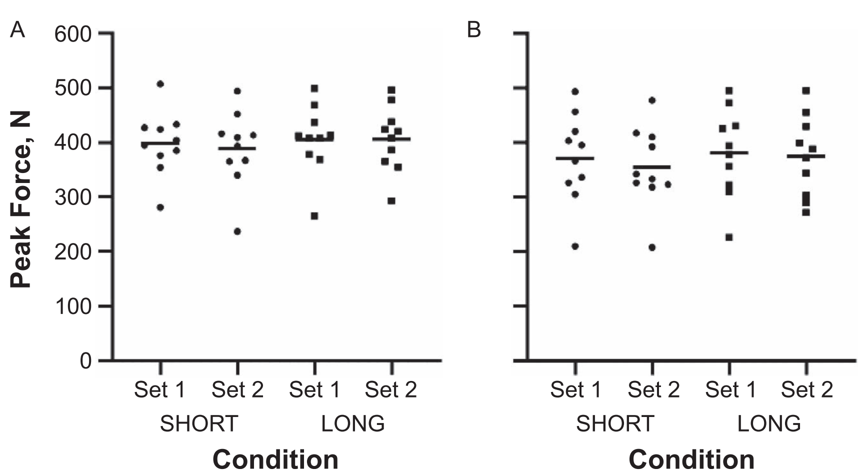

Figure 2. A, Mean and B, individual changes in eccentric hamstrings peak force during the SHORT (1-min) and LONG (3-min) interset rest interval conditions.

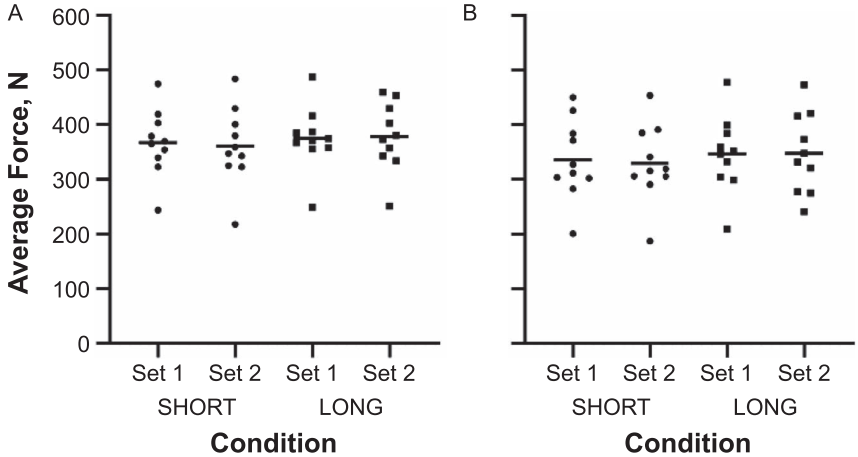

Figure 3. A, Mean and B, individual changes in eccentric hamstrings average force during the SHORT (1-min) and LONG (3-min) interset rest interval conditions.

Interlimb Asymmetries

Given the small variations between sets and small sample size, we calculated the percentage agreement between sets to determine the internal consistency of the direction of interlimb asymmetries. The percentage agreements for the tests were 90% and 70% for the SHORT and LONG groups, respectively. Interlimb asymmetries in the SHORT group were 8.99% $\pm$ 8.57% and 8.85% $\pm$ 5.08% for sets 1 and 2, respectively (Figure 6). In the LONG group, interlimb asymmetries were 8.06% $\pm$ 7.75% and 8.54% $\pm$ 8.16% for sets 1 and 2, respectively. No condition-by-set interactions ($F_{1,9} = 0.122$, $P = .74$) or main effects for condition ($F_{1,9} = 0.234$, $P = .64$) or repetitions ($F_{1,9} = 0.014$, $P = .91$) existed. The between-groups standardized mean differences for all measures are shown in Figure 7.

DISCUSSION

To our knowledge, we are the first to investigate the effects of the ISRI on NHE force indices. Although previous authors described the benefits of using a longer ISRI during RT for exercises that were largely concentric, we observed no differences between conditions or sets during the NHE, an eccentric exercise, for any force indices. However, although minimal, between-sets reductions in measures such as peak and average force production were lower during the LONG ISRI condition. Analysis of the individual repetitions showed that decrements in peak force occurred in the NHE set from repetition 4 onward. Overall, our results demonstrated that, whereas a 1-minute rest interval between sets is sufficient to maintain selected force indices during the NHE, peak force can begin to decrease midway through the set compared with the first repetition.

Our finding that the changes in force production values were not different between sets were in accordance with those of earlier researchers[21] who also noted no changes in hamstrings peak maximal eccentric torque during 6 sets of 5 repetitions each of the NHE. This result was somewhat expected because peak force is likely to occur at the beginning of the set, which was consistent with our results. Yet when the changes in peak and average force values in the dominant and nondominant limbs between sets were standardized between conditions (Figure 7), the LONG ISRI was more favorable, although the magnitude was small.

Comparatively, our finding that changes between sets were minimal during the NHE did not agree with the results

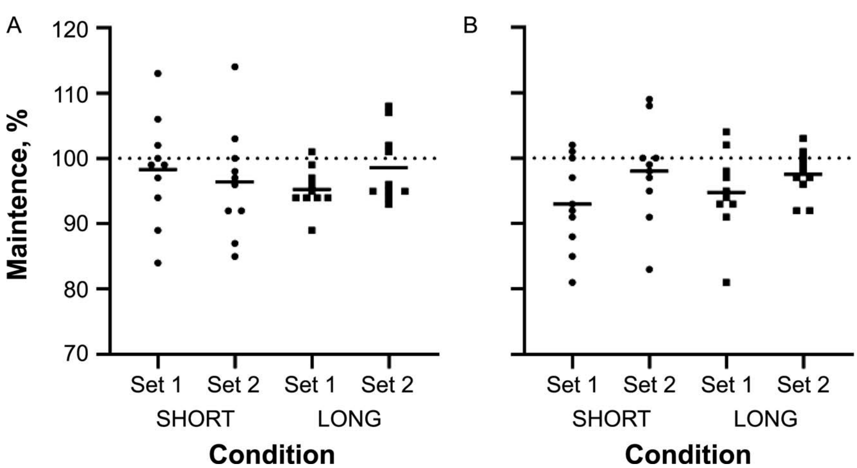

Figure 4. A, Mean and B, individual changes for percentage maintenance of eccentric hamstrings peak force during the SHORT (1-min) and LONG (3-min) interset rest interval conditions.

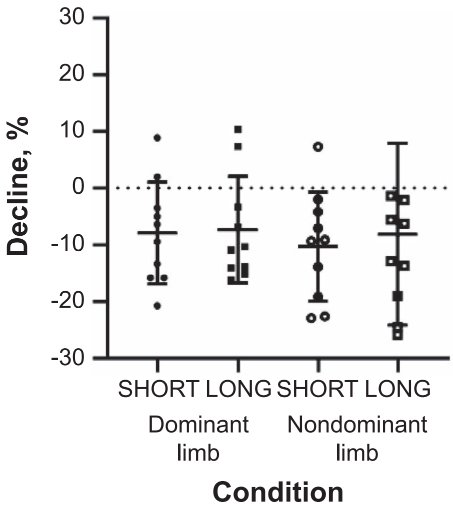

Figure 5. Percentage decline in eccentric hamstrings peak force during the SHORT (1-min) and LONG (3-min) interset rest interval conditions (Mean ± SD).

