ENHANCING THE USE OF FLYWHEEL TRAINING IN FIELD BASED TEAM SPORTS

By

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Abstract

Flywheel training is a resistance training methodology that has been implemented in sport to enhance strength, performance, and reduce likelihood of injury. This thesis appraises the literature, studies how sports practitioners apply flywheel training, and investigates how flywheel training affects strength and power amongst athletes. Chapter 1 briefly introduces flywheel training. Chapter 2 highlights discrepancies in the quality of published reviews and supports the use of flywheel training for enhancing strength and power with healthy and athletic populations. Chapters 2 and 3 identify that limited evidence is available on unilateral flywheel exercises, even though a large proportion of practitioners apply them. Chapters 2 and 3 also clearly highlight a strong bias in flywheel research and practice towards male populations and therefore less remains known about how flywheel training influences strength of female athletes. Since Chapters 2 and 3 identified limited knowledge on unilateral hamstring exercises and their relevance to performance, Chapter 4 investigates how manipulating training variables influences power across exercises. Chapter 5 reports that unilateral hamstring exercises do not significantly enhance isometric or eccentric hamstring strength but do significantly improve flywheel specific power. Considering the strong bias towards research amongst male athletes, Chapter 6 demonstrates that 7 weeks of flywheel or traditional resistance training similarly enhance isokinetic and isometric strength of female athletes. A key finding is that two weekly sessions of flywheel training can enhance strength of female athletes during a competitive in-season period. Overall, the thesis provides an up-to-date review of the literature and its limitations, a greater understanding of how practitioners use flywheel training and their perceptions, further study into the application and monitoring of unilateral flywheel training specific for development of hamstrings strength and power, and a comparison of flywheel and traditional resistance training effects on strength amongst a female athlete cohort.

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List of abbreviations

%RM; Percentage of repetition maximum

1RM; One repetition maximum

ACL; Anterior cruciate ligament

AEL; Accentuated eccentric loading

AMSTAR; Assessing the Methodological Quality of Systematic Review

ANCOVA; Analysis of covariance

ANOVA; A repeated measures analysis of variance

BFlh; Biceps Femoris long head

CI; Confidence Intervals

CMJ; Countermovement jump

COD; Change of direction

CSA; Cross-sectional area

CV; Coefficient of variation

DOMS; Delayed onset muscular soreness

d; Cohen’s *d*

E:C; Eccentric:Concentric

EIMD; Exercise induced muscle damage

ES; Effect size

GRADE; Grading of Recommendations Assessment, Development, and Evaluation

Hz; Hertz

ICC; Intraclass correlation coefficient

IGF-1; Insulin-like growth factor-1

Kg; Kilograms

M; metres

MVIC; Maximal voluntary isometric contraction

NHE; Nordic hamstring exercise

Nm; Newton metre

NSCA; National Strength and Conditioning Association

PAP; Post activation potentiation

PAPE; Post activation performance enhancement

PAR-Q; Physical activity readiness-questionnaire

PICO; Participant-intervention-comparison-outcome

PRISMA; Preferred Reporting Items for Systematic Reviews and Meta-analysis

RDL; Romanian deadlift
RM; Repetition maximum
RTP; Return to play
S&C; Strength and conditioning
SEM; Standard error of measurement
SSC; Stretch-shortening cycle
SD; Standard deviation
SPM; Statistical parametric mapping
T2; Transverse relaxation time
W; Watts

List of Figures

Figure 1.1 Example of a flywheel device with key features labelled 8
Figure 1.2 Flywheel lateral squat with handle and wearing a vest 13
Figure 2.1 Flow diagram of the study retrieval process 26
Figure 3.1 Comparing practitioners' opinions and perceptions regarding flywheel training evidence based-guidelines, necessity for familiarisation, and for strength and injury prevention 48
Figure 3.2 Comparing practitioners' opinions and perceptions of flywheel training for acute and chronic sport performance enhancement 49
Figure 3.3 Comparing practitioners' opinions and perceptions of flywheel training & traditional resistance training 49
Figure 3.4 Flywheel exercises that have been programmed by elite soccer practitioners 50
Figure 3.5 Comparing practitioners' prescription of flywheel training during the weekly micro-cycle during pre-season and in-season 50
Figure 3.6 The prerequisites to flywheel training according to therapists with responses tiered by the level of athlete 52
Figure 3.7 Comparing therapists opinions on the efficacy of flywheel training for reducing likelihood of non-contact muscular injury and enhancing strength 53
Figure 3.8 The use of flywheel training for muscular, tendon, and ligament prehabilitation and rehabilitation amongst therapists working in sport 53
Figure 3.9 The use of upper body flywheel exercises amongst therapists in sport 54
Figure 3.10 The use of lower body flywheel exercises amongst therapists in sport 55
Figure 4.1 Experimental design. Min = minutes. 6 + 2 repetitions = 6 maximal repetitions with 2 initial repetitions utilized to initiate the movement 72

Figure 4.2 The equipment utilised for the unilateral leg curl and unilateral hip extension 75
Figure 4.3 Concentric and eccentric peak power during unilateral flywheel knee flexion. *Statistically significant (p < 0.05) difference between concentric and eccentric peak power. Black dots = eccentric peak power values. White dots = concentric peak power values 76
Figure 4.4 Concentric and eccentric peak power output during unilateral flywheel hip extension. *Statistically significant (p < 0.05) difference between concentric peak power. * = Statistically significant (p < 0.05) difference between eccentric peak power. Black dots = eccentric peak power output. White dots = concentric peak power output 77
Figure 4.5 The eccentric:concentric (E:C) ratio for unilateral flywheel leg curl and hip extension exercises.* = Statistically significant ($p < 0.05$) difference between E:C ratio 78
Figure 5.2 Peak power during flywheel hip extension training 96
Figure 5.3 Peak power during flywheel unilateral leg curl training 96
Figure 5.4 The time-effects of 6-week flywheel hamstring training on knee-flexor eccentric and isometric peak torque 98
Figure 5.5 Mean (solid lines) ± SD (dashed lines) isokinetic eccentric knee flexion torque at pre and post six weeks of unilateral flywheel hamstring training (trained) or control (untrained). The thick black line and right-hand axis represent the statistical parametric mapping two-way repeated measures ANOVA time-limb interaction effect. Statistical significance ($p < 0.05$) would be indicted by the crossing of the thin dashed black line (critical threshold) at the top of the figure 98
Figure 5.6 The time-effect of 6-week flywheel hamstring training on peak power during unilateral flywheel hip extension. (N = 11, limbs tested = 22). * = $p < 0.05$ 99
Figure 5.7 The time-effect of 6-week flywheel hamstring training on peak power during unilateral flywheel leg curl.). * = $p < 0.05$ (N = 11, limbs tested = 22) 100
Figure 6.1 CONSORT diagram 111
Figure 6.2 The flywheel squat and split squat 113
Figure 6.3 Concentric strength increases after 7 weeks of flywheel or traditional resistance training. * = P < 0.05. Nm = newton metre 114
Figure 6.4 Isometric strength increases after 7 weeks of flywheel or traditional resistance training. * = P < 0.05. Nm = newton metre 115

List of tables

Table 2.1 Justification for excluded studies from reviews 23
Table 2.2 Justification for excluded reviews 24
Table 2.3 Summary of reviews that investigated the effects of flywheel training on physical capacity and strength 27
Table 2.4 Overall results of the AMSTAR 2 and GRADE recommendations for systematic reviews and meta-analyses 29
Table 2.5 Overall results of the AMSTAR 2 & GRADE recommendations for narrative reviews 29
Table 3.1 The classification by tier and sport of respondents included for the TFT questionnaire 47
Table 4.1 Flywheel unilateral hip extension *post-hoc* tests for the repeated measures ANOVAs 77
Table 4.2 Unilateral flywheel leg curl and hip extension between session reliability 79
Table 5.1 Post Hoc tests for flywheel leg curl and hip extension tests. CI = Confidence interval, $p < 0.05$ 100
Table 6.1 Training intervention for both flywheel and traditional resistance training groups 113

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DEDICATION

I dedicate this PhD to my grandfather, my hero who will always have an everlasting place in my heart.

TABLE OF CONTENTS

Abstract ii

List of abbreviations iii

List of figures iv

List of tables vi

Publications vii

Presentations viii

Acknowledgements ix

Dedication x

Table of contents xi

Chapter 1 – Background information on flywheel training 1

1.1 What is resistance training? 2

1.2 Eccentric training 3

1.3 How does the body respond to eccentric muscle actions? 3

1.4 How is eccentric resistance training applied in practice? 4

1.5 The history of flywheel training 6

1.6 How flywheel devices work 7

1.7 Training load management with flywheel training 10

1.8 The use of flywheel devices in warm ups for performance enhancement 11

1.9 Integration of flywheel training to reduce likelihood of non-contact anterior cruciate ligament injury risk 12

1.10 Integration of flywheel training to reduce likelihood of hamstring strain injury risk 13

1.11 Integration of different training methodologies to reduce hamstring likelihood of injury risk 14

1.12 Aims of thesis and summary 15

Chapter 2 – The effect of flywheel training on strength and physical capacities in sporting and healthy populations: An umbrella review 18

2.1 Abstract 19

2.2 Introduction 20

2.3 Methods 21

2.4 Results 26

2.5 Discussion 29

2.6 Limitations and future directions 30

2.7 Conclusion 40

Chapter 3 – The perception and application of flywheel training by practitioners working in field-based team sport 42
3.1 Abstract 43
3.2 Introduction 44
3.3 Methods 46
3.4 Results 47
3.5 Discussion 55
3.6 Limitations and future directions 65
3.7 Conclusion 66
Chapter 4 – The effect of flywheel inertia on peak power and its inter-session reliability during two unilateral hamstring exercises: leg curl and hip extension 67
4.1 Abstract 68
4.2 Introduction 69
4.3 Methods 72
4.4 Results 76
4.5 Discussion 79
4.6 Limitations and future directions 85
4.7 Conclusion 86
4.8 Practical applications 86
Chapter 5 – The effects of unilateral flywheel hip extension and leg curl training on isometric, isokinetic, and flywheel-based outcomes 88
5.1 Abstract 89
5.2 Introduction 90
5.3 Methods 92
5.4 Results 97
5.5 Discussion 99
5.6 Limitations and future directions 103
5.7 Conclusion 104
5.8 Practical applications 104
Chapter 6 – Comparing the effects of flywheel training and barbell training on isokinetic and isometric strength amongst female team sport athletes 105
6.1 Abstract 106
6.2 Introduction 107
6.3 Methods 109

6.4 Results 114
6.5 Discussion 115
6.6 Limitations and future directions 119
6.7 Conclusion 120
6.8 Practical applications 121
Chapter 7 – Synthesis of findings 122
7.1 Introduction 123
7.2 Discussion 124
7.3 Limitations and future directions 129
7.4 Practical applications 131
Chapter 8 – Bibliography 133
Chapter 9 – Appendix 159
9.1 Questionnaire (Flywheel in Soccer) 160
9.2 Questionnaire (Flywheel and Therapists in Sport) 164

Chapter 1 - Introduction

1.1. What is resistance training?

Resistance training methodologies have been shown to profoundly alter force production capabilities within athletes [1,2]. Resistance training interventions can be performed involving concentric (shortening under (active) tension), isometric (no change in length under (active) tension), and eccentric (lengthening under (active) tension) phases, concentric only, isometric only, eccentric only, or overloading one phase of the exercise (e.g., eccentric overload) [3–5]. Traditionally, resistance training involves the lifting of a weight (concentric muscle action) and lowering of a weight (eccentric muscle action) - with any pause before, between, or after which involves muscle tension without movement known as an isometric muscle action [6].

The use of a constant load (barbells, dumbbells, kettlebells) is commonplace to increase the demands of resistance training amongst healthy and injured sporting populations [1,7]. The neuromuscular system allows for a greater load to be lifted during the eccentric muscle action in comparison to the concentric muscle action during traditional resistance training. Evidence suggests that when loaded to concentric and eccentric maximal repetitions respectively, no differences exist between the two muscle actions for eliciting endocrine adaptations (i.e., growth hormone) [8]. As mentioned previously though, traditional resistance training is typically performed with the same load during both concentric and eccentric phases – thereby reducing some endocrine responses during traditional resistance training [8]. Evidence has indeed suggested that resistance training methodologies with a pronounced, accentuated, or prolonged eccentric component can provide desirable benefits and outcomes for athletic populations [1,9,10].

1.2. Eccentric training

Prior to exploring the use of eccentric training modalities or the incorporation of accentuated eccentric loading, it is important to briefly explore what eccentric muscle actions are, what is understood about them, and how the body responds to high intensity resistance training.

Eccentric (lengthening) muscle actions occur when external force applied exceeds the force produced by the muscle, leading to forced lengthening of the muscle-tendon system [11]. Tasks ranging from downhill running, walking downstairs, and jumping all rely on the appropriate execution of eccentric muscle actions. A variety of eccentric exercises can be performed. Examples include isotonic (i.e., additional load) or isokinetic (*i.e.,* constant speed) exercises [12]. Indeed, they are an integral part of daily movements and athletic endeavours as they support the body against gravity and store elastic recoil energy in preparation for concentric muscle actions. When compared to concentric muscle actions, eccentric muscle actions are able to elicit greater forces when matched for angular velocity [11]. Eccentric muscle actions also differ at the muscle belly, tendon, and cortical level to concentric muscle actions [13,14]. Specifically, the most well accepted differences between concentric and eccentric muscle actions occur at the nervous system and within the muscle itself [15]. From a force-velocity relationship perspective, the role of titin is likely to play a central role in explaining increased force production during eccentric muscle actions (for further information please see reviews - [15,16]).

1.3. How does the body respond to eccentric muscle actions?

To date, little still remains known about the mechanisms behind the morphological, cellular, and molecular responses to muscle damaging eccentric exercise [17,18]. Nonetheless, it is well recognised that high intensity eccentric resistance training typically induces a high degree of muscle damage [19–21]. Indeed, high intensity eccentric exercise can induce delayed onset muscular soreness (DOMS) unless the duration, frequency, and intensity is appropriately managed [12]. The damage induced during eccentric training is proposed to be due to heterogeneity in sarcomere lengthening, leading to disrupted sarcomeres [22]. This theory is generally accepted and supported by evidence that muscle length during the eccentric muscle action is critical in determining damage sustained [22]. The combination of high force and reduced recruitment of fibres causes a high mechanical stress on the involved structures – likely leading to microtears within the muscle fibres [23]. At the microscopic level, intense and naïve eccentric training leads to widespread Z-line streaming with myofibrillar and sarcolemma disruption [24]. Damage to the muscle can be highlighted by the presence of sarcoplasmic proteins (i.e., creatine kinase) within the bloodstream or by the cytoplasmic accumulation of proteins that are typically not present within muscle fibres [24,25]. Additionally, damage to the extracellular matrix and connective tissue also occurs after intense eccentric training with such changes most prominent 2-3 days post-exercise but lasting up to 5-7 days [12]. Studies in both humans and animals have shown that type II muscle fibres are most susceptible to damage after eccentric exercise [14,23]. Such a phenomenon can be explained by the differences in the Z-line and fibre type specific protein isoforms (titin) of type II fibres in comparison to type I fibres [16]. Type II fibres also have a reduced oxidative capacity and a lower ability to regulate calcium homeostasis, potentially influencing responses [11]. From a practical perspective, eccentric training can induce exercise induced muscle damage (EIMD) which presents with a variety of symptoms that can influence training negatively [26].

Although changes in perceived muscle soreness, range of motion, swelling, force generating capacity, and proprioceptive function have been long established, the response to eccentric exercise and it's side effects remain relatively poorly understood from a mechanistic perspective [11]. There is a strong evidence base to suggest that an initial bout of eccentric exercise protects against EIMD in following bouts – a phenomenon known as the repeated bout effect [27]. The repeated bout effect is characterised by a relative reduction of sarcoplasmic proteins within the blood, swelling, and functional deficits present in the following exposure [11]. Even though such positive changes can be seen after a singular exposure, it is likely that multiple bouts are more beneficial with such protective benefits lasting for months [28–30]. Importantly, the severity of the initial bout is not determining of the level of protection on subsequent bouts [11,31]. Indeed, although eccentric training and thereby the use of flywheel training is often viewed as damaging and concerning due to its negative effects, there are appropriate systems and methods to implement such training without inducing the negative side effects associated with high intensity resistance training [17,32,33]. Indeed, the application of high intensity eccentric training has shown a lot of promise and is becoming more and more practically integrated within sport [4,34,35].

1.4. How is eccentric resistance training applied in practice?

As highlighted previously, the benefits of resistance training applied appropriately and progressively lead to significant improvements in strength, power, and sport performance [11]. Indeed, the prescription of high intensity resistance training is likely to elicit desirable neuromuscular and tendon adaptations that improve strength and power performance [36–38]. Nonetheless, the loads that can be applied with traditional resistance training are often limited by concentric strength. Practitioners have therefore incorporated eccentric-only resistance training to enable the use of greater loads, showing significant strength and hypertrophy improvements [3]. Although eccentric-only training, such as the Nordic hamstring exercise (NHE) has received great interest and can benefit strength and injury outcomes with athletes [7,39], such training does not utilise the stretch-shortening cycle (SSC) [3]. Indeed, the application of resistance training that involves the stretch shortening cycle with an accentuated eccentric phase is not only more specific to sporting actions but has also elicited greater outcomes than traditional resistance training [40,41]. The application of resistance training with an accentuated eccentric load (AEL) involves resistance training where the prescribed eccentric load is superior to the concentric load with minimal interruption to the profile of the exercise [33]. An example of an AEL exercise is where additional load is used for the eccentric phase of a bench press exercise, which is then removed manually by a third party or with weight releasers before the exerciser commences the concentric phase. Many different methods to achieve eccentric overload have been proposed in practice and in the literature. In fact, AEL training, achieved via computer-guided eccentric overload was proposed over 20 years ago [42], and has seen many iterations involved in sport, elderly care, and for rehabilitation over the years since [43–46]. Although AEL resistance training has shown to favourably enhance muscular qualities [17,42,43] and performance [47], evidence on exercise selection, load prescription, and methodology remains limited [33].

The most common implementation of AEL is to utilise supramaximal eccentric loads relative to the concentric phase [33]. The use of supramaximal AEL training takes advantage of the higher force generation capabilities and selective recruitment of high threshold motor units associated with eccentric muscle actions [13]. While some evidence suggests supramaximal accentuated eccentric loading bench press protocols can acutely enhance concentric performance [48], others have highlighted that the use of supramaximal AEL protocols may elicit too much fatigue and actually decrease concentric force production [49]. When looking at the improvement of acute performance, the balance between potentiation and fatigue induced is crucial and must be carefully balanced [50]. When considering chronic adaptations to training, the use of supramaximal AEL training has shown to elicit mixed responses for strength and hypertrophy outcomes [33,40]. Specifically, within a population of untrained females, a 27% increase in quadriceps strength was seen on average after only 7 days of leg extension eccentric overload (100-110/60% of concentric 1 repetition-maximum [1RM]) training in comparison to a traditional resistance training (60% 1RM) programme (with consistent concentric and eccentric loads) [51]. Important caveats are that the protocol duration was very short (7 days), the traditional resistance training protocol used a very low % of 1RM and a high volume (72 repetitions), which may limit strength adaptations. A longer protocol (10 weeks; two sessions per week) involving healthy untrained males and females reported no difference between traditional (80% 1RM) and supramaximal AEL (eccentric/concentric 120/80% 1RM) leg extension training on concentric quadriceps strength [52]. More recently, a 5 week intervention investigated the effects of using eccentrically overloaded leg press and leg extension in comparison to traditional leg press and leg extension amongst healthy males [40]. Specifically, AEL training observed significant increases in quadriceps voluntary muscle activation and isometric strength in comparison to the traditional loading group [40]. The application of alternative accentuated eccentric loading protocols including banded plyometrics (jumps) and submaximal AEL protocols has also shown to acutely and chronically enhance strength, power, and sport performance [33]. Nonetheless, further considerations when applying high intensity resistance training to generate accentuated eccentric loading must be made. For example, a recent study showed that roughly a 10% difference was seen during iso-velocity maximal squatting between peak eccentric and isometric forces [46], which differs from the 30% difference reported during single joint exercise [53]. The values present in the literature differ greatly from isolated muscle forces seen in earlier animal studies, where eccentric forces achieved up to 80% of isometric forces [54]. Differences between multi-joint and single-joint movements are likely to be associated with the greater instability and altered activation levels associated with the performance of multi-joint movements [55]. Additionally, further research into how AEL training incorporates tools, kits, technologies and devices must be done to appreciate practicality, cost, magnitude of overload, the culture, and context of application when training with such methods [33,56,57]. Indeed, some considerable limitations remain with the application of such training and assessment methods [46]. Specifically, the major barriers limiting application of such training amongst elite sporting practitioners are the impracticality and safety concerns, greater athlete and coach perceived muscle soreness, and perceived mental fatigue associated with such methods [56]. An alternative to traditional supramaximal AEL protocols which has shown to safely and effectively elicit cyclical high intensity concentric and eccentric muscle actions is flywheel resistance training [58].

1.5. The history of flywheel training

Although flywheel devices have been researched for over one hundred years [59], there is still much to discover about their most effective use in team sports. In the 1990's, a series of developments and design innovations occurred [58], leading to the emergence of flywheel training in its current form (Figure 1.1). This novel approach was used to combat the deleterious effects of prolonged space travel [60]. Early work completed on flywheel training focused on describing and discussing the benefits of its unique concentric and eccentric resistance [58]. Specifically, researchers became interested in the eccentric phase, particularly "eccentric overload" within team sports over 20 years ago [61]. Researchers have often aimed to compare flywheel training with traditional resistance training methods. Flywheel training seem to report favourable outcomes in neuromuscular adaptations, strength, and power with a range of sedentary and active males or females [62–65]. Indeed, flywheel training has seen an exponential increase in use for both testing and training over the last 20 years [66].

1.6. How flywheel devices work

Flywheel resistance training is an adaptable and effective resistance training methodology that has made its way into a variety of strength and conditioning programmes for healthy, athletic and injured populations [66,67]. The scope of this PhD is to enhance the application of flywheel training within team sports and is not to extensively discuss the different types, functions, and purposes of flywheel designs and systems. Nonetheless, to facilitate a discussion of how to enhance the application of flywheel training the following focus is to briefly describe how flywheel devices work.

Firstly, some differences exist between traditional and flywheel resistance training. Traditional resistance training relies on load mostly being provided from the gravitational force acting upon a mass (bodyweight, additional weights) [45]. Although traditional resistance training methods (consisting of weight stack machines and free weights) are the most common types of equipment used, they have some practical limitations [56]. Specifically, the typical constant external loads used do not accommodate for strength capacity at different ranges of motion and muscle actions [68]. Some methods including spotters and weight releasers have been implemented to counteract such limitations but can still be considered impractical [45]. Flywheel training is one method that is considered a practical alternative to allow for greater eccentric loading [62]. Specifically, the load experienced during flywheel resistance training is mostly provided by the inertial force of a rotating mass [58]. Flywheel training utilises the principles of rotational dynamics (motion and forces causing objects to rotate about an axis) and kinetic energy (the form of energy possessed by an object due to its motion) [66].

During flywheel resistance training, the work performed is transformed in kinetic energy from the concentric phase to the eccentric phase. Although the flywheel device also has a weight (for example, coming from its shaft and ball bearings), although there is no gravitational force resistance component other than the mass of the equipment used (*i.e.,* harness, strap, etc.) (Figure 1.1). For example, the estimated moment of inertia of the machine used in the present thesis was 0.0011 $kg \cdot m^2$. With flywheel devices, the mass added provides the resistance (typically in the form of discs or weights which are rotated). Newton's second law for angular motion describes this behaviour:

$$T = I \cdot \alpha$$

T = torque (Nm)
I = angular moment of inertia ($kg \cdot m^2$)
α = angular acceleration ($rad \cdot s^{-2}$)

Torque (T) is the angular expression of a force (F) applied at a perpendicular distance r (lever arm) from the centre of rotation:

$$T = F \cdot r$$

With flywheel devices, the force (F) is applied to a chord or strap, which wraps around the flywheel shaft at a distance (r) (shaft radius) from the axis of rotation (as shown in Figure 1.1).

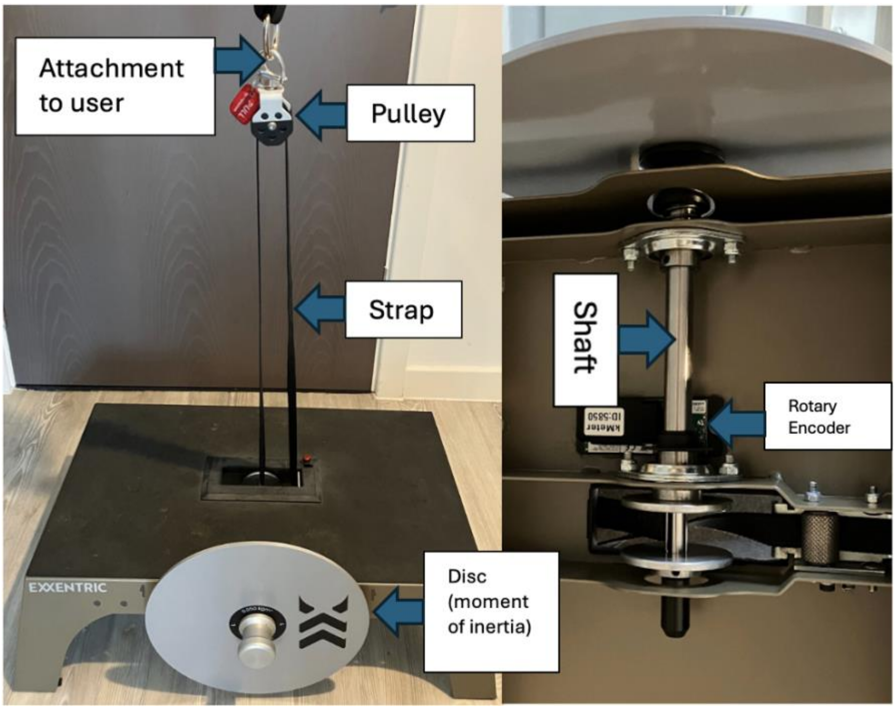


Figure 1.1 Example of a flywheel device with key features labelled.

As with all training, flywheel training is based on two independent physical entities: *force* (*F*) and *velocity* (*v*) and thereby any of their potential combinations.

Power is the product of force and velocity:

$$P = F \bullet v$$

A key point about flywheel devices is that they do not require a minimum resistance to initiate movement and therefore also do not have a maximum load (related to the user) [69]. Flywheel devices are therefore highly variable in resistance provided. The resistance provided by flywheel devices is dependent upon two factors: I (angular moment of inertia [$kg \cdot m^2$]) and α (angular acceleration [$rad \cdot s^{-2}$]). The above features make flywheel training useful as a varied high intensity stimulus but a more difficult methodology to manage effectively [70,71].

Indeed, although flywheel training can elicit high mechanical tension, essential for stimulating signalling cellular pathways that stimulate hypertrophy [72], it can be difficult to manage training intensity [69]. When performing such intense exercise, cytokines naturally increase, and local proliferation of insulin-like growth factor-1 (IGF-1) and myogenic regulatory factors occurs to manage cell activation during myogenesis and muscle regeneration [11]. Little remains known about the acute molecular responses to flywheel training specifically, with only one study performed on trained male populations to date [73]. Similarly to the eccentric resistance training presented previously, flywheel training influences local and systemic markers involved in structural and functional adaptation of skeletal muscle [73]. Specifically, increased plasma concentrations of muscle damage markers were present from 2 to 48 hours after flywheel training with trained males [73]. Similarly, but in untrained populations, flywheel training acutely induced muscle damage and inflammation [19,74]. The aforementioned findings are expected and in line with previous studies on the effects of high intensity eccentric resistance training [11]. In comparison to traditional resistance training protocols (that were similar in intensity and volume) [75,76], flywheel training also seems to elicit similar muscle damage and inflammation [25]. When analysing differences between seated flywheel squats (could also be interpreted as a leg press) and barbell squats amongst strength-trained men, greater force and quadriceps muscle use was seen with the flywheel condition [64]. Over the 5 sets (of 10 repetitions), flywheel training also allowed participants to achieve a greater range of motion and a faster eccentric phase than traditional back squats [64]. Although the limited literature reports no major differences between high-intensity resistance training and flywheel training [77], practitioners report concerns when applying high-intensity eccentric resistance training such as flywheel training [10,56]. Therefore, key considerations must be made for the monitoring and management of flywheel training.

1.7. Training load management with flywheel training

Indeed, the management of load is crucial to periodising training with the aim of enhancing performance and mitigating overuse injury occurrence and severity [69]. With traditional resistance training, the management of prescribed load has been based on measures of maximal strength (One-repetition maximum [1-RM]) and concentric linear velocity [69]. The monitoring of flywheel exercise remains difficult and has recently progressed significantly due to the development of technology – specifically encoders [78]. The most common type of encoder utilised to monitor flywheel resistance training are rotary encoders (shown in Figure 1.1) [70]. Rotary encoders are a type of position sensor used to determine the angular position of a rotating shaft [79]. Rotary encoders convert rotational mechanical displacement (by monitoring position and speed) into electrical signals [79]. The monitored pulse string that is based on the mechanical (rotational) displacement of the shaft allows for determination of mechanical outputs during flywheel resistance training [79]. Although such technology only provides information about the angular velocity of the flywheel device and not the kinematic information about the user, it allows for practical and informative objective data that can be used to monitor flywheel training in team sports [69]. Indeed, the quantification of progress through monitoring of objective data is a key aspect of understanding flywheel training [80]. Additionally, the use of real-time feedback on measures such as peak power can provide instantaneous feedback and drive intent and subsequently enhance training outcomes with athletes [66]. The application of flywheel devices and technology has grown in sport not only as a training modality but also as a method to monitor and test athletes [69]. The advancements made in flywheel technology allow for the measurement of outputs such as power, velocity, and force (as mentioned previously in the chapter). Overall, the integration of flywheel devices may provide real-time feedback on progress to aid coaches and athletes in making informed training decisions [69]. Peak power can be used to evaluate athletic performance and an athlete's physical capabilities [69,81]. Indeed, some evidence suggests that peak power measures derived from flywheel squats may be a valid and reliable assessment of strength and power with team sport athletes [81]. As alluded to previously, power is derived of two measures (force and velocity). Study into the concentric and eccentric inertia-velocity relationships has shown that as flywheel moments of inertia increases, concentric and eccentric velocity decrease [71,82]. Nonetheless, and in line with previous findings in supramaximal AEL isovelocity squatting [46], when similar high moment of inertias are prescribed (higher force), no significant difference in concentric velocity is seen [71]. Amongst a population of active males, who only performed one familiarisation session, it was reported that flywheel moment of inertia has no significant effects on peak power measures during flywheel squats [71]. This is in contrast to previous evidence that suggested that as flywheel moment of inertia increased, changes in peak power were seen accordingly [83]. Although further study is needed on the monitoring of flywheel training, the current literature suggests that velocity or power could be used to monitor flywheel training and that most studies and practitioners use power measures when applying flywheel resistance training [80]. Most of the studies on flywheel training and its relationships with moments of inertia have used the squat. Indeed, little remains known about the effect of moment of inertia alterations on unilateral exercises and their reliability even though they are commonly prescribed in practice [84]. In particular, the influence of inertia on performance measures, such as peak power, is of particular interest for the programming of flywheel training. Considering factors such as moment of inertia and peak power allow for the management of training programmes through assessment between exercises [80]. Indeed, by providing additional data on how a group or individual respond to flywheel training it is likely that coaches can enhance training and athletic performance [71].

1.8. The use of flywheel devices in warm ups for performance enhancement

As alluded to previously, flywheel training is applied in a variety of methods. Indeed, flywheel training has been applied to acutely enhance performance through post-activation performance enhancement (PAPE) or post-activation potentiation (PAP) protocols. PAP is a phenomenon that involves short-term enhancement of muscular capacity after a potentiation activity [85]. PAPE is based on the same premise (that a pre-conditioning activity enhances subsequent performance) but is typically measured in sports science using sporting tasks or strength tests [86]. Several underpinning pathways may play a role in the enhancement of athletic performance during PAPE protocols, ranging from changes within muscle to alterations in spinal pathways [86,87]. Importantly for sports scientists, pre-conditioning activities are likely to increase core body temperature, blood flow, and prepare the neuromuscular system to perform high-intensity actions [87]. PAPE protocols can therefore be integrated into training or (carefully) into competition preparation [86]. Nonetheless, little remains known about the exact mechanisms behind this phenomenon [87]. A large variety of methods have been implemented within PAPE protocols, ranging from maximal isometric to heavy dynamic high-intensity resistance exercises (i.e., >85% 1RM) [88,89]. In line with a lot of the research on flywheel training, interest into flywheel exercises as a part of PAPE protocols has grown significantly. The integration of flywheel training into PAPE protocols is warranted because of their ease of use (portability), variety in exercise prescription (versatility), and because they facilitate high-intensity (concentric and eccentric) exercise [85]. Additionally, flywheel training does not require prolonged familiarisation periods for athletes (including those without significant resistance training experience) [83,90]. Such high-intensity training has repeatedly been shown to acutely improve force and power production, which fundamentally underpins sporting actions [85]. Flywheel PAPE protocols can therefore provide significant performance benefits in a practical and time-effective manner. Flywheel PAPE protocols can also be a practical method to facilitate the introduction of flywheel training. To enhance outcomes of flywheel PAPE protocols, several key factors must be addressed: timing, intensity, exercise selection, volume, and performance test.

1.9. The integration of flywheel training into a programme to reduce likelihood of a non-contact ACL injury risk

The Anterior cruciate ligament (ACL) is an important part of knee joint stabilisation during athletic tasks [91]. The ACL is at risk of injury from a variety of complex anatomical, neuromuscular, and mechanical demands associated with high intensity changes of direction and jumping in sport [92–94]. ACL injuries are amongst some of the most problematic in sport because of their potential long-term impact on player's careers [95].

The use of resistance training as a part of ACL injury mitigation and rehabilitation is now commonplace with the aim of reducing muscle, coordination, and balance deficits [91,96,97]. Indeed, in comparison to a control group (involving no resistance training), resistance training significantly reduced strength deficits between limbs amongst amateur male soccer players over the rehabilitation period after ACL surgery and rehabilitation [97]. Although resistance training has shown to enhance rehabilitation outcomes [95], some evidence has suggested that deficits in hamstring strength have persisted for up to 10 years after elite female team sport athletes sustained ACL injuries – suggesting current approaches are not always effective [96]. Although ACL injuries are multi-factorial and relatively poorly understood, it is clear that a key aspect of mitigation and rehabilitation is development of eccentric strength [96,98]. Exercises that have a biased or accentuated eccentric phase, like flywheel training, can help improve stabilisation of the knee joint, tendon and ligament health, proprioception, and neuromuscular control [35,95,99,100]. Indeed, flywheel training is a valuable tool for rehabilitation because it allows a lot of versatility [101]. For example, the application of a flywheel lateral squat (Figure 1.2) can be manipulated by adjusting, volume, intensity, attachments used (belt or handle) during a variety of exercises (i.e., lateral squat). The use of flywheel training has also been proposed as a methodology to assess and reduce inter-limb asymmetries [102]. Inter-limb asymmetry assessments can involve anything from simple athletic tasks (one bilateral vertical jump) to complex multi-directional tests that involve a variety of physical attributes (*i.e.,* speed, manoeuvrability, strength, coordination) [102–104]. Flywheel resistance training exercises have therefore been implemented not only as a methodology to train but can also monitor and assess asymmetries and imbalances [102,105]. Currently, the link between flywheel training and inter-limb asymmetry remains unclear and mostly focused on youth male soccer players [102].