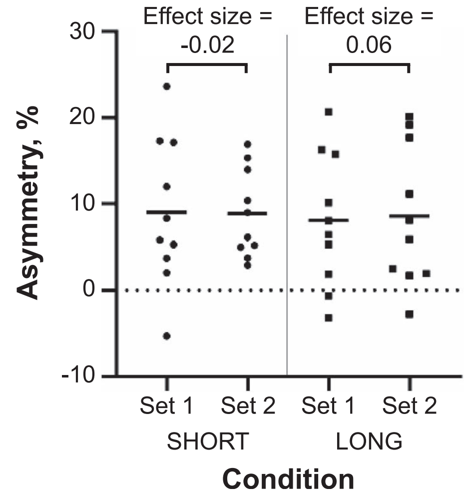

Figure 6. Mean (left) and individual (right) changes in eccentric hamstrings interlimb asymmetry between sets during the SHORT (1-min) and LONG (3-min) interset rest interval conditions.

of previous investigators[22] who assessed the ISRI during lower limb RT. For example, multiple sets of leg-extension exercise using a 10-repetition maximum load led to large reductions in performance by the second set, regardless of the duration of the ISRI (1-minute ES = 6.15, 3-minute ES = 1.54). The minimal influence of the ISRI during the NHE could be explained by the SHORT ISRI providing adequate time to recover between sets due to the eccentric muscle action that occurs during the exercise. Energy expenditure, carbohydrate use, and oxygen consumption were lower during eccentric than during concentric exercise.[5] Consequently, it is possible that, due to the eccentric nature of the NHE, a shorter ISRI between sets is sufficient to restore energy stores and thus maintain force production values in athletes familiar with the NHE.

Peak force decreased from repetition 4 onward compared with the first repetition in set 1 in the dominant and nondominant limbs and repetition 5 in set 2 for the dominant limb (Figure 1). Whereas direct comparisons with earlier work are difficult because of the differences between exercises, peak force during lower limb RT has been shown to decrease from repetition 1 to all subsequent repetitions when performing 6 repetitions of the loaded jump squat.[23] The reductions in peak force occurring later during the NHE set may reflect the lower metabolic costs that occur during eccentric muscle actions compared with concentric muscle actions, which consequently reduce mechanical force output.[24] Furthermore, the intermittent nature of the NHE may also help explain our findings. The time delay between the end of the descent phase and the return to the start position inadvertently provides a short rest interval between repetitions. Indeed, an inter-repetition rest was beneficial in reducing muscle metabolites and maintaining performance during lower limb RT.[25] Therefore, based on our findings, it may be permissible to use lower repetition ranges when prescribing the NHE or include a rest interval after each repetition to try to ensure that high levels of eccentric hamstrings force production are achieved throughout the whole set.

Percentage maintenance between sets did not differ, with participants achieving peak force values >93% across sets in both conditions. Interestingly, force maintenance values tended to be greater in the second set than in the first set. Our lower percentage maintenance values during the first set than the second set were in line with those of authors[26] who showed that the greatest declines in eccentric torque occurred at the beginning of the exercise before it reached a plateau. However, we believe the percentage decline values provide more accurate insight into the force reductions that occurred during the NHE than percentage maintenance values do. The percentage maintenance values in the set consider the mean of the peak force values from all 6 repetitions, whereas the percentage declines reflect the loss of force from the first to the 12th repetition. Consequently, the absolute percentage losses noted between repetitions 1 and 6 (>12%) along with the percentage decline values in all conditions (7%–10%) would suggest that the losses in force production during the NHE may in fact be high. For instance, losses in concentric peak force when performing 4 repetitions of the deadlift at 90% of the 1-repetition maximum and during 6 repetitions of the jump-squat exercise have been reported to be 2.3%[27] and approximately 3%, respectively.[23] Our results somewhat reflect the losses of up to 17% in average eccentric hamstrings torque described after 1 set of 5 repetitions of the NHE.[21] Subsequently, although eccentric muscle actions are known to be less fatiguing than concentric actions,[7] it may be that the specific nature of eccentric hamstrings actions means they are more susceptible to fatigue. Indeed, Paulus et al[28] recently showed that fatigue was more pronounced during eccentric exercise of the hamstrings muscles than the quadriceps muscles. Therefore, our results indicated that, when prescribing the NHE, practitioners should be cognizant of the potentially large decrements in force that can occur within the set and aim to minimize them.

The interlimb asymmetry values produced by our participants were similar to those observed in professional male team-sport athletes who had no history of hamstrings injuries in the previous season (8.77% ± 7.92%).[29] Thus, uninjured, well-trained individuals with experience performing the NHE should be expected to achieve eccentric hamstrings asymmetry values of <15% during the NHE. Indeed, individuals with higher values were at greater risk

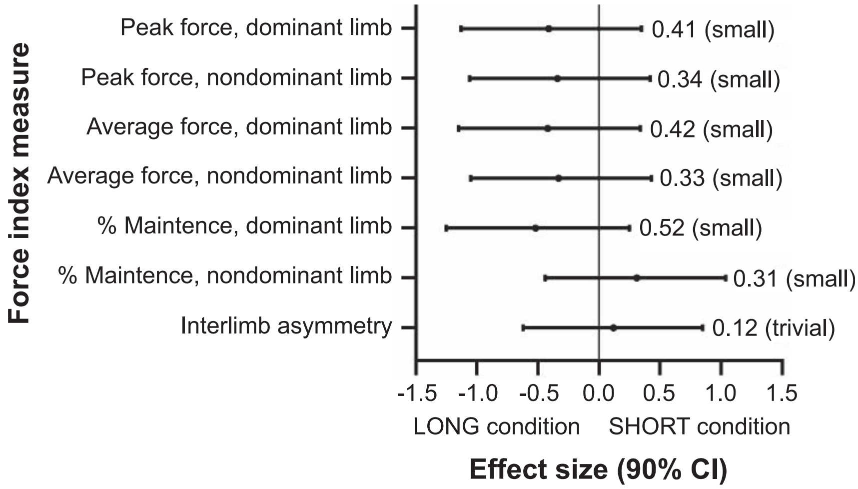

Figure 7. Between-conditions standardized mean differences with 90% CIs for force index measures.

of hamstrings strain injuries.[13] Furthermore, the high levels of variability in our asymmetry values are similar to those reported by investigators[29] who observed interlimb asymmetries during the NHE. Hence, per current recommendations, it is necessary to undertake an individual approach when interpreting interlimb asymmetry data.[30] As we found for other force index measures, interlimb asymmetries did not differ between sets or conditions. Our previous explanations for the minimal changes between sets for the other force index measures may also apply here, though our inclusion criteria that required participants to meet a minimum threshold of eccentric hamstrings strength and be injury free may also provide further rationale. For example, stronger athletes exhibited less asymmetry than did weaker athletes during lower limb strength tasks.[31] In addition, individuals with a history of hamstrings injuries displayed greater declines in knee-flexor torque production during an isokinetic endurance test in injured than uninjured legs.[14] Consequently, although further evaluation is required to determine how the ISRI length may influence eccentric hamstrings interlimb asymmetries between injured and uninjured athletes, our findings demonstrated that practitioners can use a SHORT ISRI during the NHE to maintain this quality.

Limitations

This study had certain limitations. We used SHORT and LONG ISRIs; therefore, considering the minimal differences observed between the SHORT and LONG groups, including a shorter ISRI might have provided more details regarding the minimum ISRI required. In addition, further analysis of changes in force indices across additional sets of the NHE as reported in the literature[21] might have offered insight into the fatigue aspects of exercise. However, using low-dose NHE training is a time-efficient strategy from a practitioner's perspective, and this approach was as effective in developing eccentric hamstrings strength and muscle architecture properties in young male team-sport athletes as higher volumes.[9] Also, the force indices we measured did not represent angle-specific changes in eccentric hamstrings force. This is important to acknowledge, as reductions in eccentric torque have occurred in the final 15° of range of motion after the NHE.[21] Consequently, future researchers should examine how the length of the ISRI influences angle-specific eccentric hamstrings forces, as well as the longitudinal effects of using a SHORT versus LONG ISRI, on eccentric hamstrings strength and muscle architecture properties.