Figure 1.2. A) Flywheel lateral squat with handle and B) Flywheel lateral squat wearing a vest

1.10. The integration of flywheel training to reduce likelihood of hamstring strain injury risk

The application of resistance training methods to reduce hamstring strain injuries is of considerable interest due to the large financial, health, and performance burden such injuries place upon sporting organisations and athletes [106,107]. Before exploring strategies for mitigating hamstring injuries with flywheel training, a brief description of the hamstring muscles and their demands during running will be provided. The hamstrings consist of three main muscles: semimembranosus, semitendinosus, and biceps femoris (which has a long and short head). Each muscle-tendon unit within the hamstrings differs in architecture, which has implications for how the muscle-tendon unit functions [108].

Muscle architecture

The length of a muscle fibre is an important determinant of its contractile properties [109]. Indeed, longer muscle fibres typically allow for a higher shortening velocity and work to be performed over greater length ranges [110]. Since resting fascicle length is closely linked with changes in muscle force production, it is often considered an important measure [37]. Similarly, the physiological cross-sectional area (derived from the cross-sectional area and pennation angle) is a measure that is of great relevance when measuring morphological responses to resistance training [111,112]. The semimembranosus and biceps femoris long head have pennate and bipennate structures, with large PCSAs, short fascicles, greater pennation angles and long distal tendons – likely allowing the muscles to produce greater force while limiting fascicular change [113]. Relatively, the semitendinosus and biceps femoris short head appear to have smaller PCSAs, long fascicles and smaller pennation angles – likely facilitating greater fascicular movement [108].

The hamstrings are most injured during high-speed running activities in field-based team sports, such as soccer [114]. Different running speeds, involving changes in stride length and frequency require high intensity concentric and eccentric muscle actions [115,116], which may predispose the hamstring muscles to an injury at various phases of the gait [117]. During acceleration, the hip extensors must produce large torques to generate forward propulsion of an athlete, with the maximisation of the horizontal component of ground reaction force key to accelerating quickly [116]. Based on the geometry of the musculature, the biceps femoris long head is the primary hip extensor[113], exhibiting a greater amount of muscular activation during acceleration in comparison to the other hamstring muscles [118]. When running at high speeds, the hamstring musculature must actively lengthen to decelerate the forward swinging femur and tibia [119], with overall peak force and activation demands occurring during the swing phase [108,118]. It is worth adding that relative activation of the medial hamstring (semitendinosus and semimembranosus) peaks during the mid swing phase of high-speed running [118]. Meanwhile, peak strain for the biceps femoris long head occurs during the late terminal swing phase of the gait pattern, potentially increasing injury risk [113]. Although the swing phase is taxing, the stance phase also involves lengthening of the hamstrings and has also been highlighted as a portion of the gait pattern that can also be risky due to the large knee extension and hip flexion torques placed upon the hamstrings during high-speed running [120].

1.11. Integration of different training methodologies to reduce hamstring likelihood of injury risk

The application of a multi-component injury prevention programme encompassing different training methodologies is considered best practice and a gold-standard approach [7,121]. It is therefore crucial that flywheel is integrated with other resistance training methodologies to reduce likelihood of injury rather than focusing solely on flywheel training or other methodologies individually. A majority of training approaches for the hamstrings specifically have evolved to incorporate exercises with an accentuated eccentric component [7,61,122]. It has been postulated that the application of hamstring eccentric training would shift hamstring torque-joint angle favourably towards longer muscle lengths and potentially reduce likelihood of overstretching during sporting actions [116,123]. Indeed, the application of eccentric training such as the Nordic hamstring exercise improved architectural, strength, and injury outcomes [124,125]. Although the Nordic hamstring exercise is a common, practical and effective exercise for reducing injury risk [126], it's efficacy remains debated by researchers and practitioners [39,127]. It's argued that several aspects of the exercise, including the velocity and range of motion, are not related to the demands of the hamstrings (at the hips and knee) during running activities [128]. Additionally, the uptake and adherence to evidence-based guidelines when applying the Nordic hamstring exercise is problematic [127,129]. Although the prominence of other training and testing methods, including isometric versions of exercises have shown promise and can be valuable [128,130], the incorporation of exercises involving concentric and accentuated eccentric loading seem to be particularly beneficial [33]. A comprehensive hamstring resistance training programme (hip and knee dominant) with an accentuated eccentric phase has shown to increase collagen synthesis and evidenced that such a programme causes adaptation within the hamstring musculotendinous junction [122].

Specifically, the use of flywheel resistance training to enhance morphological and strength adaptations of the hamstrings muscles has shown a lot of promise [61,131–133]. For example, a 10-week bilateral flywheel leg curl training intervention significantly enhanced concentric (Hedges g = 0.79, moderate) and eccentric (Hedges g = 1.14, moderate) knee flexor peak torque while significantly reducing hamstring injury incidence of professional Swedish soccer players [61]. Similarly, 10 weeks of flywheel squat and leg curl training (performed 1-2 times per week) reduced injury severity and sport performance amongst elite youth male soccer players [131]. A 39-week intervention period showed that flywheel Romanian deadlifts improved Biceps Femoris long head fascicle length and hamstring eccentric strength significantly [133]. Recently, 6 weeks of flywheel eccentrically overloaded leg curl (2 seconds up; 1 second down) significantly increased biceps femoris long head fascicle length (14%) while no differences were seen in fascicle length with bilateral flywheel leg curl amongst healthy males [134]. In contrast to the previous studies, flywheel training did not enhance strength or power [134]. Although promising, a lot of flywheel training hamstring exercises remain under investigated and are yet to be thoroughly investigated. Additionally, it is important to mention that although eccentric training is certainly a part of the puzzle, it should be incorporated as an adjunct of a holistic training programme [95,115]. For example, the incorporation of training to specifically focus on enhancing running mechanics, pelvic control, and eccentric hamstring strength have been proposed to be important to optimise performance and injury prevention during prehabilitation and rehabilitation [117].

1.12. Aims of thesis and summary

The present chapter presents some basic foundational knowledge on resistance training and its benefits. Following this, the chapter highlights how resistance training methods have evolved to incorporate greater eccentric demands while appreciating its pitfalls and limitations. Of the methodologies that have evolved over the years, flywheel training has gained a lot of traction and interest from researchers and practitioners alike. Indeed, flywheel training has become recognised as a valid resistance training methodology by many working in field-based team sports. Nonetheless, some key questions and issues remain surrounding the application of flywheel training. The present thesis will therefore aim to address these key questions to enhance the use of flywheel training in field-based team sports.

The thesis's aims are, firstly, to appraise the literature on flywheel training, secondly, to understand how flywheel training is perceived and applied; and lastly, to understand how it can practically be utilised to enhance strength and power performance in field-based team sports. Consequently, the chapters of this PhD thesis are structured as follows:

Chapter 2 provides a detailed summary of how flywheel training enhances strength and physical capacities in healthy and athletic populations. The quality and limitations of current evidence (expert-based reviews and meta-analytical evidence) are also summarized to generate important research avenues to further explore.

Chapter 3 describes current application and perception of flywheel-based resistance training in field-based team sports, aiming to contextualise how flywheel scientific literature is being applied and to identify whether gaps in current knowledge and application of flywheel training exist.

Chapter 4 explains how altering flywheel moment of inertia would influence concentric and eccentric peak power and eccentric:concentric peak power ratio during unilateral flywheel leg curl and hip extension exercises. Additionally, another objective of the present chapter was to analyse the inter-session reliability of concentric, eccentric, and the eccentric:concentric ratio of peak power during both exercises.

Chapter 5 investigated whether unilateral flywheel hamstring training (a combination of hip extension and knee flexion exercises) enhances eccentric, isometric knee flexor strength and flywheel derived power more than a control condition.

Chapter 6 compares the effects of a flywheel and traditional resistance training intervention on isometric and concentric quadriceps strength amongst a youth female team sport population during the in-season period.

Chapter 7 discusses the impact of the thesis on flywheel training literature, practice, and explores future directions that should be investigated.

Chapter 2 – The effect of flywheel training on strength and physical capacities in sporting and healthy populations: An umbrella review.

Publication arising from this chapter:

de Keijzer, K. L., González, J. R., & Beato, M. (2022). The effect of flywheel training on strength and physical capacities in sporting and healthy populations: An umbrella review. *PloS one*, *17*(2), e0264375.

2.1 Abstract

The aim of Chapter 2 was to provide a detailed summary of how flywheel training enhances strength and physical capacities in healthy and athletic populations. The eleven reviews included were analysed for methodological quality according to the Assessing the Methodological Quality of Systematic Review 2 (AMSTAR 2) and the Grading of Recommendations Assessment, Development and Evaluation (GRADE) criteria. Two were systematic reviews, six were systematic reviews with meta-analyses and three were narrative reviews. Although the included reviews support use of flywheel training with athletic and healthy populations, the umbrella review highlights disparity in methodological quality and over-reporting of studies (38 studies were included overall). Flywheel post-activation performance enhancement protocols can effectively enhance strength and physical capacities acutely with athletes and healthy populations. All relevant reviews support flywheel training as a valid alternative to traditional resistance training for enhancing muscular strength, power, and jump performance with untrained and trained populations alike. Similarly, reviews included report flywheel training enhances change of direction performance—although conclusions are based on a limited number of investigations. However, the reviews investigating the effect of flywheel training on sprint performance highlight some inconsistency in attained improvements with elite athletes (e.g., soccer players). To enhance training outcomes, it is recommended practitioners individualize (*i.e.*, create inertia-power or inertia-velocity profiles) and periodize flywheel training using the latest guidelines. This umbrella review provides an analysis of the literature's strengths and limitations, creating a clear scope for future investigations.

2.2 Introduction

Flywheel training has evolved from its origins of helping astronauts maintain muscle mass when living in non-gravity environments for prolonged periods of time to becoming a valuable tool to train, monitor, and test team sport athletes [58,81,135]. Indeed, flywheel resistance training has enhanced neuromuscular and strength outcomes within a wide spectrum of clinical and sport performance contexts [32,136]. If flywheel training is completed with a certain technique, practitioners may be able to elicit a safe, effective, and more demanding eccentric phase (and obtain eccentric-overload) when compared to traditional resistance training (involving dumbbells or barbells) [67,137]. The introduction of flywheel training into team sport strength training often elicits favourable acute and chronic improvements in physical capacity and sport performance [138,139]. Additionally, flywheel training allows for an unlimited resistance throughout the entire range of motion [62,63], with optimised muscle loading at any given joint angle [67]. Such features allow for greater versatility in application of flywheel training [140].

Within a short period of time, eleven reviews (of which 8 were systematic reviews) have been published on the topic of flywheel training. Overall, the published literature suggests that flywheel training can improve strength and sport performance measures [61,131,141]. Specifically, the application of flywheel training has shown to improve jump [142], sprint [133,143], and change of direction (COD) performance [84,135]. Although a great deal of effort had gone into the synthesis and discussion of the flywheel literature, findings of systematic reviews have at times contrasted [77,142,144]. Reviews have ranged from a variety of topics including monitoring, periodisation, and testing of flywheel training [69,80,136]. Nonetheless, inconsistency in the literature exists regarding the effects of flywheel training on adaptations in strength and power, especially in comparison to other resistance training methods. A key systematic review with meta-analysis published by Maroto-Izquierdo et al., [142] in 2017 reported a greater magnitude of muscle hypertrophy and physical performance after flywheel training in comparison to traditional resistance training. Conversely, another systematic review with meta-analysis published by Vicens-Bordas et al., [77] in 2018 reported no differences between flywheel and traditional resistance training methods for enhancing strength. Although the two systematic reviews differed only by a year in publication, several key factors may have influenced the pooled results of the meta-analysis and the reviews conclusions. Specifically, differences in the number of included databases searched, selection of search syntax, and the data analysis performed may have contributed to the contrasting findings [145]. A subsequent letter to the editor identified 6 of the 9 studies included in the review by Maroto-Izquierdo et al., [142] did not actually compare flywheel training to traditional resistance training. Additionally, a mixture of randomised, non-randomised and unpublished studies were included in the review and meta-analysis. inherently increasing the risk of bias, contrasting the PRISMA guidelines, and conflicting with the inclusion criteria of the systematic review [144,146]. Overall, reviews conducted on flywheel training have synthesised research and created practical recommendations and guidelines for male populations [77,142]. Such literature provides key references for practitioners and aids decision making. The development of practical recommendations is associated with enhanced prescription of training [32]. Although a great amount of effort has gone into research and evidence synthesis amongst male populations [77,142], less remains known about the effects of flywheel training amongst female populations [147]. Specifically, only 7 studies (involving only 64 young adults) were available and have been systematically analysed [147]. It is important to continue to study how female populations respond to high intensity resistance training methods [148]. A high intensity barbell squat protocol (80% 1RM; 5 x 5 sets) induced a greater and more prolonged decrement in jump performance amongst females (12%) than males (6%) [149]. Indeed, greater research into the influence of factors such as intensity, volume, and progressive overload amongst female athletes is needed to understand the hypertrophic, strength, and performance improvements that can be seen with female populations [148]. The lack of evidence for the use of flywheel training amongst female populations and especially athletes is discussed and addressed accordingly in the present chapter.

A proposed method to reduce the impact of limitations of individual reviews and meta-analyses is to synthesize and appraise them in the form of an umbrella review [145]. Umbrella reviews may help to better understand the evidence landscape by comparing conclusions based on all relevant published data. Umbrella reviews also allow for a greater analysis of bias in the literature which may implicitly affect the validity of the scientific evidence and misguide application [145]. Such analysis, although very important, is generally not performed in reviews and meta-analyses – meaning that bias often infiltrates practice undetected [150]. This chapter aims to provide a detailed summary of how flywheel training enhances strength and physical capacities in healthy and athletic male and female populations. The quality and limitations of current evidence (expert-based reviews and meta-analytical evidence) are summarized, and important research avenues to explore.

2.3. Methods

Experimental approach to the problem

The present review was performed according to the current guidelines [145] and followed the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement guidelines [146]. Supporting information can be found here.

Search results

Two reviewers (KDK and MB) conducted a literature search on the following databases: PubMed, SPORTDiscus and Web of Science. The search syntaxes (including keywords and Boolean operators) have been reported here:

Pubmed search: ((((eccentric overload training) OR (flywheel training)) AND (sport performance [MeSH]) OR (muscular strength) Filters applied: Full text, Meta-Analysis, Review, Systematic Review, English; SportDiscus search: ((((eccentric overload training) OR (flywheel training)) AND (sport performance [MeSH]) OR (muscular strength); Web of Science search: TOPIC: (eccentric overload training) OR TOPIC: (flywheel training) AND TOPIC: (sport performance) OR TOPIC: (muscular strength).

ResearchGate was also utilized to find any other relevant texts not identified with the primary literature search. Screening of all bibliographies of selected texts was also performed. Duplicates were identified and removed by two reviewers separately (KDK and MB). The final search was conducted on September 15, 2021. Two reviewers (KDK and MB) independently screened titles and abstracts to identify studies that matched the research aim and inclusion criteria, with a third reviewer (JRG) consulted for discrepancies.

Inclusion criteria

Search records were limited to full-text articles in English. Utilizing the Participant-Intervention-Comparison-Outcome (PICO) process for evidence-based practice, the subsequent inclusion criteria were applied:

Participants: Ranging from healthy adults and amateurs to professional sporting populations between the ages of 17–40.

Interventions: Single and multi-component flywheel training programmes aiming to enhance physical and/or strength capacity.

Comparison group: Usual (no additional training) or alternative resistance training.

Outcome measures: Jumping performance, sprinting performance, change of direction performance, swimming performance, isokinetic strength performance, eccentric hamstring strength performance, one-repetition maximum (1RM) strength, concentric power, eccentric power.

All reviews and studies that do not fit the inclusion criteria have been detailed below (Table 2.1 and Table 2.2).

Table 2.1 Justification for excluded studies from reviews

Review	**Study**	**Justification**
Allen et al., 2021	Fiorilli et al., (2020)	13 yrs. old
	Gonzalo-Skok et al., (2019)	15 yrs. old
	Raya Gonzalez et al., (2021)	Age not reported
Javier Nuñez et al., (2017)	Onambele et al., (2008)	70 yrs. old
	Naczk et al., (2014)	Shoulder adduction/abduction exercises
Liu et al., (2020)	Fiorilli et al., (2020)	13 yrs. old
	Sanchez-Sanchez et al., (2019)	Combined high intensity interval training and flywheel training
	Chaabene et al., (2019)	Nordics, no flywheel training
	Siddle et al., (2019)	Nordics, no flywheel training
	Bourgeois et al., (2017)	15 yrs. old; No flywheel training
	Lockie et al., (2014)	Enforced deceleration programme, no flywheel training
Maroto-Izquierdo et al., (2017)	Naczk et al., (2014)	Shoulder adduction/abduction exercises
	Naczk et al., (2016)	Elbow flexor/extensor exercises
Petré et al., (2018)	Bruseghini et al., (2015)	68 yrs. old
	Caruso et al., (2005)	59 yrs. old
	Lundberg et al., (2012)	Aerobic + Flywheel training
	Lundberg et al., (2014)	Aerobic + Flywheel training
	Naczk et al., (2014)	Shoulder adductor/abductor
	Naczk et al., (2016)	Elbow flexor/extensor
	Onambele et al., (2008)	70 yrs. old
	Owerkowicz et al., (2016)	Aerobic + Flywheel training
Raya González et al., (2020)	Raya Gonzalez et al., (2018)	15 yrs. old
Raya González et al., (2021b)	Onambele et al., (2008)	70 yrs. old
	Sanudo et al., (2019)	65 yrs. old
Tesch et al., (2017)	Alkner et al., (2003)	Space, limb unloading

	Alkner and Tesch (2004a)	Space, limb unloading
	Alkner and Tesch, (2004b)	Space, limb unloading
	Alkner et al., (2016)	Space, limb unloading
	Rittweger et al., (2005)	Space, limb unloading
	Nielsen et al., (2016)	Space, limb unloading
	Irimia et al., (2017)	Space, limb unloading
	Cotter et al., (2015)	Space, limb unloading
	Owerkowicz et al., (2016)	Space, limb unloading
	Tesch et al., (2004b)	Limb unloading
	Haddad et al., (2005)	Space, concurrent training
	Fernandez Gonzalo et al., (2014a)	No sport performance
	Bruseghini et al., (2015)	68 yrs. old
	Onambele et al., (2008)	70 yrs. old
	Romero-Rodriguez et al., (2011)	Athletes with tendinopathy
	Abat et al., (2014 & 2015)	Patellar tendinopathy
	Greenwood et al., (2007)	37 ±13 yrs. old, injured
	Fernandez Gonzalo et al., (2014c)	63 yrs. old
	Fernandez Gonzalo et al., (2016a)	61 yrs. old
	Oliviera et al., (2015)	46 yrs. old
	Sarmiento et al., (2014)	78 yrs. old
Vicens Bordas et al., (2018)	Greenwood et al., (2007)	37 ±13 yrs. old, injured
	Onambele et al., (2008)	70 yrs. old
	Caruso et al., (2005)	58 yrs. old

Table 2.2. Justification for excluded reviews

Review	**Justification**
Douglas et al., 2017 [9]	Not specific to flywheel training
Kingma et al., 2007 [151]	Injured population
Tinwala et al., 2017 [152]	Reviewing technology
Vogt and Hoppeler, 2014 [17]	Not specific to flywheel training
Wonders, 2019 [101]	Rehabilitation focus

Mosteiro-Muñoz and Domínguez, 2017 [153]	Rehabilitation focus
Beato and Dello Iacono, 2020 [32]	Commentary

Methodological quality and quality of the evidence assessment

The Assessing the Methodological Quality of Systematic Reviews 2 (AMSTAR 2) checklist was used to determine quality of reviews included. Reviews were classified and scored by two reviewers (KDK and MB), if classification remained unclear, a third reviewer was included in the discussion (JRG). The 16 items of the checklist were answered with a 'yes' or 'no', with each 'yes' equalling 1 point. Reviews were classified as high (>80% items satisfied), moderate (40 to 80% items satisfied), or low quality (<40% items satisfied). An adapted form of the GRADE principles is applied to assess the quality of the evidence provided in the reviews included, as performed previously [38]. Reviews were classified into five GRADE categories: high; moderate; low; very low; no evidence from systematic review. A review was categorized as high quality if it consisted of at least two high-quality studies. Reviews with at least one high or two moderate quality studies were rated as moderate quality. If a review only includes moderate quality primary studies and/or primary studies presenting inconsistent results, that review was classified as low quality. Reviews are categorized as very low quality if they lack medium to high quality studies. Lastly, if the quality of the primary studies was not assessed by the reviewers, the GRADE system was not applied, and the review was classified as 'no evidence from systematic review'.

Study coding and data extraction

The following moderator variables were extracted from the included reviews: (1) author details and year of publication, (2) main variables analysed, (3) main objective of the review, (4) type of investigation, (5) review content (investigations and participants included as well as investigation duration), (6) main findings or conclusions reported. Data extraction, methodological quality assessment and quality of the evidence evaluation were performed independently by two authors (KDK and MB) and discrepancies between the authors were resolved in consultation with a third reviewer (JRG).

2.4. Results

The flow diagram (Figure 2.1) shows the retrieval process followed for this umbrella review. Initially, 2742 reviews were identified with the search criteria, while 1 additional review was found through a secondary search. Following this step, duplicate records were removed, and reviews were excluded based on their titles and/or abstracts. 18 full-text reviews were assessed, with 11 reviews included in the umbrella review.

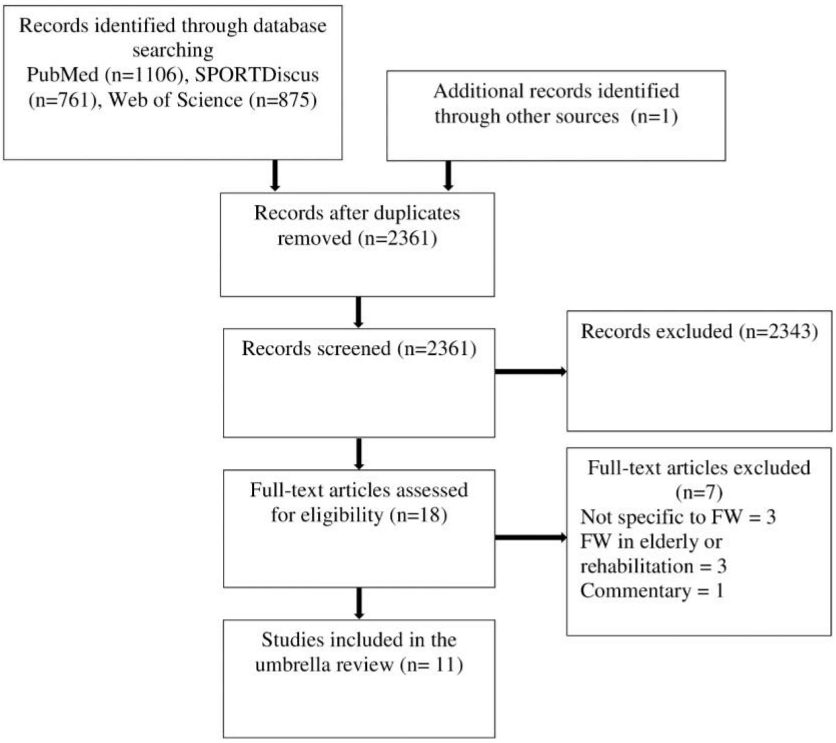
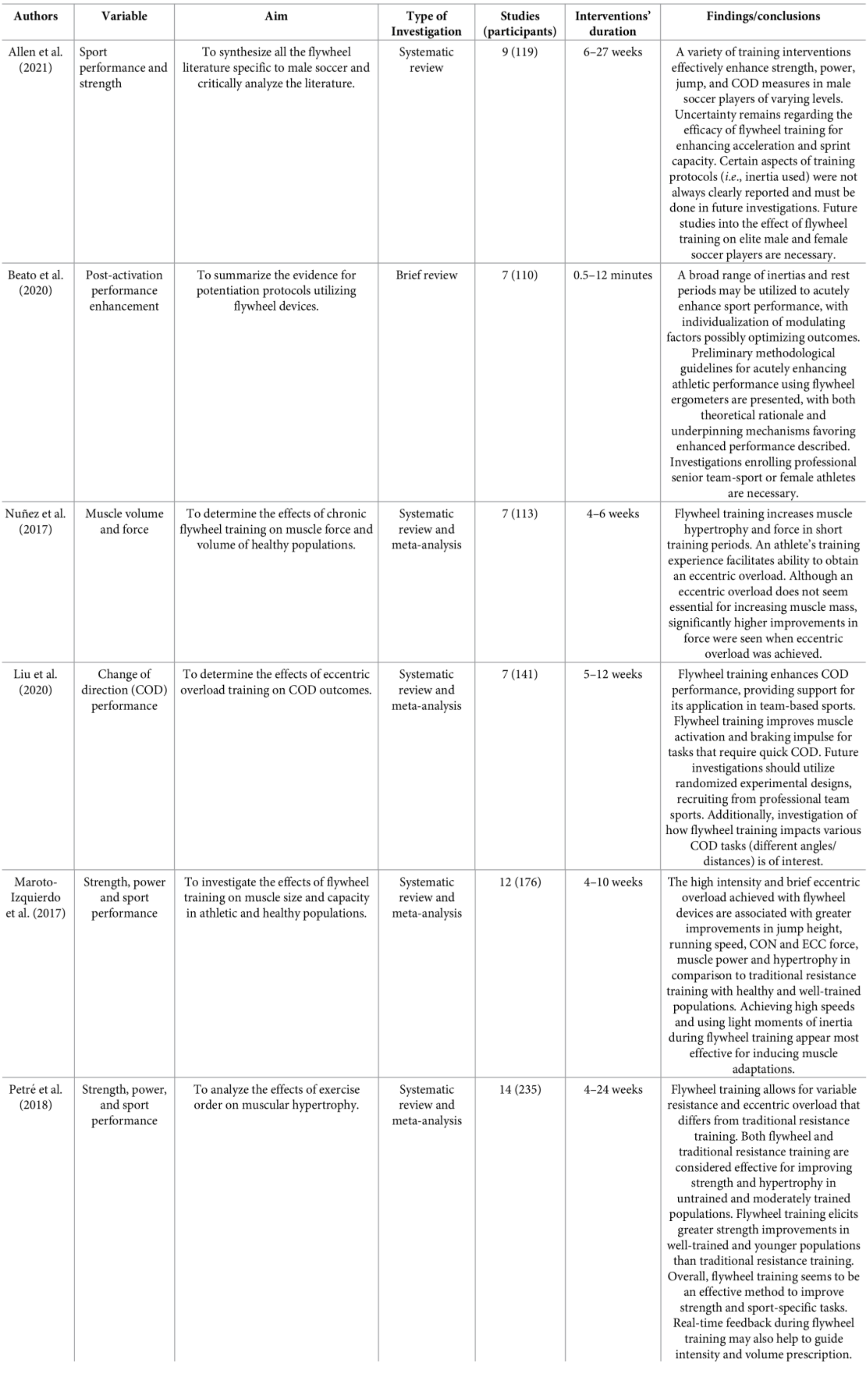


Figure 2.1 Flow diagram of the study retrieval process.

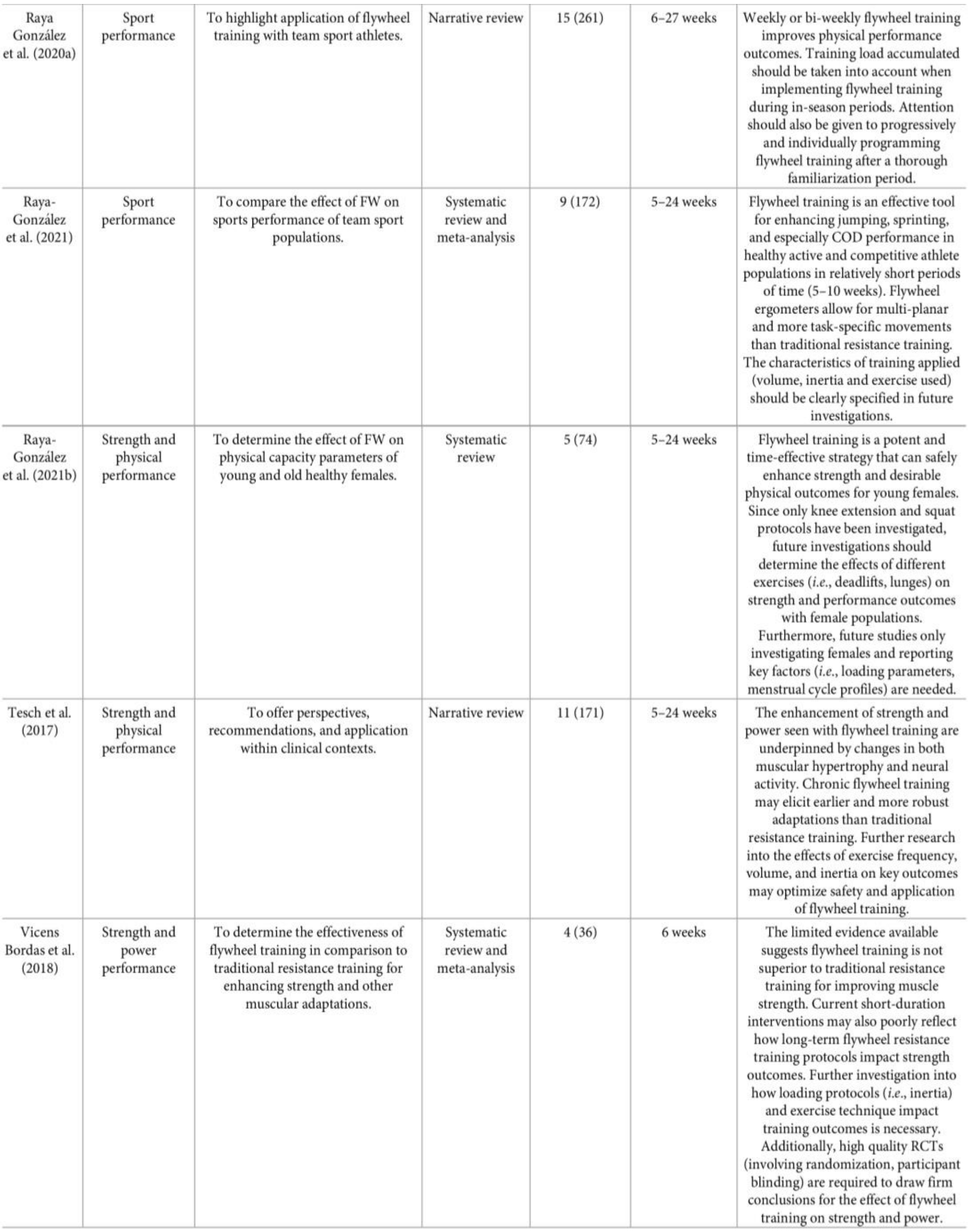
Descriptive characteristics of the umbrella review

All of the studies that were included in the umbrella review are summarized in Table 2.3. These reviews were published between 2000 and 2021 and comprised of 38 primary studies corresponding to 608 participants in the experimental groups and 477 participants in the control groups. The 11 selected reviews either analysed strength, chronic/acute physical capacity, or both. Studies that did not match the inclusion criteria were excluded.

Table 2.3 Summary of reviews that investigated the effects of flywheel training on physical capacity and strength.



Authors	Variable	Aim	Type of Investigation	Studies (participants)	Interventions' duration	Findings/conclusions
Allen et al. (2021)	Sport performance and strength	To synthesize all the flywheel literature specific to male soccer and critically analyze the literature.	Systematic review	9 (119)	6–27 weeks	A variety of training interventions effectively enhance strength, power, jump, and COD measures in male soccer players of varying levels. Uncertainty remains regarding the efficacy of flywheel training for enhancing acceleration and sprint capacity. Certain aspects of training protocols (*i.e.*, inertia used) were not always clearly reported and must be done in future investigations. Future studies into the effect of flywheel training on elite male and female soccer players are necessary.
Beato et al. (2020)	Post-activation performance enhancement	To summarize the evidence for potentiation protocols utilizing flywheel devices.	Brief review	7 (110)	0.5–12 minutes	A broad range of inertias and rest periods may be utilized to acutely enhance sport performance, with individualization of modulating factors possibly optimizing outcomes. Preliminary methodological guidelines for acutely enhancing athletic performance using flywheel ergometers are presented, with both theoretical rationale and underpinning mechanisms favoring enhanced performance described. Investigations enrolling professional senior team-sport or female athletes are necessary.
Nuñez et al. (2017)	Muscle volume and force	To determine the effects of chronic flywheel training on muscle force and volume of healthy populations.	Systematic review and meta-analysis	7 (113)	4–6 weeks	Flywheel training increases muscle hypertrophy and force in short training periods. An athlete's training experience facilitates ability to obtain an eccentric overload. Although an eccentric overload does not seem essential for increasing muscle mass, significantly higher improvements in force were seen when eccentric overload was achieved.
Liu et al. (2020)	Change of direction (COD) performance	To determine the effects of eccentric overload training on COD outcomes.	Systematic review and meta-analysis	7 (141)	5–12 weeks	Flywheel training enhances COD performance, providing support for its application in team-based sports. Flywheel training improves muscle activation and braking impulse for tasks that require quick COD. Future investigations should utilize randomized experimental designs, recruiting from professional team sports. Additionally, investigation of how flywheel training impacts various COD tasks (different angles/ distances) is of interest.
Maroto-Izquierdo et al. (2017)	Strength, power and sport performance	To investigate the effects of flywheel training on muscle size and capacity in athletic and healthy populations.	Systematic review and meta-analysis	12 (176)	4–10 weeks	The high intensity and brief eccentric overload achieved with flywheel devices are associated with greater improvements in jump height, running speed, CON and ECC force, muscle power and hypertrophy in comparison to traditional resistance training with healthy and well-trained populations. Achieving high speeds and using light moments of inertia during flywheel training appear most effective for inducing muscle adaptations.
Petré et al. (2018)	Strength, power, and sport performance	To analyze the effects of exercise order on muscular hypertrophy.	Systematic review and meta-analysis	14 (235)	4–24 weeks	Flywheel training allows for variable resistance and eccentric overload that differs from traditional resistance training. Both flywheel and traditional resistance training are considered effective for improving strength and hypertrophy in untrained and moderately trained populations. Flywheel training elicits greater strength improvements in well-trained and younger populations than traditional resistance training. Overall, flywheel training seems to be an effective method to improve strength and sport-specific tasks. Real-time feedback during flywheel training may also help to guide intensity and volume prescription.