CONCLUSIONS

To our knowledge, we are the first to examine the effects of different ISRIs during the NHE. Our results demonstrated that the use of a SHORT ISRI was adequate to maintain force indices and interlimb asymmetries between sets during the NHE. Thus, practitioners can use our findings when prescribing the NHE within an injury-prevention program for uninjured players who are accustomed to the exercise. However, clinicians should be aware of the potential for large reductions in eccentric hamstrings strength to occur during a set and, hence, an intraset ISRI may be useful. Overall, although our work provides practitioners with guidance on the effective prescription of the NHE, current guidelines for its prescription require additional study.

REFERENCES

1. de Salles BF, Simão R, Miranda H, Bottaro M, Fontana F, Willardson JM. Strength increases in upper and lower body are larger with longer inter-set rest intervals in trained men. *J Sci Med Sport*. 2010;13(4):429–433. doi:10.1016/j.jsams.2009.08.002
2. McMahon S, Jenkins D. Factors affecting the rate of phosphocreatine resynthesis following intense exercise. *Sports Med*. 2002;32(12):761–784. doi:10.2165/00007256-200232120-00002
3. Schoenfeld BJ, Pope ZK, Benik FM, et al. Longer interset rest periods enhance muscle strength and hypertrophy in resistance-trained men. *J Strength Cond Res*. 2016;30(7):1805–1812. doi:10.1519/JSC.0000000000001272
4. Suchomel TJ, Wagle JP, Douglas J, et al. Implementing eccentric resistance training—part 1: a brief review of existing methods. *J Funct Morphol Kinesiol*. 2019;4(2):38. doi:10.3390/jfmk4020038
5. Penailillo L, Blazevich A, Nosaka K. Energy expenditure and substrate oxidation during and after eccentric cycling. *Eur J Appl Physiol*. 2014;114(4):805–814. doi:10.1007/s00421-013-2816-3
6. Baroni BM, Stocchero CM, do Espirito Santo RC, Ritzel CH, Vaz MA. The effect of contraction type on muscle strength, work and

fatigue in maximal isokinetic exercise. *Isokinet Exerc Sci*. 2011;19(3):215–220. doi:10.3233/IES-2011-0421
7. Read PJ, Jimenez P, Oliver JL, Lloyd RS. Injury prevention in male youth soccer: current practices and perceptions of practitioners working at elite English academies. *J Sports Sci*. 2018;36(12):1423–1431. doi:10.1080/02640414.2017.1389515
8. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2019;53(21):1362–1370. doi:10.1136/bjsports-2018-100045
9. Lacome M, Avrillon S, Cholley Y, Simpson BM, Guilhem G, Buchheit M. Hamstring eccentric strengthening program: does training volume matter? *Int J Sports Physiol Perform*. 2020;15(1):81–90. doi:10.1123/ijspp.2018-0947
10. Matthews MJ, Heron K, Todd S, et al. Strength and endurance training reduces the loss of eccentric hamstring torque observed after soccer specific fatigue. *Phys Ther Sport*. 2017;25:39–46. doi:10.1016/j.ptsp.2017.01.006
11. Anastasi SM, Hamzeh MA. Does the eccentric Nordic hamstring exercise have an effect on isokinetic muscle strength imbalance and dynamic jumping performance in female rugby union players? *Isokinet Exerc Sci*. 2011;19(4):251–260. doi:10.3233/IES-2011-0420
12. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med*. 2016;50(24):1524–1535. doi:10.1136/bjsports-2015-095362
13. Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. *Am J Sports* Med. 2015;43(11):2663–2270. doi:10.1177/0363546515599633
14. Lord C, Ma'ayah F, Blazevich AJ. Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scand J Med Sci Sports*. 2018;28(3):1235–1243. doi:10.1111/sms.13007
15. Drury B, Green T, Ramirez-Campillo R, Moran J. Influence of maturation status on eccentric hamstring strength improvements in youth male soccer players after the Nordic hamstring exercise. *Int J Sports Physiol Perform*. 2020;15(7):990–996. doi:10.1123/ijspp.2019-0184
16. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191.
17. Fernandes JF, Moran J, Clarke H, Drury B. The influence of maturation on the reliability of the Nordic hamstring exercise in male youth footballers. *Transl Sports Med*. 2020;3(2):148–153. doi:10.1002/tsm2.124
18. Bishop C, Read P, Chavda S, Jarvis P, Turner A. Using unilateral strength, power and reactive strength tests to detect the magnitude and direction of asymmetry: a test-retest design. *Sports (Basel)*. 2019;7(3):58. doi:10.3390/sports7030058
19. Tufano JJ, Conlon JA, Nimphius S, et al. Maintenance of velocity and power with cluster sets during high-volume back squats. *Int J Sports Physiol Perform*. 2016;11(7):885–892. doi:10.1123/ijspp.2015-0602
20. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. 2009;41(1):3–13. doi:10.1249/MSS.0b013e31818cb278
21. Marshall PW, Lovell R, Knox MF, Brennan SL, Siegler JC. Hamstring fatigue and muscle activation changes during six sets of Nordic hamstring exercise in amateur soccer players. *J Strength Cond Res*. 2015;29(11):3124–3133. doi:10.1519/JSC.0000000000000966
22. Senna G, Willardson JM, de Salles BF, et al. The effect of rest interval length on multi and single-joint exercise performance and perceived exertion. *J Strength Cond Res*. 2011;25(11):3157–3162. doi:10.1519/JSC.0b013e318212e23b
23. Hansen KT, Cronin JB, Newton MJ. The effect of cluster loading on force, velocity, and power during ballistic jump squat training. *Int J Sports Physiol Perform*. 2011;6(4):455–468. doi:10.1123/ijspp.6.4.455
24. Gonzalez-Izal M, Lusa Cadore E, Izquierdo M. Muscle conduction velocity, surface electromyography variables, and echo intensity during concentric and eccentric fatigue. *Muscle Nerve*. 2014;49(3):389–397. doi:10.1002/mus.23926
25. Girman JC, Jones MT, Matthews TD, Wood RJ. Acute effects of a cluster-set protocol on hormonal, metabolic and performance measures in resistance-trained males. *Eur J Sport Sci*. 2014;14(2):151–159. doi:10.1080/17461391.2013.775351
26. McNeil CJ, Allman BL, Symons TB, Vandervoort AA, Rice CL. Torque loss induced by repetitive maximal eccentric contractions is marginally influenced by work-to-rest ratio. *Eur J Appl Physiol*. 2004;91(5–6):579–585. doi:10.1007/s00421-003-0996-y
27. Moir GL, Graham BW, Davis SE, Guers JJ, Witmer CA. Effect of cluster set configurations on mechanical variables during the deadlift exercise. *J Hum Kinet*. 2013;18(39):15–23. doi:10.2478/hukin-2013-0064
28. Paulus J, Croisier JL, Kaux JF, Bury T. Eccentric versus concentric—which is the most stressful cardiovascularly and metabolically? *Curr Sports Med Rep*. 2019;18(12):477–489. doi:10.1249/JSR.0000000000000666
29. Ribeiro-Alvares JB, Oliveira GDS, De Lima-E-Silva FX, Baroni BM. Eccentric knee flexor strength of professional football players with and without hamstring injury in the prior season. *Eur J Sport Sci*. 2021;21(1):131–139. doi:10.1080/17461391.2020.1743766
30. Bishop C, Lake J, Loturco I, Papadopoulos K, Turner A, Read P. Interlimb asymmetries: the need for an individual approach to data analysis. *J Strength Cond Res*. 2021;35(3):695–701. doi:10.1519/JSC.0000000000002729
31. Bailey CA, Sato K, Burnett A, Stone MH. Force-production asymmetry in male and female athletes of differing strength levels. *Int J Sports Physiol Perform*. 2015;10(4):504–508. doi:10.1123/ijspp.2014-0379

Address correspondence to Benjamin Drury, MSc, Department of Applied Sport Sciences, Hartpury University, Hartpury, Gloucestershire, GL193BE, United Kingdom. Address email to ben.drury@hartpury.ac.uk.