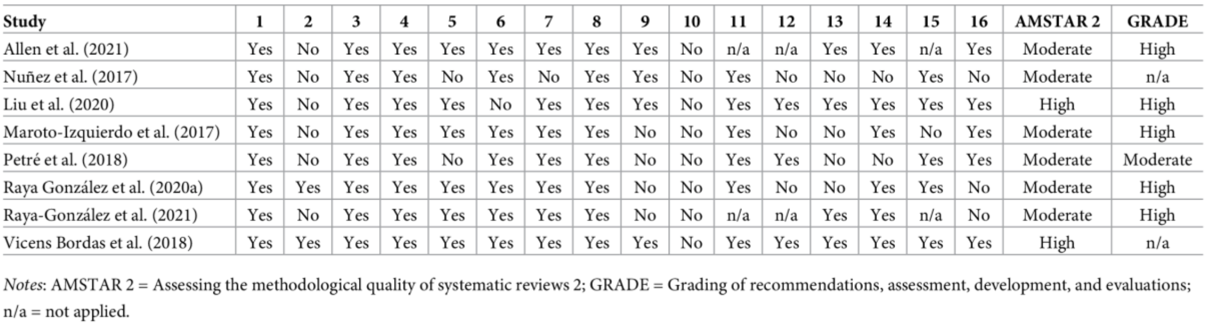
Raya González et al. (2020a)	Sport performance	To highlight application of flywheel training with team sport athletes.	Narrative review	15 (261)	6–27 weeks	Weekly or bi-weekly flywheel training improves physical performance outcomes. Training load accumulated should be taken into account when implementing flywheel training during in-season periods. Attention should also be given to progressively and individually programming flywheel training after a thorough familiarization period.
Raya-González et al. (2021)	Sport performance	To compare the effect of FW on sports performance of team sport populations.	Systematic review and meta-analysis	9 (172)	5–24 weeks	Flywheel training is an effective tool for enhancing jumping, sprinting, and especially COD performance in healthy active and competitive athlete populations in relatively short periods of time (5–10 weeks). Flywheel ergometers allow for multi-planar and more task-specific movements than traditional resistance training. The characteristics of training applied (volume, inertia and exercise used) should be clearly specified in future investigations.
Raya-González et al. (2021b)	Strength and physical performance	To determine the effect of FW on physical capacity parameters of young and old healthy females.	Systematic review	5 (74)	5–24 weeks	Flywheel training is a potent and time-effective strategy that can safely enhance strength and desirable physical outcomes for young females. Since only knee extension and squat protocols have been investigated, future investigations should determine the effects of different exercises (*i.e.*, deadlifts, lunges) on strength and performance outcomes with female populations. Furthermore, future studies only investigating females and reporting key factors (*i.e.*, loading parameters, menstrual cycle profiles) are needed.
Tesch et al. (2017)	Strength and physical performance	To offer perspectives, recommendations, and application within clinical contexts.	Narrative review	11 (171)	5–24 weeks	The enhancement of strength and power seen with flywheel training are underpinned by changes in both muscular hypertrophy and neural activity. Chronic flywheel training may elicit earlier and more robust adaptations than traditional resistance training. Further research into the effects of exercise frequency, volume, and inertia on key outcomes may optimize safety and application of flywheel training.
Vicens Bordas et al. (2018)	Strength and power performance	To determine the effectiveness of flywheel training in comparison to traditional resistance training for enhancing strength and other muscular adaptations.	Systematic review and meta-analysis	4 (36)	6 weeks	The limited evidence available suggests flywheel training is not superior to traditional resistance training for improving muscle strength. Current short-duration interventions may also poorly reflect how long-term flywheel resistance training protocols impact strength outcomes. Further investigation into how loading protocols (*i.e.*, inertia) and exercise technique impact training outcomes is necessary. Additionally, high quality RCTs (involving randomization, participant blinding) are required to draw firm conclusions for the effect of flywheel training on strength and power.

Abbreviations: 1RM = one repetition maximum; RCT = Randomized control trial; COD = Change of direction; CON = Concentric; ECC = Eccentric.

Methodological quality assessment and quality of the evidence evaluation

The methodological quality of the 11 included reviews is presented in Tables 2.3 and 2.4. Two reviews were rated as high quality, while six were considered moderate quality and three of low quality using the AMSTAR 2 checklist. Critically, several AMSTAR 2 criteria were not met by a majority of reviews included. Most reviews did not explicitly state that methods were established a priori (item 2). Reviews did not list excluded studies/justify exclusion (item 7), while all lacked a risk of bias assessment of individual studies included in their respective reviews (item 9). Furthermore, most reviews included did not consider the likelihood of publication bias (item 15). According to the adapted GRADE principles applied in the present umbrella review, five investigations were rated as high quality. One review was rated as moderate quality, while the other five reviews did not critically appraise the included studies and could therefore not be assigned a GRADE rating.

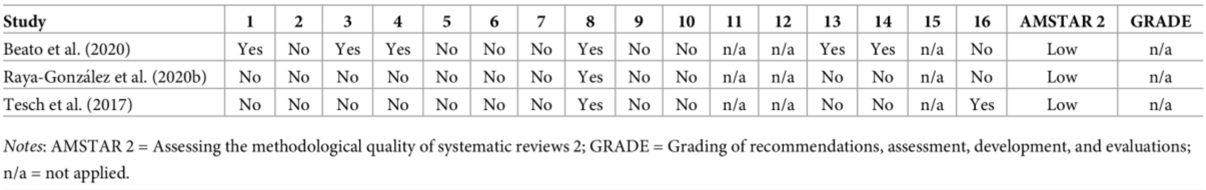
Table 2.4. Overall results of the AMSTAR 2 and GRADE recommendations for systematic reviews and meta-analyses.



Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	AMSTAR 2	GRADE
Allen et al. (2021)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	n/a	n/a	Yes	Yes	n/a	Yes	Moderate	High
Nuñez et al. (2017)	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	No	No	No	Yes	No	Moderate	n/a
Liu et al. (2020)	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	High	High
Maroto-Izquierdo et al. (2017)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	Yes	No	Yes	Moderate	High
Petré et al. (2018)	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Moderate	Moderate
Raya González et al. (2020a)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No	No	Yes	Yes	No	Moderate	High
Raya-González et al. (2021)	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	n/a	n/a	Yes	Yes	n/a	No	Moderate	High
Vicens Bordas et al. (2018)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	High	n/a

Notes: AMSTAR 2 = Assessing the methodological quality of systematic reviews 2; GRADE = Grading of recommendations, assessment, development, and evaluations; n/a = not applied.

Table 2.5. Overall results of the AMSTAR 2 and GRADE recommendations for narrative reviews.



Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	AMSTAR 2	GRADE
Beato et al. (2020)	Yes	No	Yes	Yes	No	No	No	Yes	No	No	n/a	n/a	Yes	Yes	n/a	No	Low	n/a
Raya-González et al. (2020b)	No	No	No	No	No	No	No	Yes	No	No	n/a	n/a	No	No	n/a	No	Low	n/a
Tesch et al. (2017)	No	No	No	No	No	No	No	Yes	No	No	n/a	n/a	No	No	n/a	Yes	Low	n/a

Notes: AMSTAR 2 = Assessing the methodological quality of systematic reviews 2; GRADE = Grading of recommendations, assessment, development, and evaluations; n/a = not applied.

2.5. Discussion

This review provides a thorough summary of flywheel training and the evidence specific to strength and physical capacities in healthy and athletic populations. Additionally, it summarizes the quality and limitations of current evidence (Tables 2.4 and 2.5). The 11 included reviews and the 38 primary studies are the basis for the implementation of flywheel training in sports (*i.e.,* intensity, volume, frequency, exercises). Considering the relevance and impact of the narrative reviews on the literature and practice, they were also included in the present umbrella review. Although the narrative reviews are considered, their evidence is appraised in a different format. This hopefully allows practitioners and researchers to consider the findings of the systematic and narrative reviews independently alongside the methodological qualities of the reviews (presented in tables 2.4 and 2.5).

Post-activation performance enhancement (PAPE)

The phenomenon defined as PAPE involves the enhancement of voluntary athletic performance following an activation activity (*i.e.,* resistance training) [85,87]. Although the mechanisms underpinning PAPE remain debated, the research and application of flywheel PAPE protocols has seen a substantial increase over the past decade [85]. The present umbrella review reports that flywheel training methods may be particularly effective when aiming to prepare for sporting activities such as jumping and changing direction [2,85]. In support of such findings, a flywheel deadlift and squat PAPE protocol achieved *moderate* enhancements in eccentric isokinetic hamstring strength [154]. It is essential to consider that PAPE protocols were originally developed to enhance fast, plyometric, or sport-specific movements rather than maximal strength, potentially explaining the difference in literature available [50,85].

Similar to strength outcomes, only one study in the present chapter analysed running speed, reporting a 0.7% (*trivial*) change in 20-metre sprint time [85]. In agreement with the review, another study reported no improvement in 5- metre acceleration performance after a similar flywheel half-squat PAPE protocol [89]. Although single set protocols enhanced diving performance and force parameters of a mixed cohort of swimmers [155,156], it remains unclear if a single set is sufficient to enhance other physical performance parameters [90]. Specifically, future investigations must investigate the effects of altering volume on performance of change of direction and jumping tasks. If practitioners can dedicate time to individualizing PAPE protocols (as a part of rehabilitation or non-team settings), this may optimize outcomes. Ideally, practitioners would optimise the modulating factors (*i.e.,* familiarization and experience) associated with PAPE prior to implementing protocols. Nonetheless, the review supports the use of 3-4 sets of 6 repetitions of flywheel half-squats using a variety of moments of inertia (0.03-0.11 kg·m^2) and rest periods (3-9 min) to enhance jump and COD performance [89,157–160]. No differences between leg extension and squat existed when compared as PAPE conditioning activities [161]. Practitioners therefore do not need to prioritise similarity between the conditioning activity and subsequent athletic task as this does not appear to be a key factor for inducing PAPE [85,161].

Chronic Performance

Strength

The development of muscular strength is paramount to improving key muscular qualities, such as rate of force development [2]. Improvements in muscular strength are essential to optimizing sport performance and neuromuscular function of athletic and healthy populations [2,67]. The use of flywheel training for eliciting improvements in muscular strength are of significant interest to the scientific community, a fact that is evidenced by the multiple systematic and narrative reviews on the topic [67,77,137].

Systematic reviews. All of the systematic reviews (*moderate* to *high* AMSTAR 2 and *no rating* to *high* GRADE) supported flywheel training for enhancement of strength performance [77,138,142,147,162,163]. Most of the reviews conclude that flywheel training is a valid alternative to traditional resistance training methods [77,138,147,163]. In fact, Petre et al. (2018) reported large improvements in maximal strength (ES = 1.33) when 1-3 sessions were performed per week [138]. The reported improvements in strength after flywheel training may be due to the effective development of both peripheral and central mechanisms [138]. Specifically, greater muscle activation, alterations in muscle morphology and to the length-tension relationship may be key to enhancements seen in the literature following flywheel training [62,72,134]. A significant amount of evidence suggests that mechanical loading can induce significant fascicle length and/or pennation angle changes [112,164,165]. Similarly, the evidence on flywheel training suggests that improvements in strength also appear to occur alongside rapid changes in pennation angle and/or fascicle length [62,72]. Changes within the muscle (such as longer muscle fibres) due to training allow for a higher shortening velocity and work to be executed at longer muscle lengths [110]. Indeed, resting fascicle length is strongly linked to changes in muscle force production – making it a key outcome measure [37]. Importantly, strength improvements are typically seen after 5 to 10 weeks of flywheel training [77,138,142,162], with one review highlighting that well-trained individuals may benefit more so than untrained individuals when training with the flywheel method [138]. Although it remains unclear why this occurs, it is possible that greater training experience or strength may allow for greater activation and control of the musculature during intense eccentric actions [11].

Discord between systematic reviews exists regarding flywheel training and whether it is more effective [142] or equivalent to traditional resistance training for enhancing strength [77,138,147,163]. Such differences are most probably due to the difference in inclusion criteria (*i.e.,* different control groups or tests/measurements) which alter the findings of the meta-analyses and conclusions drawn from the systematic reviews [77,142]. It remains difficult to conclude whether flywheel training is more effective with well-trained populations. Conclusions are limited by lacking well designed studies directly comparing the two methodologies [65,77], with future research needed to clarify if differences exist.

Strength – *What about females?*

As highlighted previously, extensive research has been conducted on male populations [77,142]. However, there is less information available regarding the effects of flywheel training on female populations [147]. Specifically, only 100 females have been systematically analysed (36 older and 64 young adults) [147]. Considering the limited evidence that has been systematically analysed to date [147], additional research published more recently is also considered and appraised.

The systematic review (*moderate* AMSTAR 2 and *high* GRADE) reports that flywheel training can elicit significant benefits for female populations [20,60,72,166]. One of the first studies including female populations reported increases in quadriceps cross-sectional area (>6%) and isometric strength (10-12%) [60]. Considering the short duration of the protocol (5 weeks) involving 2-3 sessions per week (4 x 7 flywheel knee extension), the favourable changes highlight how promising flywheel training could be for enhancing strength amongst females [60]. A similar protocol also lasting 5 weeks (involving 3 sessions per week) similarly enhanced quadriceps cross-sectional area (6.5-7.4%) but elicited greater isometric quadriceps strength (39%) amongst a mixed cohort of males and females in comparison to the previous study [72]. The novel finding of this study were the reported changes in fascicle length (9.9%) and pennation angle (7.7%) over only a 35 day period [72]. The early studies completed on flywheel training amongst female populations are limited inherently by the inclusion of males within the analysis and the limited number of females actually investigated (5 females only, 29% of the sample between the studies) [60,72]. More recently, a longer intervention (8 weeks) involving a similar protocol of flywheel knee extensions (2-3 times per week; 4 x 7 reps; 0.05 kg·m^2) assessed the effects of flywheel training on males and females separately [65]. Within the range of 10-39% improvement in strength previously reported [60,72], a *moderate* improvement (17%) in 1RM was seen after 12 weeks of training amongst healthy females [65]. In line with previous findings reporting changes of 6 to 7%, the 8 week flywheel resistance training intervention elicited changes in muscle cross-sectional area of 5 to 8% [65]. Similar to the development of strength, the study reported a *moderate* improvement (26%) in flywheel derived knee extension power [65]. This study was the first to report the use of flywheel devices to practically assess changes amongst healthy females. Similarly, the use of flywheel devices to assess changes after interventions was already becoming more commonly utilised with female sporting and elderly populations alike [166–168]. The study is also of interest because it compares traditional resistance training methods (weight stack machines) to flywheel resistance training amongst female populations [65]. Within the study, a greater volume (4 x 8-12 repetitions) was applied for weight stack machines [65]. Indeed, although 22% fewer repetitions were applied with flywheel resistance training, similar improvements in strength and power (20-30%) were seen [65]. It was previously reported amongst males that flywheel training (6%) induces greater quadriceps volume gains than traditional resistance training (3%) [62]. Based on the discrepancies reported in the previous studies, it is possible that females and males respond to flywheel training and traditional resistance training differently.

Within the systematic review, only one study investigated the effects of flywheel training on physical performance parameters amongst female athletes [166]. The randomized control trial involved male and female basketball and volleyball players performing weekly sessions of flywheel squats (4 sets x 8 reps; inertia = 0.11 kg·m^2) over a 24-week period. The study found that weekly flywheel squat training elicited a *very large* improvement in concentric (61%) and eccentric (57%) power [166]. Although the study involved a protocol that can be considered very feasible and practical, it has some limitations. Firstly, the moment of inertia was not altered throughout the duration of the study. As evidenced in the first chapter, altering the moment of inertia plays a crucial part in the progressive overload applied with flywheel training [69]. Similarly, the volume of training (4 sets x 8 reps) was not altered over the five-month training period, possibly limiting enhancements seen with the resistance training protocol. Importantly, the study also did not separate the male and female sample for their analysis, limiting the conclusions of the study to a mixed cohort, rather than solely for a female athlete population. The one review on flywheel training amongst female populations also provided some guidelines and recommendations for practice and research, detailing what is reported in the literature regarding training intensity, volume, and exercise type.

Firstly, a large variety of moments of inertia (0.025 to 0.14 kg·m^2) are utilised within the limited flywheel training literature available on female populations. The variety in moments of inertia and specifically the lack of altering of moments of inertia during interventions highlights the limited knowledge and evidence available on how to periodise flywheel training more generally [136]. Amongst male populations, a similar range of moments of inertia have been recommended (0.05 to 0.11 kg·m^2) – although there is no evidence to suggest such ranges are appropriate for female athletic populations. In addition to the findings of the review, another study highlighted the effects of 6 different moments of inertia during leg extension on peak power obtained between males and females [169]. The study reported 44% lower power in women than men and a smaller difference in power decrement between the moments of inertia applied amongst females [169]. Such differences between power outputs remain under investigated but have been postulated to be associated with females better capacity to maintain movement velocity, an inability of females to increase movement velocity with smaller moments of inertia, or due to lean body mass differences between males and females [169].

Amongst male athletic populations, flywheel training and traditional resistance training elicited similar enhancements in strength and muscle volume [141] – even though it remains unknown how such training differs amongst female athletic populations. Several studies have more recently investigated the effect of flywheel training on female athlete populations [170]. Specifically, one study investigated the effects of 6 weeks of flywheel training on strength and performance measures on youth female soccer players [170]. Similar to previous findings amongst male soccer players [141], a 6 week flywheel squat intervention enhanced isokinetic strength of female soccer players [170]. In particular, the study on female youth athletes showed greater increases in eccentric strength than concentric strength [170]. Another study compared the efficacy of flywheel training to bodyweight exercises amongst amateur male and female volleyball players, reporting greater increases after 6 weeks of flywheel training in concentric and eccentric strength [171]. Although the present evidence is interesting, it remains unclear whether flywheel training is more effective than traditional resistance training methodologies (*i.e.,* barbell) for enhancing strength amongst this population.