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Comparison of flywheel versus traditional resistance training in elite academy male Rugby union players

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Comparison of flywheel versus traditional resistance training in elite academy male Rugby union players

Jordan Murton[a], Robin Eager[b] and Ben Drury[c]

[a]Gloucester Rugby Ltd, Kingsholm Gloucester, UK; [b]Rugby Football Union, Twickenham Stadium, Twickenham, UK; [c]Department of Applied Sport Sciences, Hartpury University, Gloucestershire, UK

ABSTRACT

This study investigated the effects of flywheel inertia training (FIT) vs traditional resistance training (TRT) over four weeks in academy male rugby union (RU) players. Sixteen elite male academy RU players (age = 18.0 ± 1.0 years, body mass = 93.0 ± 13.1 kg) were allocated into either FIT (n = 8) or TRT (n = 8) groups. Pre and post measures of countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) were completed. Relative peak force (PF), relative peak power (PP) and jump height (H) were measured for CMJ and SJ with reactive strength index measured for the DJ. Both groups showed improvements in all measures, except for SJ peak power, following TRT. Within-group analysis showed significant increases following TRT in CMJ-H (2.79 cm, 90% CI = −0.70, 4.89 cm; p = 0.002; ES = 0.51) and SJ-H (3.68 cm, 90% CI = 1.25, 6.11 cm; p = 0.002; ES = 0.88) with a significant improvement following FIT for CMJ-PP (1.96Wkg-1, 90% CI = −0.89, 4.80 Wkg-1; p = 0.022; ES = 0.55). No significant between-group differences (p > 0.05) were evident. These findings suggest both FIT and TRT are effective for developing lower-body strength and power qualities in male academy RU players.

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Introduction

Rugby union (RU) is a contact sport that involves high-intensity bouts of exercise exertion, contact, tackling, acceleration and scrummaging (Duthie et al., 2006). To meet the physical demands of RU, high levels of strength and power are required (Argus et al., 2012). The development of these physical qualities is particularly important in academy RU players as these distinguish between playing levels (Jones et al., 2018) and age groups (Darrall-Jones et al., 2015). Therefore, to support the long-term athletic development (LTAD) of youth RU players the training of strength and power is necessary (Durguerian et al., 2019). Moreover, the specific targeting of these qualities becomes more vital as the youth athlete reaches adolescence as both during and after peak height velocity greater increases in strength and power occur (Moran et al., 2017). This can have important consequences for youth RU players since strength and power can also predict future senior level placings (Fontana et al., 2017). Consequently, the inclusion of training

CONTACT Ben Drury ben.drury@hartpury.ac.uk Department of Applied Sport Sciences, Hartpury University, Hartpury GL19 3BE, UK

activities that maximizes the development of strength and power in youth RU players is advocated (Till et al., 2020).

In youth athletes, the inclusion of resistance training (RT) has been shown to be highly effective for improving strength and power (Behm et al., 2017) as well as reducing injury risk (Soomro et al., 2016). Previous research investigating the effects of RT on strength and power in youth RU players has focused upon traditional resistance-training (TRT) in which equalized loads are used for both the concentric and eccentric phases of an exercise (Harries et al., 2018; Smart & Gill, 2013; Weakley et al., 2019). However, this may provide a sub-optimal stimulus since greater forces are produced during eccentric muscle actions compared to concentric actions (Westing et al., 1988). Subsequently, the use of eccentric resistance training (ERT), to overload the eccentric phase of a given movement, is recommended (Wagle et al., 2017). This has importance for youth RU players as eccentric strength in academy RU players is associated with integral match activities such as sprinting (Bridgeman et al., 2020). Also, the inclusion of lower-body eccentric injury prevention exercises has been reported to reduce injury incidence and severity in RU players (Evans & Williams, 2017). However, to the authors knowledge, previous research has not investigated the efficacy of ERT within this population.

Flywheel inertia training (FIT) is an effective ERT modality due to the accentuated eccentric muscle action that occurs from the energy stored in the flywheel system from the preceding concentric action (Martinez-Aranda & Fernandez-Gonzalo, 2017). Increases in strength and power in youth male adolescent team sport athletes have been reported following 10 weeks of FIT (De Hoyo et al., 2015; Raya-González et al., 2021). However, a limitation of these studies is that the control group did not complete any form of RT (Beato & Dello Iacono, 2020). Additionally, though Stojanović et al. (2021) reported greater improvements in power following eight weeks of FIT compared to TRT in youth male basketball players, no differences in strength were observed. Furthermore, whilst increases in lower-body strength and power were found following six weeks of FIT in adult RU players, both the experimental groups performed FIT but at just different intensities (Sabido et al., 2019). Consequently, the benefits of implementing FIT for youth male RU remains unclear. Since the development of physical qualities to optimize LTAD in young RU players is essential (Owen et al., 2020), further knowledge on the effects of ERT within this population will provide practitioners with important training guidance. Accordingly, the aim of this study was to investigate the effects of FIT, compared to TRT, on changes in lower-body strength and power in elite academy male RU players.

Methods

Study design

A randomized-controlled trial, with a repeated measures design, was undertaken to assess lower-body strength and power changes following four weeks of either TRT or FIT in elite academy RU players. Before and after the training intervention, measures of lower-body strength and power were assessed using the countermovement jump (CMJ), squat jump (SJ) and drop jump (DJ) tests. These tests were specifically chosen as they have been shown to be associated with performance measures and KPI's during RU match play (Cunningham et al., 2018) as well as sprint performance in RU players (Furlong et al., 2019).

Training sessions were performed twice per week, in the evening, during the off-season period and were separated by 48–72 hours in line with players' training schedule. All participants achieved 100% compliance with the scheduled RT sessions. Testing sessions occurred at the same time of day (evening) to correspond with the participants normal training sessions.

Participants

An *a priori* power analysis (G*Power; University of Düsseldorf, Dusseldorf, Germany) was conducted to determine a minimum sample size for the study. Sample size was calculated on a power of (1-β) 0.90, an alpha error of 0.05 and an effect size of 0.58 based on previous research investigating the effects of FIT training in young male team sport athletes (De Hoyo et al., 2015). As a result, a minimum total sample size of 12 participants was required. Subsequently, 16 elite male academy RU players (age = 18.0 ± 1.0 years, body mass = 93.0 ± 13.1 kg) volunteered to participate in the study. Players were randomly assigned to either TRT or FIT groups according to a computer-generated sequence (www.randomizer.org). No control group was used (i.e. players who did not perform any training), since this would have resulted in an impractical approach that would not be representative of the participants training. Participants were physically active and were members of an elite club academy pathway with at least one year of RT experience within a supervised programme. All participants were free from injury at the time of the intervention. After explaining the scope of the study, written informed consent was obtained from all players. Parental consent was obtained for participants under 18 years of age. The Hartpury University Research Committee provided ethical approval (ETHICS2019-77) prior to the beginning of testing, and the study was completed in accordance with the Declaration of Helsinki.

Procedures

Participants in the FIT group were familiarized with the flywheel device in the weeks leading up to the training intervention during their routine RT sessions. In the week before the start of the training intervention, both groups undertook baseline measures of jumping performance. All participants performed a standardized warm-up, similar to that which preceded their typical strength training programme, including lunge variations, mobility exercises and activation/potentiation exercises. Participants were familiar with the testing measures as these had been previously performed as part of their strength and power testing battery. Specifically, measures of bilateral CMJ, SJ and DJ were obtained. To collect all jumping measures, participants stood upon a force platform (Pasco, Rosedale, USA) sampling at 1000 Hz. A total of two trials were performed for each jump measure with each trial separated by a minimum of two minutes of rest. The same measures were again assessed upon completion of the training intervention.

Training programme

The four-week training intervention was performed alongside the athletes' rugby training commitments. Both groups performed one upper-body, one lower-body and one total-

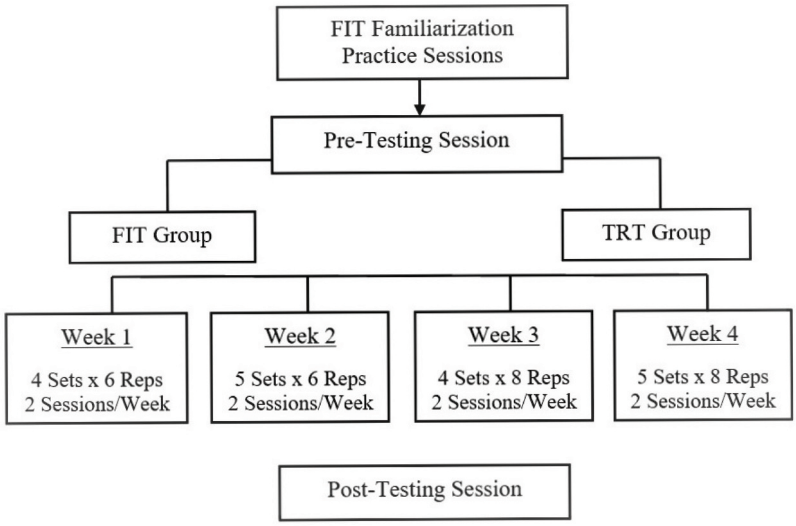

Figure 1. Overview of experimental procedures.

body RT session per week. Both the TRT and FIT groups completed the same training volume of upper-body and lower-body exercises although the RT method for the lower-body exercises were dictated by the respective training conditions which the participants were allocated to. The FIT group performed all lower-body exercises on an inertial flywheel training device (K-box, Bromma, Sweden) including the squat, Romanian deadlift and Bulgarian split squat. Similarly, the TRT group performed the same exercises but used barbells for the back squat and Romanian deadlift exercises and dumbbells for the Bulgarian split squat exercise. These exercises were specifically chosen due to their inclusion within the athletes current training programme as well as their biomechanical similarity (i.e. lower body bilateral, lower-body unilateral, hip hinge). The loading for the FIT group was guided by previous research with increases in weekly training volume, rather than intensity, prescribed over the course of the training intervention (De Hoyo et al., 2015). A breakdown of weekly training volume during the meso-cycle can be viewed in Figure 1. An inertia flywheel intensity of 0.05 $kg{\cdot}m^2$ was used throughout the intervention and participants utilized a self-selected rest period between sets to ensure maximum performance. All training sessions were supervised by the club's strength and conditioning staff.

Anthropometrics

Prior to performance testing, data on age and body mass was recorded. Participants' body mass was measured, using a calibrated electronic scale (SECA model 813, Birmingham, United Kingdom), to the nearest 0.1 kg.

Vertical jumps

Participants started in a tall standing position on the dual-force platforms, with feet placed hip width to shoulder width apart and hands akimbo. If a participant removed their hands from the hips or flexed the knees during the jump, that jump was discarded and participants were asked to repeat the trial. Once in the correct starting position, participants were required to quickly descend into the countermovement position, to a self-selected depth, before immediately executing a maximal effort vertical jump and landing back in the start position on the force platforms (Van Hooren & Zolotarjova, 2017). The same protocol was completed for the SJ except that participants were required to slowly descend into their self-selected depth where they paused for three-seconds prior to performing the ascent phase of the jump (Van Hooren & Zolotarjova, 2017). Measures of relative concentric peak force ($N \cdot kg^{-1}$), relative concentric peak power ($W \cdot kg^{-1}$) and jump height (cm) were recorded for each effort with the average of the two trials used for further analysis.

Drop jump

The drop jump (DJ) was performed from a box height of 0.40 m. Participants were required to step off the box with hands akimbo and immediately rebound off the force platform with maximal intent, with emphasis also on minimizing ground contact time whilst maximizing jump height (Pedley et al., 2017). Participants' technique was visually inspected for each trial and if technique was deemed incorrect, the trial was discarded and an additional trial performed. The average of the two accepted trials was recorded for further analysis.

Force platform analysis

All jumping measures collected were analysed using commercially available software (ForceDecks, Vald Performance Pty Ltd., Brisbane, Australia). The onset of movement was defined as the point when the total vertical ground reaction force (vGRF) deviated −20 N from body weight, and the take-off (TO) was set to the point when the total vGRF dropped below 20 N. Maximal vertical jump height (H) was calculated using the flight time method in which flight time was calculated as the time interval between take-off and touch down. Peak force (PF) and peak power (PP) values were defined as the highest values of force and power that were achieved during the concentric phase of the movement, respectively. Values for PF and PP were normalized to body mass to allow comparisons between groups and for any post intervention changes in body mass to be taken into consideration. To calculate RSI, jump height (cm) was divided by ground contact time (s).

Statistical analysis

Statistical analysis was performed using JASP (version 13.1, University of Amsterdam, Amsterdam, Netherlands) with statistical significance set at $p < 0.05$. The normality of data was assessed via the Shapiro–Wilk test and visual inspection of the Q–Q plots with the homogeneity of variances tested using the Levene test. Within-session relative reliability was calculated using intraclass correlation coefficient (ICC), and absolute reliability was calculated via typical error expressed as a coefficient of variation (CV%) ± 90% confidence limits using a customized Excel spreadsheet (Hopkins, 2015). Good and acceptable CV values were considered <5% and between 5% and 10%, respectively (Cormack et al., 2008). The ICC was interpreted in line with previous recommendations where values >0.90 = excellent, 0.75–0.90 = good, 0.50–0.75 = moderate, and <0.50 = poor (Koo & Li, 2016). A paired-samples t-test was used to evaluate within-group differences, and an analysis of covariance (ANCOVA) was performed to detect possible between-group differences, assuming baseline values as covariates. Due to sample size per group being below 20 participants, effect sizes (ES) for within-group changes and between-group differences were calculated using Hedges *g* (Goulet-Pelletier & Cousineau, 2018) by dividing the difference between groups' change scores by their pooled SD for each performance variable. ES were interpreted using previously outlined ranges; <0.19 = trivial, 0.2–0.59 = small, 0.6–1.19 = moderate, 1.2–1.99 = large and 2.0–4.0 = very large (Hopkins et al., 2009).

Results

Within-session reliability data are presented in Table 1 and show that data reported excellent absolute (ICC) and acceptable relative (CV%) reliability scores. Table 2 shows the changes in strength and power measures for both groups. Within-group analysis showed significant improvements in the TRT group for CMJ-H ($p = 0.002$, ES = *moderate*) and SJ-H ($p = 0.002$, ES = *moderate*). In the FIT group, a within-group significant improvement was found for CMJ-PP ($p = 0.022$, ES = *small*) with a trend for improvement in CMJ-H also noted ($p = 0.054$, ES = *small*). No statistically significant between-group differences ($p > 0.05$) were found for all measures. However, between-group standardized differences (Figure 2) showed greater improvements for TRT in CMJ-PF, CMJ-H, SJ-H and RSI whilst SJ-PP was greater for FIT. Figure 3 displays the individual changes in the TRT and FIT groups for all measures.

Discussion

This study investigated the effects of FIT compared to TRT in elite male academy RU players. Our findings showed that both FIT and TRT were effective in increasing lower-body strength and power measures following a four-week off-season RT programme. However, despite no between-group statistically significant differences, the magnitude of the changes tended to favour the TRT group to a small effect for all measures except SJ-PP. Overall, our findings suggest that both TRT and FIT improve lower-body strength and power qualities in elite academy male RU players to a similar extent.

The increases in vertical jump performance over four weeks in the TRT group in our study are similar to those previously reported in male academy RU players following between 12 and 15 weeks of TRT (Harries et al., 2018; Smart & Gill, 2013; Weakley et al., 2019). Our changes, which occurred in a shorter time period, may be explained by the elite playing status of our participants. Indeed, factors such as training age (Till et al., 2017) and strength level (Cormie et al., 2010) have been shown to influence changes in strength and power following RT. Alternatively, whilst the FIT group showed increases in all vertical jump measures these were smaller compared to those recently reported after ten weeks in young elite male soccer players (Raya-González et al., 2021) and eight weeks in elite adolescent male basketball players (Stojanović et al., 2021). Similar to the aforementioned

Table 1. Reliability data with 90% confidence intervals for pre and post tests in both traditional resistance training (TRT) and flywheel inertia training (FIT) groups.