Narrative reviews. Narrative reviews included in this chapter conclude that flywheel training is a valid resistance training method for enhancing strength (*low* quality and no GRADE applied) amongst males [67,137]. Specifically, investigations applying flywheel training in a weekly and bi-weekly manner have enhanced strength during the in-season period with athletic populations [61,141,166]. Flywheel training can elicit larger force, torque, and muscle activation during the eccentric phase in comparison to the concentric phase [62,63,169]. In support of this, several reviews highlight that such an "eccentric overload" can be particularly beneficial for strength outcomes [67]. Exposure to optimized loading during both concentric and eccentric phases experienced with flywheel training may partly explain the distinct adaptations experienced in such short periods of time [62,63,169]. Such improvements are very attractive when training frequency is typically reduced [56,57,140]. Nonetheless, caution is also warranted as such outcomes are largely dependent upon appropriate movement familiarization and technique [67,137]. Although further study into the impact of training experience on strength outcomes is warranted [20], weekly or bi-weekly flywheel training can be considered a viable method to enhance strength with athletes [61,141,166,172]. More recently, interventions individualizing and progressively increasing inertia have been performed – enhancing performance and strength measures similarly to traditional resistance training amongst males [172,173]. Nonetheless, future investigation into the effects of optimal frequency, varying training specificity, individualization, and appropriate progression criteria are necessary to develop application [137].

Sprint

Sprint performance is frequently investigated because of its relevance to sporting demands and more generally because of its role as a physical capacity in human movement [142,174]. Nonetheless, no review has been specifically dedicated to solely investigating speed or sprinting ability, as performed with strength [77] or COD performance [139].

Systematic reviews. Four systematic reviews [138,142,162,174] (*moderate* or *high* quality) were included in the present chapter. Training protocols with varying training exposure elicited favourable adaptations amongst soccer players [61,173] and team-sport athletes [133,143,175]. The versatility of flywheel training in team-based environments is supported by the enhancements in sprint performance after squat [176], leg curl [61], leg press [175], and multi-exercise flywheel programmes [84]. Favourably, such improvements in performance are seen after 5-10 weeks of training [174]. Furthermore, the application of flywheel multi-planar and sport-specific movements may also be beneficial for enhancement of sprint performance [174]. Changes towards faster muscle phenotypes [43] or improvements in rate of production and retention of power during sprint strides are some explanations for why sprint performance is enhanced with high intensity eccentric training such as flywheel training [138]. The enhancement of concentric and eccentric strength has been seen alongside enhancement of sprint performance in athletic populations [65,69]. Nonetheless, some investigations have reported limited benefits of *trivial* enhancements in sprint performance after flywheel training [84,131,135,141,177]. Recently, a randomized control trial investigating the effects of flywheel lateral squat training on physical capacity of U16 elite soccer players reported no enhancement of sprint performance – possibly due to the low training dose used (weekly session) [135]. Alternatively, differences in familiarisation protocols or training experience of the athletes may be key factors impacting outcomes [174]. One review specifically suggests that variation in sprint test outcomes may be specifically related to varying distances and instructions during sprint tests [138]. The literature supports the notion that flywheel training must be appropriately dosed to optimise efficacy [138,162], which may not be possible in the context of prolonged congested fixture periods in-season [56]. Of the four systematic reviews, one had large heterogeneity (I^2 = 89%) when considering sprint performance [138] and only one review accounted for the reliability measures of included individual studies [162]. Further investigation of low-dose flywheel training is therefore warranted to determine the effects of manipulating different training parameters during in-season periods on sprint performance [133,141].

Narrative reviews. Flywheel training programmes included in the reviews are typically performed weekly or bi-weekly with team sport athletes [67,137], reflecting flywheel training frequency reported in professional soccer [140]. Although Tesch et al. (2017) [67] reported that sprint performance can be enhanced after application of flywheel training, other narrative reviews reported inconsistent findings in both shorter (<10 m) and longer sprints (>20 m) amongst males [137]. Although inconsistent findings in sprint performance have been reported after flywheel training, several investigations highlight that other resistance training methods were similarly ineffective for enhancing sprint performance during in-season periods. For example, neither flywheel nor 80% 1RM squat training enhanced 10 m and 30 m sprint performance with semi-professional soccer players [141]. Similarly, neither plyometric and resistance training protocols nor the addition of flywheel training to such training enhanced sprint performance outcomes with young males [84,135]. Although not included in any systematic or narrative reviews, a more recent study was completed on the effects of flywheel training on sprint performance amongst female professional soccer players [170]. The intervention progressively increased training intensity (increasing moment of inertia when > 4 watts·kg^{-1}) and volume over the 6-week period. Nonetheless, no improvements were seen in sprint performance amongst the flywheel training group in comparison to the control group [170]. The present review highlights the need for further high-quality studies on the topic (*i.e.,* randomized control trials) to better understand how to optimally implement flywheel training to develop sprint performance amongst male and female athletic populations.

Change of direction

Change of direction (COD) tasks are often characterized by demanding braking actions followed by immediate and high propulsive forces required to re-accelerate in a new direction [178]. Such actions are commonly performed in sport and are predominantly of interest for team-based sport athletes more so than healthy populations [179,180]. Flywheel devices have been utilized to replicate similar movement patterns and transition from eccentric to concentric phases, which are believed to be particularly beneficial for enhancing change of direction outcomes [105]. Logically, improvements in COD ability are therefore expected after appropriate application of flywheel training with athletic populations.

Systematic reviews. Two systematic reviews and meta-analyses investigating this topic were rated *moderate* or *high* on both AMSTAR 2 and GRADE [139,174]. Although only involving three studies, Raya-Gonzalez et al. [174] reported flywheel training elicits significantly favourable outcomes in comparison to control conditions amongst athletes. Similarly, Liu et al. [139] reported beneficial COD outcomes after flywheel training. Such improvements in COD performance with team-based sport athletes were reported in comparison to regular training [178] and to traditional resistance training [84,141,175,181]. Flywheel training appears to improve performance by reducing braking time and enhancing braking impulse during COD movements [139]. A systematic review by Allen et al. [162] (rated *moderate* and *high* on AMSTAR 2 and GRADE) also supported the efficacy of flywheel training for enhancing COD ability with adult male soccer players. Specifically, a variety of protocols appeared effective for enhancing COD performance parameters with youth and semi-professional soccer players [84,141,178]. Even though such improvements are reported, appropriate familiarization and adequate flywheel training technique are key to ensure COD performance enhancement with athletes [162,174].

Narrative reviews. Two narrative reviews (rated *low* on AMSTAR 2, no GRADE applied) reached similar conclusions to the systematic reviews previously mentioned [67,137]. Specifically, the authors highlight that other practical limitations affect flywheel training frequency and suggest that weekly training may still be effective for obtaining COD adaptations [84,141]. Similarly, Raya-Gonzalez et al. [137] propose at least 8-11 weeks (one training session a week) and 6 weeks of flywheel training be performed to enhance COD performance. Individualizing inertia chosen may further enhance COD outcomes [67,169], although the optimal method to determine appropriate exercise inertia (intensity) remains unclear [71]. Nonetheless, the various tests (L-drill, V-cut) included in the narrative reviews suggest that flywheel training can enhance different types of COD tasks required in team-based sports [67,137]. It is important to caveat the present findings with a brief discussion of different change of direction tests presented. As defined by Jones *et al.,* [182], change of direction ability "is the ability to decelerate, reverse, or change movement direction and accelerate again". Change of direction tests can come in many different forms and assess different qualities. For example, a 5-0-5 change of direction or V-cut test requires greater eccentric demands (and longer ground contact times) in comparison to tests involving smaller turns and velocity maintenance (*i.e.,* curved line sprinting) [183,184]. Similarly, other tests (*i.e.,* Illinois test) can differ in movement strategies employed by athletes and incorporate transitional movements (*i.e.,* side shuffle or back pedal) which thereby assesses manoeuvrability alongside other physical qualities [185]. One of the tests employed to assess change of direction (L-drill) within the narrative reviews would also be affected by the athlete's manoeuvrability, anaerobic capacity (due to prolonged duration), and sprint ability rather than solely change of direction ability [186]. Different change of direction tests therefore involve a variety of physical (*i.e.,* eccentric strength) and technical (*i.e.,* deceleration, acceleration) qualities that must be considered when assessing change of direction ability [187]. Consideration for the tests selected and conclusions drawn from such tests are therefore important and must be considered when assessing responses to training [67,137]. Overall, the recommendations provided by the narrative reviews presented are useful, nonetheless their methodological limitations should be considered by practitioners (Table 1.2).

Although the reviews performed on COD performance and flywheel training involve a variety of team-based sports, they are predominantly based on a limited number of investigations [137,139,162,174]. This reflects the smaller number of investigations assessing the effects of flywheel training programmes on COD ability in comparison to other physical qualities (*e.g.,* jump performance). The obtained enhancements of jump ability in athletic and healthy populations also seem to be more consistent when compared to COD outcomes, which may be explained by a greater variation and disparity in training doses and tests (likely assessing different aspects of agility) utilized.

Jump

Jumping performance is often utilized as a key indicator for lower-limb power, strength and physical ability with both healthy and athletic populations [142,188]. Improvements in energy production and storage during the stretch-shortening cycle may be related to the transition from eccentric to concentric phases during flywheel training [64]. Moreover, the high eccentric demands of flywheel exercise may be an effective method to stimulate lower limb strength and power parameters, which can have a positive transfer to jumping performance [174].

Systematic reviews. Four systematic reviews and meta-analyses have specifically investigated the impact of flywheel training on jumping performance [138,142,147,162,174]. The first systematic review on the topic (rated *moderate* and *high* on AMSTAR 2 and GRADE, respectively) conducted by Maroto-Izquierdo et al., [142] reported significant improvements ($p < 0.01$) in jump ability amongst males after 4-10 weeks of flywheel training, although it only involved 3 studies. Petre et al. [138] and Raya-Gonzalez [174] meta-analysed 7 and 8 studies, respectively. The greater number of studies included, and the quality of the reviews (rated as *moderate* and *high*) further enhances confidence in application of flywheel training for jump performance enhancement in both athletic and healthy male and female populations. In agreement with previous findings [142], both reported enhancement of jump performance after flywheel training protocols spanning 5-24 weeks [138,174]. The only systematic review investigating the effects of flywheel training on female populations reported improvements in jump ability [147]. The study by Fernandez-Gonzalo et al., [20] found that two to three sessions of flywheel squat training (4 x 7 repetitions; 0.14 $kg{\cdot}m^2$) per week over a 6 week period enhanced squat jump (8%) and countermovement jump (6%) performance amongst physically active females. Another study investigating a mixed cohort of male and female athletes reported that countermovement jump performance (3%) was *trivially* changed [166]. It is likely that the large amount of jumping within training and competition (basketball and volleyball) already experienced by the athletes and the limited volume of flywheel training (1 session per week) they were exposed to led to the current findings [166]. Based on these findings, it remains unclear if team sport athletes can see enhancements of performance measures in-season after flywheel training and how such training may differ from the effects of traditional resistance training. The review reported a greater enhancement of performance was seen when participant level was lower (healthy adults vs. team-sport athletes) and when weekly frequency was increased (1 vs. 3 weekly sessions) amongst females [147]. This is in line with the commonly accepted knowledge that less well trained populations respond more to training interventions and greater frequency of training improves outcomes [6,189,190]. Separate to the review, a recent investigation studied the effect of flywheel training on jump performance measures of youth female team-sport athletes [191]. The study found that variable and standard flywheel training enhanced performance significantly after only 6 weeks. Similarly amongst males, the systematic review by Allen et al. [162] observed that flywheel training frequently enhanced jumping ability of soccer players (only 1 of 7 studies did not report improvements). Overall, despite the promising results of the aforementioned findings, the meta-analyses included a variety of participants (healthy adults and team-sport athletes) [138,174]. In fact, one of the meta-analyses included also reported high heterogeneity ($I^2 = 81\%$) [138], limiting conclusions. Further investigation into how flywheel training can enhance jumping performance of athletic populations may help optimize practical recommendations and conclusions.

Narrative reviews. Two narrative reviews and commentaries discussed the application of flywheel training for jump performance enhancement [67,137]. The narrative review by Tesch et al. [67] reported enhancement of jump ability in healthy populations after flywheel training but does not provide conclusions for healthy athletic populations. On the other hand, Raya-Gonzalez et al. [137] reviewed the application of how the flywheel paradigm is used to enhance jumping performance specifically in team-sport athletes. This review reported 3-10% improvements in CMJ performance when 4-6 sets of 6-10 repetitions of all-out flywheel half squats were performed [137]. Nonetheless, when multi-exercise programmes (including flywheel training) were implemented, no significant improvements in jump ability were seen [137]. Differences in response to training highlight that training specificity and exercise selection may be important considerations when designing flywheel training programmes. When implementing flywheel training, it is recommended that practitioners use lower inertias for power-based actions and individualize training (*i.e.,* create inertia-velocity or inertia-power profiles) if feasible [69,71].

2.6. Limitations and future directions

A limitation of the present chapter is that majority of the reviews included utilized the same primary studies, highlighting a considerable over-reporting among reviews. As addressed earlier in the chapter, several limitations related to the methodological quality of the systematic and narrative reviews included affect the conclusions on the efficacy of flywheel training for developing strength and physical capacity. Recently, one study assessed the relationship between jump, sprint, and flywheel assessments amongst elite youth basketball players – suggesting flywheel devices can be included as a part of testing and assessment of inter-limb asymmetries [192]. Although some practical recommendations are available on the topic of asymmetry assessment using flywheel devices [102], further evidence is needed for it to be further integrated into practice. Considering the practicality of collecting data with flywheel devices, future studies should aim to further elucidate the daily fluctuations in flywheel training parameters. Such research would allow practitioners to better understand how flywheel training may vary in output measures. Specifically for female athletic populations, future studies must include and consider appropriate changes to key aspects of training, such as moment of inertia and volume to enhance flywheel training prescription with female athletes. Furthermore, it is recommended to avoid using the term “eccentric overload” to define flywheel training. Instead, the term “eccentric overload” should only be used when confirmed (with appropriate measurements) and should be defined as a larger eccentric output in comparison to the respective concentric output – in line with previous recommendations [67,80]. The present review echoes the need for further high-quality studies on PAPE and chronic flywheel protocols with elite athlete and female populations to enhance application [32,147]. Research into the differences between flywheel and traditional resistance training for strength and physical capacity parameters is of interest and necessitates specific attention, especially with female athletes [32,77]. Finally, further investigation into loading parameters, training frequency, and familiarisation will enhance the quality of training protocols and outcomes.

2.7. Conclusion

This chapter provides a detailed summary on the effects of flywheel training for strength and physical capacity parameters in healthy and athletic populations and summarizes the quality and limitations of current evidence. Moreover, it provides an analysis of the literature’s strengths and limitations, creating a clear scope for future investigations and reviews. The 11 included reviews (including 38 primary studies) highlight that application of flywheel training with sports and healthy populations varies in prescription of exercise intensity, volume, frequency, and exercises. The variation in populations, protocols utilized, and methodological quality ratings of reviews included should be individually considered when interpreting findings. The evidence on flywheel PAPE protocols highlights that such protocols are effective for enhancing isokinetic hamstring strength, jump, and COD performance with athletes, although further high-quality investigations are necessary to confirm current findings. All reviews support use of flywheel training for enhancing muscular strength, power, and jump performance with healthy and athletic male populations. Meanwhile, little evidence is available for the use of flywheel training amongst young athletic female athletes. Importantly, no studies have compared the use of flywheel training to traditional resistance training methods amongst this population for enhancing strength. Future studies should aim to address this gap in the literature. All systematic review and narrative reviews also conclude flywheel training improves change of direction performance – although conclusions are limited to fewer investigations than other physical parameters. Additionally, some of the COD tests employed are likely to involve other physical and technical qualities (*i.e.,* manoeuvrability) and may not represent solely COD ability. Future studies into this area should thoroughly discuss and justify tests selected. The reviews investigating the effect of flywheel training on sprint performance report some inconsistency in attained improvements with elite athletes (*e.g.,* soccer players). To optimize training outcomes, it is recommended practitioners individualize (*i.e.,* create inertia-power or inertia-velocity profiles) and periodize flywheel training using the latest guidelines [69,136]. Exploring inertia-power or velocity relationships can provide practitioners with a greater understanding of the demands and outcomes of flywheel training. Indeed, a greater understanding of such relationships allows for a more specific targeting of adaptations (strength, endurance, power) during flywheel resistance training [71]. A more in-depth analysis of the inertia-power/velocity relationship allows for the prescription of training based on velocity (mean or loss) which may enhance performance and reduce injury risk, although further study is necessary to confirm this. Indeed, the prescription of individualised inertia-power profiles remains difficult in practice. This can occur for a variety of reasons including limited equipment, time, and staff to alter moments of inertia throughout training. Therefore, practitioners sometimes select a moment of inertia that they deem to be most appropriate for the group. Although this can be selected more arbitrarily, based on perception of difficulty or just based on the range present in recommended guidelines, practitioners can also complete an inertia-power profile for the group that is more likely to target specific outputs. It is likely that this compromise is the most feasible and practical way of introducing the use of inertia-power or velocity profiles in field-based team sports. Further research into use of flywheel training and inertia-power/velocity profiles is necessary.

Chapter 3 - The perception and application of flywheel training by practitioners working in field-based team sport.

Publication arising from this chapter:

de Keijzer, K.L., McErlain-Naylor, S. A., Brownlee, T. E., Raya-González, J., & Beato, M. (2022). Perception and application of flywheel training by professional soccer practitioners. *Biology of Sport*, *39*(4), 809-817.

de Keijzer, K. L., Raya-González, J., López Samanés, Á., Moreno Perez, V., & Beato, M. (2023). Perception and use of flywheel resistance training amongst therapists in sport. Frontiers in Sports and Active Living, 5, 1141431.