	Baseline TRT		Post TRT		Baseline FIT		Post FIT	
Test	ICC	CV%	ICC	CV%	ICC	CV%	ICC	CV%
CMJ-PP	0.97 (0.97–0.99)	1.14 (0.80–2.40)	0.98 (0.92–0.99)	1.83 (1.29–3.30)	0.96 (0.84–0.99)	1.83 (1.29–3.29)	0.95 (0.77–0.99)	1.92 (1.35–3.44)
CMJ-PF	0.99 (0.77–0.99)	2.41 (1.70–4.32)	0.95 (0.78–0.99)	2.97 (2.10–5.34)	0.98 (0.90–0.99)	2.05 (1.45–3.68)	0.93 (0.66–0.98)	3.48 (2.46–6.26)
CMJ-H	0.98 (0.90–0.99)	2.62 (1.85–4.71)	0.99 (0.96–0.99)	1.69 (1.19–3.04)	0.97 (0.85–0.99)	2.84 (1.99–5.08)	0.98 (0.90–0.99)	1.89 (1.33–3.40)
SJ-PP	0.90 (0.52–0.98)	5.20 (3.67–9.34)	0.98 (0.91–0.99)	2.19 (1.54–3.93)	0.96 (0.83–0.99)	2.76 (3.41–4.96)	0.99 (0.96–0.99)	1.98 (1.39–3.55)
SJ-PF	0.96 (0.81–0.99)	2.65 (1.87–4.76)	0.95 (0.75–0.99)	2.14 (1.51–3.85)	0.95 (0.76–0.99)	2.23 (1.57–4.00)	0.92 (0.64–0.98)	2.44 (1.72–4.39)
SJ-H	0.98 (0.92–0.99)	2.11 (1.49–3.79)	0.98 (0.93–0.99)	2.31 (1.63–4.14)	0.97 (0.87–0.99)	2.47 (1.75–4.42)	0.99 (0.96–0.99)	0.87 (0.61–1.56)
RSI	0.99 (0.98–0.99)	1.51 (1.06–2.71)	0.98 (0.93–0.99)	3.42 (2.41–6.14)	0.99 (0.97–0.99)	2.05 (1.54–4.10)	0.96 (0.81–0.99)	5.64 (3.98–10.14)

ICC = intraclass correlation coefficient; CV% = coefficient of variation; CMJ-PP = countermovement jump relative peak power; CMJ-PF = countermovement jump relative peak force; CMJ-H = countermovement jump height; SJ-PP = squat jump relative peak power; SJ-PF = squat jump relative peak force; CMJ-H = squat jump height; RSI = reactive strength index.

Table 2. Baseline vs Post Intervention Changes in Strength and Power Measures for Traditional (TRT) and Flywheel Inertia Training (FIT) Groups.

	TRT (n = 8)				FIT (n = 8)			Between Group Differences		
Variables	Baseline	Post	Difference (90% CI)	Effect Size (90% CI)	Baseline	Post	Difference (90% CI)	Effect Size (90% CI)	F	p
CMJ-PP (W·kg-^{1})	50.59 ± 6.04	52.85 ± 5.43	2.26 (−0.58–5.11)	0.39 (−0.46, 1.20)	48.70 ± 3.53	50.66 ± 3.23	1.96 (−0.89 4.80)	0.55 (−0.29, 1.39)*	0.145	0.710
CMJ-PF (N·kg-^{1})	22.18 ± 1.77	23.11 ± 2.35	0.93 (−0.61, 2.47)	0.42 (−0.41, 1.25)	24.65 ± 2.26	25.10 ± 2.40	0.45 (−1.09, 1.99)	0.18 (−0.64, 1.01)	0.356	0.561
CMJ-H (cm)	36.66 ± 4.92	39.45 ± 5.36	2.79 (−0.70, 4.89)	0.51 (−0.32, 1.35)*	36.64 ± 4.31	38.45 ± 3.64	1.81 (−0.29, 3.90)	0.43 (−0.40, 1.26)	1.031	0.328
SJ-PP (W·kg^{-1})	50.48 ± 6.02	50.19 ± 5.98	−0.29 (−6.38, 5.80)	−0.05 (−0.87, 0.78)	46.98 ± 4.94	51.24 ± 7.95	4.27 (−1.82, 10.36)	0.22 (−0.60, 1.05)	1.627	0.224
SJ-PF (N·kg-^{1})	20.75 ± 1.99	21.25 ± 1.44	0.50 (−0.81, 1.82)	0.27 (−0.55, 1.10)	20.98 ± 1.52	21.40 ± 1.39	0.42 (−1.71, 3.02)	0.27 (−0.55, 1.10)	2.454	0.988
SJ-H (cm)	35.63 ± 4.23	39.31 ± 5.53	3.68 (1.25, 6.11)	0.88 (0.02, 1.74)*	34.89 ± 3.89	36.54 ± 2.63	1.65 (−0.78, 4.08)	0.47 (−0.36, 1.30)	3.292	0.093
RSI	1.97 ± 0.35	2.22 ± 0.47	0.25 (−0.16, 0.65)	0.57 (−0.27, 1.41)	1.94 ± 0.40	2.07 ± 0.42	0.13 (−0.27, 0.54)	0.30 (−0.53, 1.13)	0.436	0.521

CMJ-PP = countermovement jump relative peak power; CMJ-PF = countermovement jump relative peak force; CMJ-H = countermovement jump height; SJ-PP = squat jump relative peak power; SJ-PF = squat jump relative peak force; SJ-H = squat jump height; RSI = reactive strength index; CI = confidence interval; * = within-group statistical significance (p < 0.05).

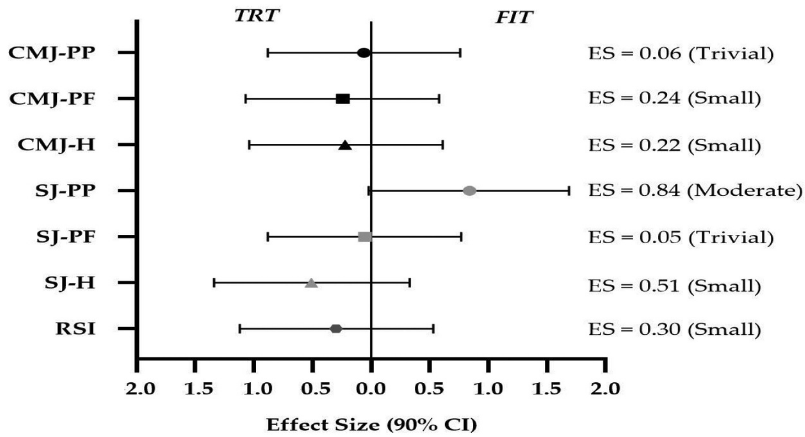

Figure 2. Between group standardized differences with 90% Confidence Intervals for Traditional Resistance Training (TRT) vs Flywheel Inertia Training (FIT).

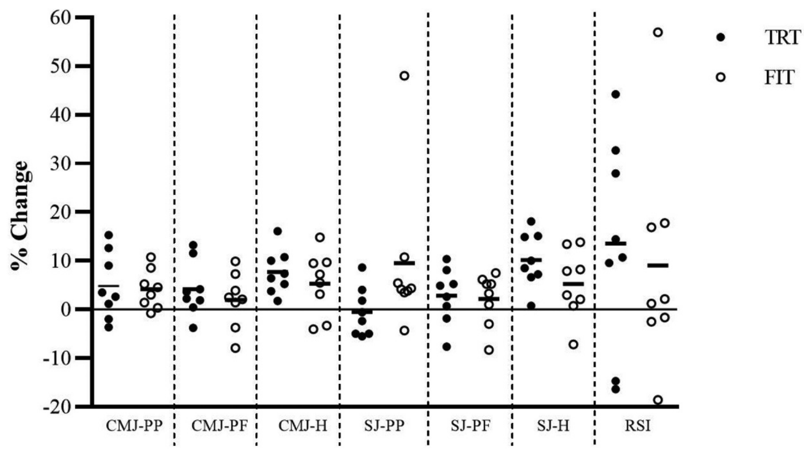

Figure 3. Individual % changes in all strength and power measures following the four-week training intervention in both Traditional Resistance Training (TRT) and Flywheel Inertia Training (FIT) groups.

studies though, our participants had no previously exposure to FIT. Therefore, our smaller increases are likely explained by the shorter training intervention we used since a longer training duration and more training sessions have a greater effect on adaptations to RT in adolescent males (Moran et al., 2017). Overall, our findings demonstrate that in well-trained youth male adolescent athletes, increases in lower-limb strength and power measures can occur within as litte as four weeks following either TRT or FIT.

Whilst limited research exists examining the effects of TRT or ERT in academy rugby players on RSI, our changes are greater than those previously reported within a similar population. Douglas et al. (2018) reported *trivial* changes after four weeks of either lower-body TRT (ES = 0.07) or accentuated eccentric loading (ES = −0.03) in resistance-trained academy RU players (19.4 years). In contrary to our study though, participants competed in weekly pitch-based training and match play which may have negatively impacted training adaptations. Indeed, previous research in RU athletes has found that the concurrent training prescription of both RT and endurance can impair strength improvement (Robineau et al., 2016). Interestingly though, despite our participants training programme not including plyometric exercises, the improvements in RSI are similar to those reported (ES = 0.58) in young male collegiate RU players following six weeks of plyometric training (Jeffreys et al., 2019). Since the RSI is associated with both concentric (Beattie et al., 2017) and eccentric (Kipp et al., 2018) forces, it is likely that both RT methods can positively influence performance. Thus, our results would suggest that both TRT and FIT are useful strategies for enhancing RSI in male academy RU players.

Although we reported no statistically significant between-group differences, between-group standardized differences marginally favoured TRT. The lower effects for FIT may be related to the novelty of the ERT stimulus for the participants. Tous-Fajardo et al. (2006) showed that individuals with more experience of FIT achieved greater eccentric and concentric peak forces than athletes of the same calibre who were novices to the exercise. Therefore, whilst our participants were familiarized with the FIT device, the short-term nature of our intervention may have limited its effectiveness compared to TRT. Additionally, the training intervention prescribed for the FIT group may have not been optimal due to their limited prior exposure to ERT. Stojanović et al. (2021) only included two flywheel exercises per session with a frequency of one to two times per week and a maximum of four sets per exercises, in which their participants, like ours, had not performed FIT previously. Therefore, our participants may have benefited from a less progressive training programme to facilitate adequate recovery and adaptation. Indeed, regular intense eccentric training in novice individuals has been shown to not allow for complete repair of muscle damage which subsequently impairs strength (Krentz & Farthing, 2010).

Our study is not without limitations. Firstly, as our data was collected from a small sample size, the results are generalizable only to similar samples of subjects and levels of competition. Secondly, due to the training intervention taking place within the off-season it was not within the scope of this study to investigate the effects of FIT on field-based measures of performance such as sprint speed and COD. However, such measurements could have provided further information regarding the transfer of FIT to sport specific RU tasks as greater improvements in speed and COD have been shown after FIT compared to TRT (Maroto-Izquierdo et al., 2017). Finally, whilst the focus of our study was on the lower-body, future research should also investigate the effects of upper-body FIT. This may have important implications for both performance and injury prevention for RU players since the upper-body is heavily involved in physical contact (i.e. tackling, scrums, fending, rucks and mauls) during training sessions and competition (Twist et al., 2012).

Conclusion

Our findings have important implications for practitioners working with elite male academy RU players. Considering the importance of developing strength and power in young male RU players, the training interventions used here provide guidance on the TRT and FIT methods that can be used to enhance these qualities. Whilst our findings showed that TRT may, overall, be favourable to FIT, it is important to note that the magnitude of this was marginal and therefore both are valuable RT methods to incorporate into training to improve lower-body strength and power. Future research investigating FIT in youth male athletes should examine the effects of different training prescription factors (e.g., intensity, volume and frequency) and the concurrent integration of both FIT and TRT to optimize strength, power and speed.

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ORCID

Ben Drury http://orcid.org/0000-0002-3828-3136

References

Argus, C. K., Gill, N. D., & Keogh, J. W. (2012). Characterization of the differences in strength and power between different levels of competition in rugby union athletes. *The Journal of Strength & Conditioning Research*, *26*(10), 2698–2704. https://doi.org/10.1519/JSC.0b013e318241382a

Beattie, K., Carson, B. P., Lyons, M., & Kenny, I. C. (2017). The relationship between maximal strength and reactive strength. *International Journal of Sports Physiology and Performance*, *12*(4), 548–553. https://doi.org/10.1123/ijspp.2016-0216

Beato, M., & Dello Iacono, A. (2020). Implementing flywheel (isoinertial) exercise in strength training: Current evidence, practical recommendations, and future directions. *Frontiers in Physiology*, *11*, 569. https://doi.org/10.3389/fphys.2020.00569

Behm, D. G., Young, J. D., Whitten, J. H., Reid, J. C., Quigley, P. J., Low, J., Li, Y., Lima, C. D., Hodgson, D. D., Chaouachi, A., Prieske, O., & Granacher, U.. (2017). Effectiveness of traditional strength vs. power training on muscle strength, power and speed with youth: A systematic review and meta-analysis. *Frontiers in Physiology*, *8*, 423. https://doi.org/10.3389/fphys.2017.00423

Bridgeman, L. A., McGuigan, M. R., Gill, N. D., & Dulson, D. K. (2020). Relationships between concentric and eccentric strength, jumping performance, speed and change of direction in academy rugby union players. *Sport Performance & Science Reports*. https://sportperfsci.com/relationships-between-concentric-and-eccentric-strength-jumping-performance-speed-and-change-of-direction-in-academy-rugby-union-players/

Cormack, S. J., Newton, R. U., McGuigan, M. R., & Doyle, T. L. (2008). Reliability of measures obtained during single and repeated countermovement jumps. *International Journal of Sports Physiology and Performance*, *3*(2), 131–144. https://doi.org/10.1123/ijspp.3.2.131

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine and Science in Sports and Exercise*, *42*(8), 1566–1581. https://doi.org/10.1249/MSS.0b013e3181cf818d

Cunningham, D. J., Shearer, D. A., Drawer, S., Pollard, B., Cook, C. J., Bennett, M., Russell, M., & Kilduff, L. P. (2018). Relationships between physical qualities and key performance indicators during match-play in senior international rugby union players. *PLOS ONE*, *13*(9), e0202811. https://doi.org/10.1371/journal.pone.0202811

Darrall-Jones, J. D., Jones, B., & Till, K. (2015). Anthropometric and physical profiles of English academy rugby union players. *The Journal of Strength & Conditioning Research*, *29*(8), 2086–2096. https://doi.org/10.1519/JSC.0000000000000872

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/ijspp.2013-0547

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. *The Journal of Strength & Conditioning Research*, *32*(10), 2750–2761. https://doi.org/10.1519/JSC.0000000000002772

Durguerian, A., Piscione, J., Mathieu, B., & Lacome, M. (2019). Integrating strength and power development in the long-term athletic development of young Rugby union players: methodological and practical applications. *Strength and Conditioning Journal*, *41*(4), 18–33. https://doi.org/10.1519/SSC.0000000000000452

Duthie, G. M., Pyne, D. B., Marsh, D. J., & Hooper, S. L. (2006). Sprint patterns in rugby union players during competition. *Journal of Strength and Conditioning Research*, *20*(1), 208–214. https://doi.org/10.1519/00124278-200602000-00034