3.1. Abstract

Little is known about how practitioners working in sport apply flywheel resistance training even though growing evidence supports the integration of different training methodologies for developing strength and reducing likelihood of injury. This chapter aims to investigate how flywheel training literature is perceived and applied by practitioners. Therefore, two separate questionnaires were developed to firstly assess perceptions and applications of practitioners working in soccer and secondly within rehabilitation in sport more generally. Fifty-one practitioners working in soccer completed the *flywheel in soccer* questionnaire focusing on topics ranging from strength, performance, and injury prevention. Fifty-two practitioners working in sport completed the second questionnaire focusing on practical applications, strength and injury prevention amongst therapists working in sport. Most practitioners agreed that flywheel training can improve strength, with most preferring the use of power over velocity outputs. Additionally, of exercises that remain less investigated, most practitioners are likely to prescribe a hip hinge and unilateral leg curl. The present chapter also highlights uncertainty regarding the perceived difference between traditional and flywheel training methods for enhancing strength. Overall, a limited amount of participants working solely with female athletes took part in the questionnaires (<10%), biasing the present findings towards male athletes.

3.2. Introduction

Demands in sports such as male soccer are showing an increasing frequency of high-intensity actions (e.g., sprints, high-speed running, accelerations) in recent years, highlighting the need for appropriate training to ensure success [193]. Similarly, the high-speed running and maximal speed obtained by female soccer players are related to individual and team performance [147]. The demanding nature of male and female soccer is highlighted by the high incidence of injury to the thigh, knee and ankle [194,195]. To optimise performance of such actions in competition, practitioners must systematically program resistance training [196], recovery [197], and injury prevention strategies [100]. Resistance training plays an important role for enhancement of strength, performance, and reduction of injury likelihood within professional soccer [56,198] and more generally to reduce likelihood of injury, improve performance, and rehabilitate athletes from injury in sport [100,199,200]. Multiple factors including prolonged national and international travel commitments, fixture congestion, and time dedicated to technical-tactical training often limit the time for strength training in field-based team sports [57,201]. Practitioners have therefore tried to implement different strength training methodologies to efficiently prepare athletes. In recent years, flywheel-based exercise has become more commonly applied by soccer and team sports practitioners as an alternative to traditional resistance training to cope with the aforementioned demands [32,65].

Flywheel training is a resistance training method that has become popular for sport performance and rehabilitation purposes with a variety of healthy and injured athletic populations [202]. Indeed, as evidenced in Chapter 2, flywheel training has been employed with success for enhancing strength and performance in healthy and athletic populations [77,138]. The combination of maximal concentric muscle actions and subsequent high eccentric loads experienced with flywheel training exposes athletes to unique muscular and neural demands [11,32,56,65]. Specifically, exposure to intense eccentric training has been shown to enhance motor unit discharge rate and synchronization, as well as selective recruitment of higher-order motor units [11]. In fact, flywheel training is particularly effective for challenging the eccentric portion of movements, which are often underloaded and difficult to overload with traditional isotonic resistance training methods [32,56]. If flywheel training is performed appropriately, an eccentric overload (which should be confirmed by mechanical outputs) can be achieved [80]. A key benefit of flywheel training is the ability to monitor, adapt, and optimise short- and long-term training with both concentric and eccentric mechanical outputs [69,70]. A variety of bilateral and unilateral flywheel exercises are often prescribed in practice [84,135,173]. Indeed, the variety afforded with flywheel training alongside the maximal resistance provided during both concentric and eccentric phases elicits unique adaptations [95]. Several examples supporting the efficacy of flywheel training are reported in the literature. For example, 10 weeks of flywheel squat and leg curl training enhanced CMJ height (Hedges $g = 0.60$), sprint performance ($g = -0.84$, *moderate*) and reduced injury severity of elite youth soccer players [131]. Similarly, 16 sessions of bilateral flywheel leg curl performed over 10 weeks with professional Swedish soccer players significantly improved isokinetic eccentric hamstring strength ($g = 1.14$, *moderate*), 30 m sprint ($g = -0.79$, *moderate*), and reduced injury occurrence [61]. A narrative review on the benefits of flywheel training also highlights its potential use for rehabilitation and strength development with non-athletic, elderly, and injured populations [67]. Indeed, the methodological advantages associated with flywheel training protocols has increased application as an injury prevention strategy with male soccer players [7,61,100]. Nonetheless, practitioners working in sport perceive intense eccentric training methods such as the flywheel to be very taxing and difficult to program in-season [56]. In support of this, the current scientific literature does not provide specific considerations for load and risk management when implementing flywheel training in professional soccer [7].

Although flywheel training is applied in a variety of methods in sport environments [32,134], the perceptions and application of flywheel training methodologies amongst practitioners working in sport remain unknown. It is possible what practitioners perceive of flywheel training and what is stated in the literature may differ drastically. If such differences exist, it is important to identify them, discuss them, and help guide evidence-based practice. In fact, addressing how flywheel training is applied by practitioners and highlighting their concerns is important to reduce barriers between research and practice [198]. Considering differences between applied practice and scientific evidence has been previously reported in soccer [129]; the present chapter wanted to firstly address this population specifically (through the *Flywheel in Soccer* [FIS] Questionnaire). In addition to this, discordance between practice and evidence was also a common finding amongst coaches and physiotherapists in the literature [56,203]. Specifically, surveyed therapists have mostly portrayed negative views on the value and clarity of research [203]. This highlights that differences may also exist between therapist application and the underpinning evidence base in general [140,199]. Indeed, recommendations and best practice proposed within the scientific literature often contrasts what is performed by therapists working in sports. Such differences are due to factors including the unpredictability associated with the in-season period, time, personnel, or equipment available [199]. Considering therapists have dynamic roles whereby they are often considered to be amongst the most influential members of staff related to injury prevention in elite sport [140,204], their perception and application of flywheel training is also of great interest. Considering this has never been investigated previously, the present chapter also investigates the use of flywheel training amongst therapists working in field-based team sports (through *the Therapist Flywheel Training* [TFT] questionnaire).

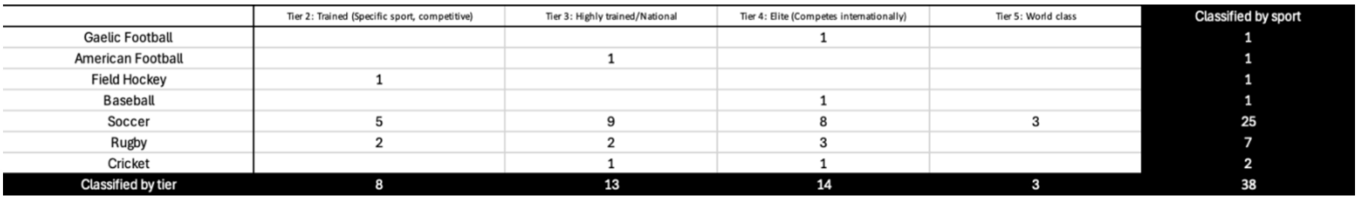
Considering how niche flywheel training is and the limited evidence available for its use in physiotherapy, a greater sample involving therapists (working within the multi-disciplinary team to prevent or rehabilitate injuries while aiming to enhance performance) with athletes across multiple field-based team sports is of interest. Investigating such insights and approaches in all field-based team sports could bridge the gap between current evidence and practice as well as develop future research directions. Additionally, focusing on this can highlight barriers to evidence-based practice and provide future research directions [56,199]. This chapter is the first to contextualise the way flywheel scientific literature is being applied in sport and to identify whether gaps in current knowledge and application of flywheel training exist. Such an approach has been utilised with a variety of topics associated with elite athlete performance [56,100]. This chapter investigates difficulties that practitioners face when applying flywheel training and may be useful for the development of new research questions. Subsequent guidelines may increase practitioners' confidence in the application of flywheel training [56], further enhancing implementation. The overarching aims of chapter 3 are to describe current application and perception of flywheel-based resistance training, aiming to contextualise how flywheel scientific literature is being applied and to identify whether gaps in current knowledge and application of flywheel training exist. It was hypothesised that flywheel training exercise prescription and frequency would vary and would be altered throughout the season amongst practitioners working in soccer. It was hypothesised that discrepancies between therapist beliefs and evidence would exist regarding the efficacy of flywheel training for reduction of injury likelihood. It was also hypothesised that flywheel devices would mostly be used during late-stage rehabilitation and for reduction of injury likelihood amongst therapists.

3.3. Methods

Participants

Fifty-one practitioners participated in the flywheel in soccer (FIS) questionnaire, including 21 strength and conditioning (S&C) coaches, 15 sport scientists, 8 fitness coaches, and 7 physiotherapists who on average had more than 2 years' experience working with flywheel training. Thirty-six worked with male players only, 3 worked with female players only, and 12 worked with male and female soccer players. Fifty-two therapists completed the therapist flywheel training (TFT) questionnaire, although only thirty-eight practitioners (12 ± 8 yrs. of experience) met the inclusion criteria of working in field-based team sports (Table 3.1). Participants were recruited through social media platforms and authors' professional networks. Sample size was maximized through chain sampling whereby participants were encouraged to invite relevant persons within their networks. Both surveys were approved by the University of Suffolk (Ipswich, UK) research ethics committee. All participants gave electronic informed consent prior to participation.

Table 3.1 The classification by tier and sport of respondents included for the TFT questionnaire.



	Tier 2: Trained (Specific sport, competitive)	Tier 3: Highly trained/National	Tier 4: Elite (Competes internationally)	Tier 5: World class	Classified by sport
Gaelic Football			1		1
American Football		1			1
Field Hockey	1				1
Baseball			1		1
Soccer	5	9	8	3	25
Rugby	2	2	3		7
Cricket		1	1		2
Classified by tier	8	13	14	3	38

Experimental approach to the problem

Participants completed either the Flywheel In Soccer (FIS) (SurveyMonkey, California, US) or therapist flywheel training (TFT) (QuestionPro, California, USA) electronic questionnaires. For the FIS questionnaire, a 5-point Likert scale was used for 14 questions, which were grouped into topics and sub-topics: 1) strength and performance, 1.1 PAPE and methodological considerations, 1.2 chronic strength outcomes, 1.3 chronic performance outcomes; 2) injury prevention. Three general application and training questions were also included, allowing practitioners to provide more detail about their application of flywheel training. For the TFT questionnaire, nine multiple choice questions on application and perceptions of flywheel training (prerequisites, use of technology, barriers, and upper- and lower-body exercises) preceded two 6-point Likert scale statements on strength and reduction of injury likelihood. For the TFT questionnaire, videos of included exercises were available (with names and execution) where relevant to standardize exercise terminology and execution between therapists.

Quantitative Analysis

Frequencies were determined for each Likert-type scale or close- ended question response, with many of the responses also presented as frequency plots. The Likert scale (strongly agree, agree, neither agree nor disagree, disagree, strongly disagree) allowed participants to report their level of agreement regarding each statement. For the FIS questionnaire, all participants were included in each analysis whereas if a respondent did not report working within a field-based team sport for the TFT questionnaire, they were excluded from the analysis, as seen in Table 3.1.

3.4. Results

Flywheel in soccer (FIS) questionnaire

Practitioners experience with flywheel devices

Thirty-three participants had ≥ 2 years of experience of programming flywheel training, with a further 14 reporting < 2 years of experience and four having no experience.

Familiarisation and Post-Activation Performance Enhancement (PAPE)

Almost all participants (*n*= 47/51) agreed familiarisation is necessary to optimise flywheel training, with few neither agreeing nor disagreeing (*n*= 3/51) and only one single participant disagreeing (Figure 3.1).

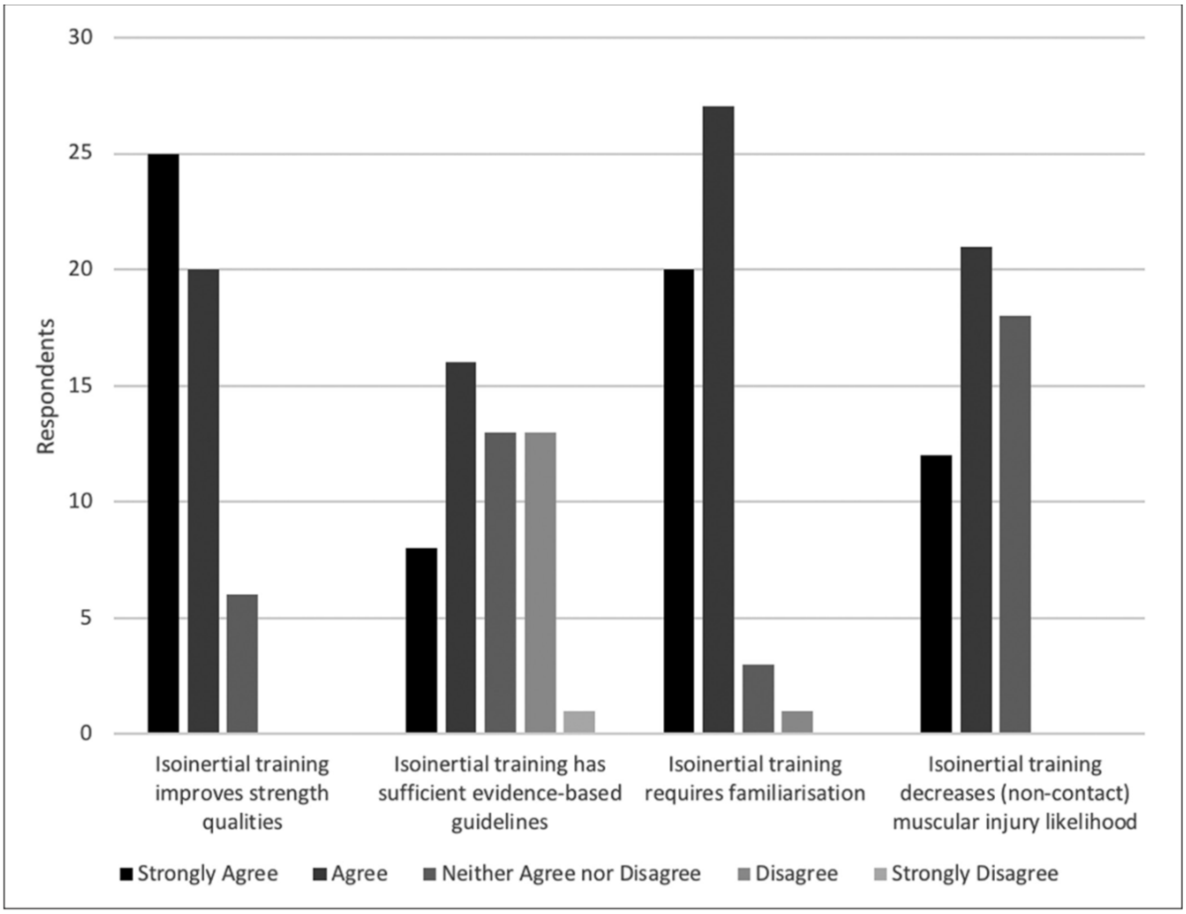


Figure 3.1. Comparing practitioners' opinions and perceptions regarding flywheel training evidence based-guidelines, necessity for familiarisation, and for strength and injury prevention (n = 51 for each statement).

One participant did not believe familiarisation sessions are necessary, nine believed one session is needed, 12 participants believed two sessions were necessary, 13 believed three sessions were needed, while nine and two participants stated four and five sessions were necessary, respectively. Finally, five participants also reported that they believe familiarisation is a player dependent process. Most participants (*n*= 37/51) believe that within the scientific literature '*flywheel training is well supported for acute sport performance enhancement*', with some (*n*= 11/51) unsure and few (*n*= 3/51) disagreeing (Figure 3.2).

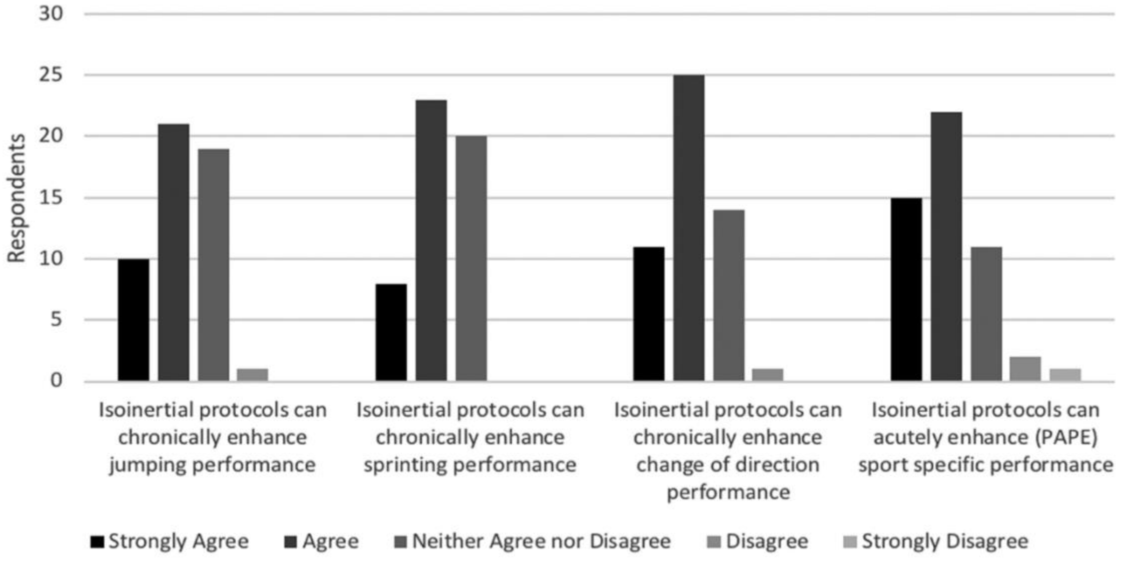


Figure 3.2. Comparing practitioners' opinions and perceptions of flywheel training for acute and chronic sport performance enhancement (*n*= 51 for each statement).