Evans, K., & Williams, M. (2017). The effect of Nordic hamstring exercise on hamstring injury in professional rugby union. *British Journal of Sports Medicine*, *51*(4), 316–317. https://doi.org/10.1136/bjsports-2016-097372.84

Fontana, F. Y., Colosio, A. L., Da Lozzo, G., & Pogliaghi, S. (2017). Player's success prediction in rugby union: From youth performance to senior level placing. *Journal of Science and Medicine in Sport*, *20*(4), 409–414. https://doi.org/10.1016/j.jsams.2016.08.017

Furlong, L. A., Harrison, A. J., & Jensen, R. L. (2019). Measures of strength and jump performance can predict 30-m sprint time in rugby union players. *The Journal of Strength & Conditioning Research*. https://doi.org/10.1519/JSC.0000000000003170

Goulet-Pelletier, J. C., & Cousineau, D. (2018). A review of effect sizes and their confidence intervals, part I: The Cohen's d family. *The Quantitative Methods for Psychology*, *14*(4), 242–265. https://doi.org/10.20982/tqmp.14.4.p242

Harries, S. K., Lubans, D. R., Buxton, A., MacDougall, T. H., & Callister, R. (2018). Effects of 12-week resistance training on sprint and jump performances in competitive adolescent rugby union players. *The Journal of Strength & Conditioning Research*, *32*(10), 2762–2769. https://doi.org/10.1519/JSC.0000000000002119

Hopkins, W. G. (2015). Analysis of reliability with a spreadsheet (Excel Spreadsheet). Available at: sportsci. org/resource/stats/xrely. xls.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Jeffreys, M. A., Croix, M. B., Lloyd, R. S., Oliver, J. L., & Hughes, J. D.. (2019). The effect of varying plyometric volume on stretch-shortening cycle capability in collegiate male rugby players. *The Journal of Strength & Conditioning Research*, *33*(1), 139–145. https://doi.org/10.1519/JSC.0000000000001907

Jones, B., Weaving, D., Tee, J., Darrall-Jones, J., Weakley, J., Phibbs, P., Read, D., Roe, G., Hendricks, S., & Till, K. (2018). Bigger, stronger, faster, fitter: The differences in physical qualities of school and academy rugby union players. *Journal of Sports Sciences*, *36*(21), 2399–2404. https://doi.org/10.1080/02640414.2018.1458589

Kipp, K., Kiely, M. T., Giordanelli, M. D., Malloy, P. J., & Geiser, C. F. (2018). Biomechanical determinants of the reactive strength index during drop jumps. *International Journal of Sports Physiology and Performance*, *13*(1), 44–49. https://doi.org/10.1123/ijspp.2017-0021

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Krentz, J. R., & Farthing, J. P. (2010). Neural and morphological changes in response to a 20-day intense eccentric training protocol. *European Journal of Applied Physiology*, *110*(2), 333–340. https://doi.org/10.1007/s00421-010-1513-8

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. https://doi.org/10.1515/hukin-2017-0096

Martinez-Aranda, L. M., & Fernandez-Gonzalo, R. (2017). Effects of inertial setting on power, force, work, and eccentric overload during flywheel resistance exercise in women and men. *The Journal of Strength & Conditioning Research*, *31*(6), 1653–1661. https://doi.org/10.1519/JSC.0000000000001635

Moran, J., Sandercock, G. R., Ramírez-Campillo, R., Meylan, C., Collison, J., & Parry, D. A. (2017). A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training. *Journal of Sports Sciences*, *35*(11), 1041–1051. https://doi.org/10.1080/02640414.2016.1209306

Owen, C., Till, K., Weakley, J., Jones, B., & Cortis, C.. (2020). Testing methods and physical qualities of male age grade rugby union players: A systematic review. *PLOS ONE*, *15*(6), e0233796. https://doi.org/10.1371/journal.pone.0233796

Pedley, J. S., Lloyd, R. S., Read, P., Moore, I. S., & Oliver, J. L. (2017). Drop jump: A technical model for scientific application. *Strength and Conditioning Journal*, *39*(5), 36–44. https://doi.org/10.1519/SSC.0000000000000331

Raya-González, J., Castillo, D., de Keijzer, K. L., & Beato, M. (2021). The effect of a weekly flywheel resistance training session on elite U-16 soccer players' physical performance during the competitive season. A randomized controlled trial. *Research in Sports Medicine*, 1–15. https://doi.org/10.1080/15438627.2020.1870978

Robineau, J., Babault, N., Piscione, J., Lacome, M., & Bigard, A. X. (2016). Specific training effects of concurrent aerobic and strength exercises depend on recovery duration. *The Journal of Strength & Conditioning Research*, *30*(3), 672–683. https://doi.org/10.1519/JSC.0000000000000798

Sabido, R., Pombero, L., & Hernández-Davó, J. L. (2019). Differential effects of low vs. high inertial loads during an eccentric-overload training intervention in rugby union players: A preliminary study. *The Journal of Sports Medicine and Physical Fitness*, *59*(11), 1805–1811. https://doi.org/10.23736/s0022-4707.19.09425-8

Smart, D. J., & Gill, N. D. (2013). Effects of an off-season conditioning program on the physical characteristics of adolescent rugby union players. *The Journal of Strength & Conditioning Research*, *27*(3), 708–717. https://doi.org/10.1519/JSC.0b013e31825d99b0

Soomro, N., Sanders, R., Hackett, D., Hubka, T., Ebrahimi, S., Freeston, J., & Cobley, S. (2016). The efficacy of injury prevention programs in adolescent team sports: A meta-analysis. *The American Journal of Sports Medicine*, *44*(9), 2415–2424. https://doi.org/10.1177/0363546515618372

Stojanović, M. D., Mikić, M., Drid, P., Calleja-González, J., Maksimović, N., Belegišanin, B., & Sekulović, V. (2021). Greater power but not strength gains using flywheel versus equivolumed traditional strength training in junior basketball players. *International Journal of Environmental Research and Public Health*, *18*(3), 1181. https://doi.org/10.3390/ijerph18031181

Till, K., Weakley, J., Read, D. B., Phibbs, P., Darrall-Jones, J., Roe, G., Chantler, S., Mellalieu, S., Hislop, M., Stoke, K., Rock, A., & Jones, B. (2020). Applied sport science for male age-grade Rugby union in England. *Sports Medicine – Open*, *6*(1), 14. https://doi.org/10.1186/s40798-020-0236-6

Till, K., Darrall-Jones, J., Weakley, J. J., Roe, G. A., & Jones, B. L. (2017). The influence of training age on the annual development of physical qualities within academy rugby league players. *The Journal of Strength & Conditioning Research*, *31*(8), 2110–2118. https://doi.org/10.1519/JSC.0000000000001546

Twist, C., Waldron, M., Highton, J., Burt, D., & Daniels, M. (2012). Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *Journal of Sports Sciences*, *30*(4), 359–367. https://doi.org/10.1080/02640414.2011.640707

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. https://doi.org/10.1123/ijspp.1.3.293

Van Hooren, B., & Zolotarjova, J. (2017). The difference between countermovement and squat jump performances: A review of underlying mechanisms with practical applications. *The Journal of Strength & Conditioning Research*, *31*(7), 2011–2020. https://doi.org/10.1519/JSC.0000000000001913

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

Weakley, J. J., Till, K., Darrall-Jones, J., Roe, G. A., Phibbs, P. J., Read, D. B., & Jones, B. L. (2019). Strength and conditioning practices in adolescent rugby players: Relationship with changes in physical qualities. *The Journal of Strength & Conditioning Research*, *33*(9), 2361–2369. https://doi.org/10.1519/JSC.0000000000001828

Westing, S. H., Seger, J. Y., Karlson, E., & Ekblom, B. (1988). Eccentric and concentric torque-velocity characteristics of the quadriceps femoris in man. *European Journal of Applied Physiology and Occupational Physiology*, *58*(1–2), 100–104. https://doi.org/10.1007/BF00636611