Chronic adaptations

Views on practicality and strength development with traditional resistance training and flywheel equipment are reported in Figure 3.1. More than half of participants (*n*= 33/51) agreed that an eccentric overload is necessary during flywheel training, with some (*n*= 16/51) remaining unsure, and few (*n*= 2/51) disagreeing. The most frequently programmed flywheel exercise is the squat, with other exercises reported in Figure 3.4. Practitioners' views on flywheel familiarisation and effectiveness for increasing strength are reported in Figure 3.1. Practitioner application did not differ majorly during pre- and in-season periods (Figure 3.5).

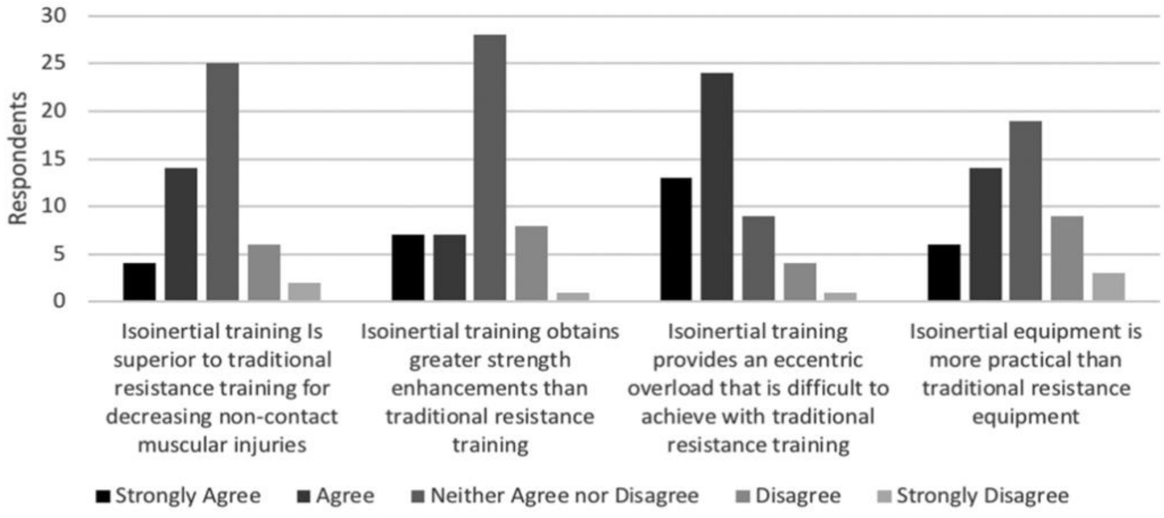


Figure 3.3. Comparing practitioners' opinions and perceptions of flywheel training and traditional resistance training (n = 51 for each statement).

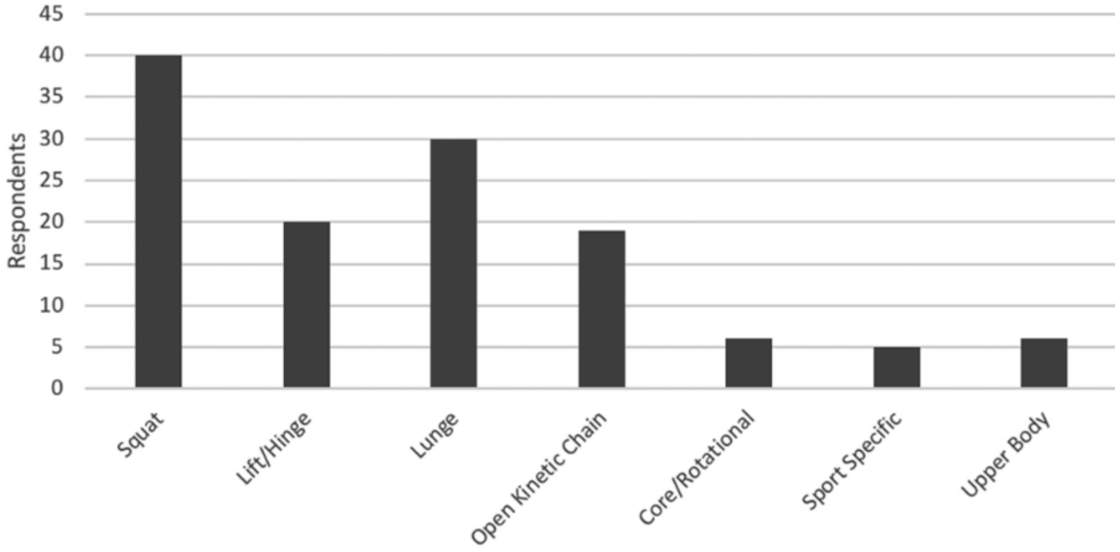


Figure 3.4. Flywheel exercises that have been programmed by elite soccer practitioners (n = 51).

Injury prevention

Flywheel training was considered by many (*n*= 33/51) practitioners to be an effective method of reducing non-contact muscular injuries, with the rest (*n*= 18/51) remaining unsure (Figure 3.1). When flywheel training was compared to traditional resistance training methods, some (*n*= 18/51) believed that flywheel methods were superior while few (*n*= 8/51) disagreed that flywheel training was superior to traditional resistance training methods (Figure 3.3). Participants mostly (*n*= 25/51) stated they neither agreed nor disagreed with the statement.

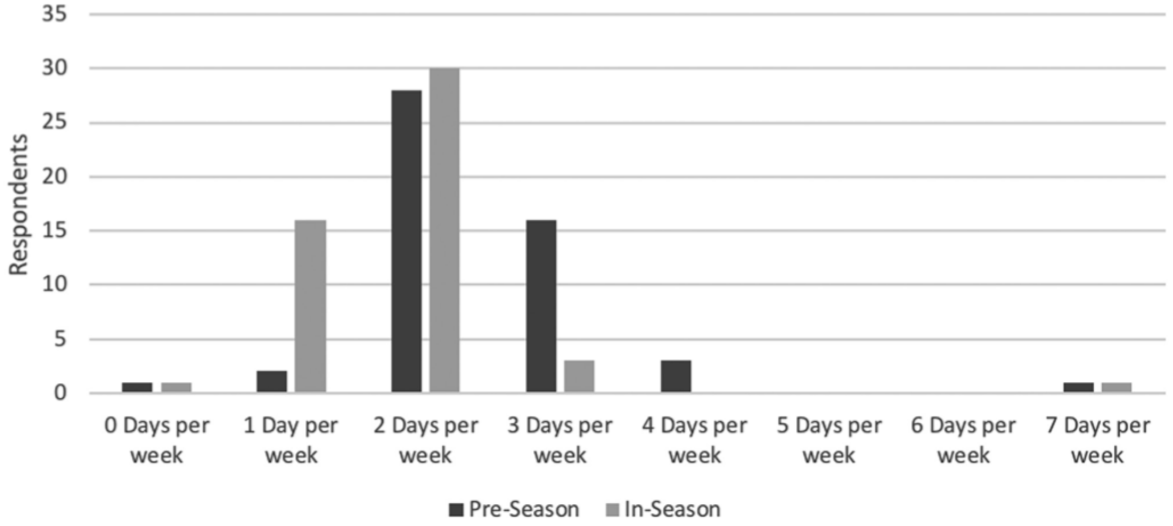


Figure 3.5. Comparing practitioners' prescription of flywheel training during the weekly micro-cycle during pre-season and in-season (n = 51 for each statement).

Therapists flywheel training (TFT) questionnaire

Most participants were physiotherapists (n= 29/38) while others were either sports rehabilitators (n= 5/38), an academic (n= 1/38), a sports therapist (n= 1/38), chiropractor (n= 1/38), or S&C coach (n= 1/38). Participants were categorized using a framework developed recently [24]. Therapists reported to have worked with trained (Tier 2 [n= 8/38]), well-trained/national (Tier 3 [n= 13/38]), elite/international (Tier 4 [n= 14/38]) or world-class (Tier 5 [n= 3/38]) athletes. Therapists who worked with Tier 2 & 3 athletes were predominantly based with males (n= n= 18/38) or mixed (n= 17/38) populations, while few worked with females only (n= 3/38). Majority of the respondents to the TFT questionnaire worked with national or international soccer players (n= 17/38), while respondents from cricket, Gaelic football, American football, field hockey and baseball made up only 17% of the sample (n= 6/38). The second most represented sport was rugby, which consisted of 7 practitioners who worked with athletes categorised as tier 2 through to tier 4. Only three participants worked with world class athletes, all of whom were working in soccer.

Use of flywheel training

A similar number of therapists stated they have often (n = 12/38) or sometimes (n = 10/38) used flywheel training, while few rarely used it (n = 2/38) or do not intend to use it (n = 2/38). Interestingly, quite a few therapists reported never having used flywheel training but would like to within their practice (n = 12/38).

Flywheel training prerequisites

Most therapists would prioritize movement competency and familiarization (*n*= 32/38) amongst their athletes prior to initiating flywheel training, with no differences between tier of athlete evidenced (Figure 3.6). Following this, the need for sufficient strength (*n*= 6/38) and training age (*n*= 7/73) were perceived as perquisites to flywheel training, while some others remained unsure about what is necessary prior to initiating flywheel training (*n*= 3/38).

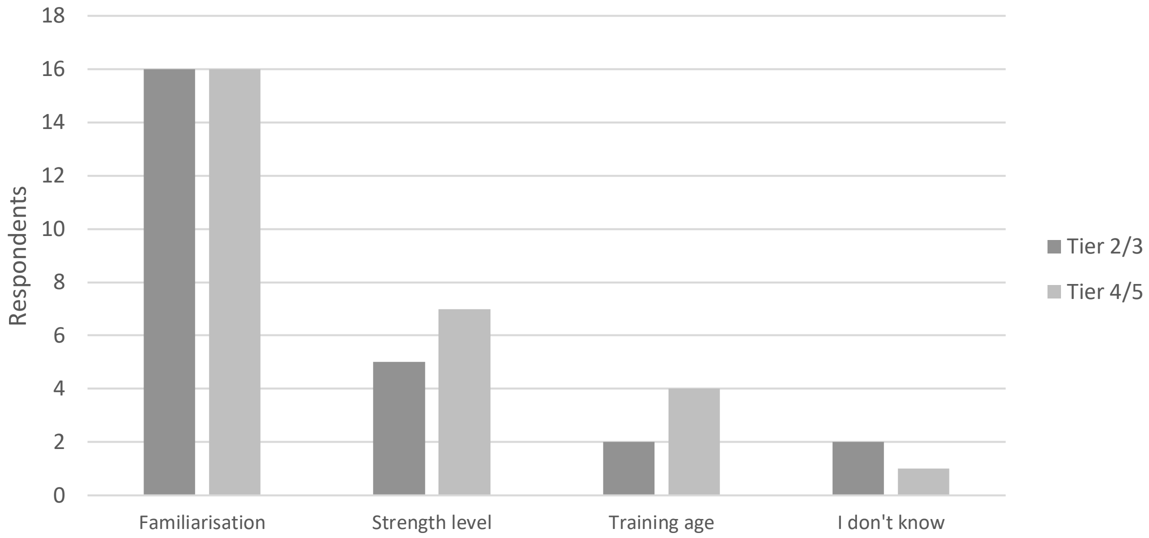


Figure 3.6 The prerequisites to flywheel training according to therapists with responses tiered by the level of athlete (classified by McKay's framework). N = 38 for each statement.

Flywheel training for enhancing strength

A majority (75%) of therapists perceive flywheel training to be effective for enhancing strength (Figure 3.7). Less than 10% of therapists do not believe flywheel training to be effective for enhancing strength while 11% were unsure. Although limited by the very small sample size (n= 3/38), most physiotherapists working with competitive and national level female athletes reported not knowing or not believing that flywheel training can effectively improve strength outcomes.

Flywheel training for reducing likelihood of injury and rehabilitation

Most (81%) therapists perceive flywheel training to be effective for reducing likelihood of non-contact muscular injuries, while 8% do not believe so (Figure 3.7). Specifically, therapists are most likely to use flywheel training to prevent likelihood of muscular injuries (66%) over tendon (61%) or ligament injuries (55%) (Figure 3.8). The most prominent use of flywheel training amongst therapists is during the return to play and re-integration stage (Figure 3.8).

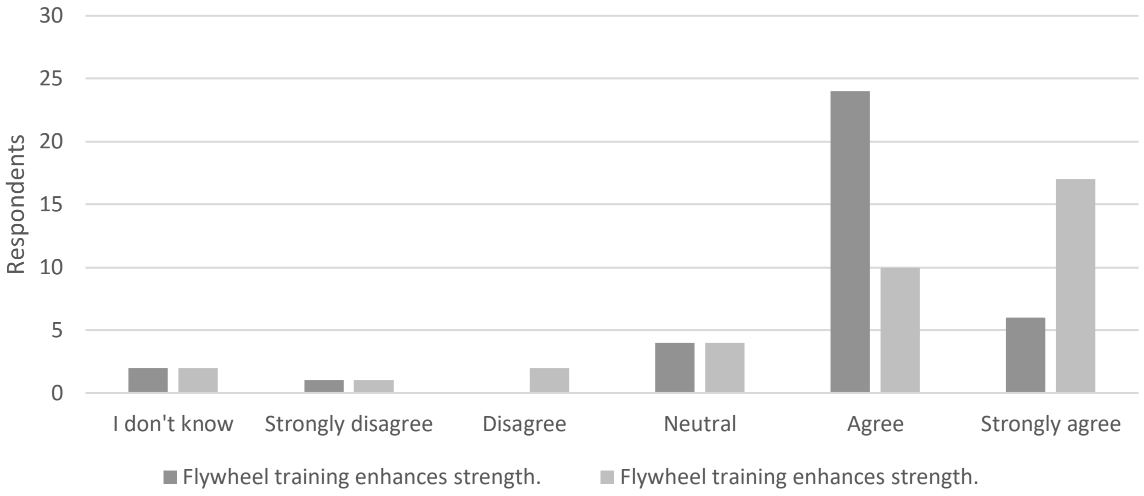


Figure 3.7. Comparing therapists opinions on the efficacy of flywheel training for reducing likelihood of non-contact muscular injury and enhancing strength. N = 37 for each statement.

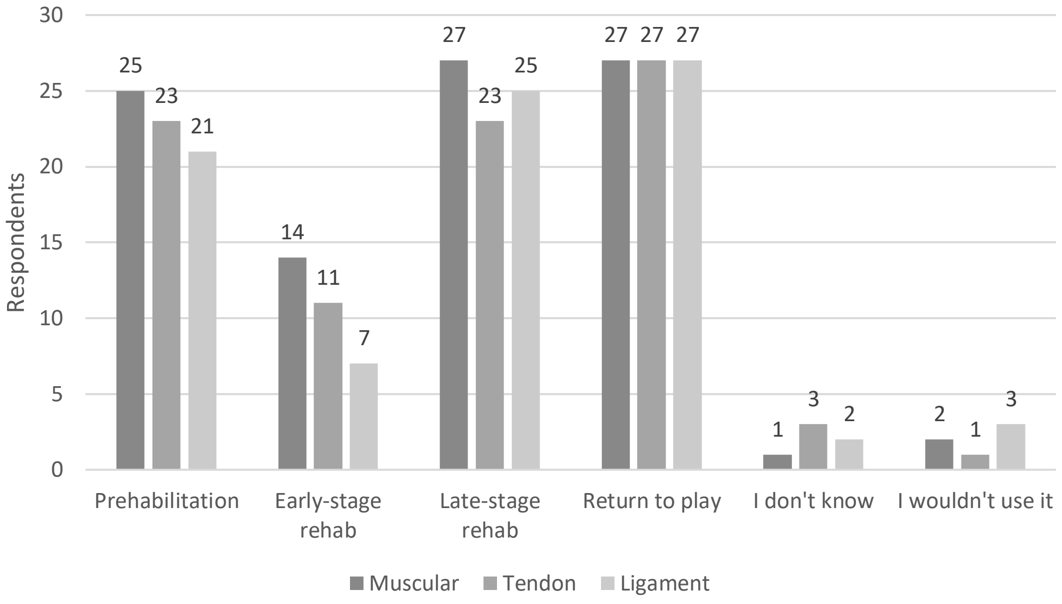


Figure 3.8. The use of flywheel training for muscular, tendon, and ligament prehabilitation and rehabilitation amongst therapists working in sport. Rehab = Rehabilitation. N = 38.

Mechanical outputs used during flywheel training

Most therapists prefer peak (n= 24/38) or average (n= 21/38) power over peak (n = 18/38) or average (n = 16/38) speed/velocity as a metric to monitor or program flywheel training. Only few (n = 4/38) stated they would not use metrics with one respondent stating they would use asymmetry (balance).

Flywheel exercise selection

Although a majority of therapists would utilize the single arm bent over row (SABOR) (71%) or single arm push (66%), 94% of therapists reported they would use rotational exercises (Figure 3.9). Interestingly, 17% of therapists suggested they wouldn't know if they'd use the single arm push while 6% suggested they remained unsure about the use of a flywheel SABOR. The lower body exercises most favoured by therapists are the squat (91%), unilateral leg curl (86%), and forward lunge (83%) (Figure 3.10). Although still utilised by the majority of practitioners (74-80%), the lateral squat, unilateral hip extension, and Romanian Deadlift were not as likely to be utilised by the surveyed practitioners. The two unilateral hamstring exercises are amongst the lower body exercises that the surveyed practitioners are most unsure about prescribing (9%) (Figure 3.10).

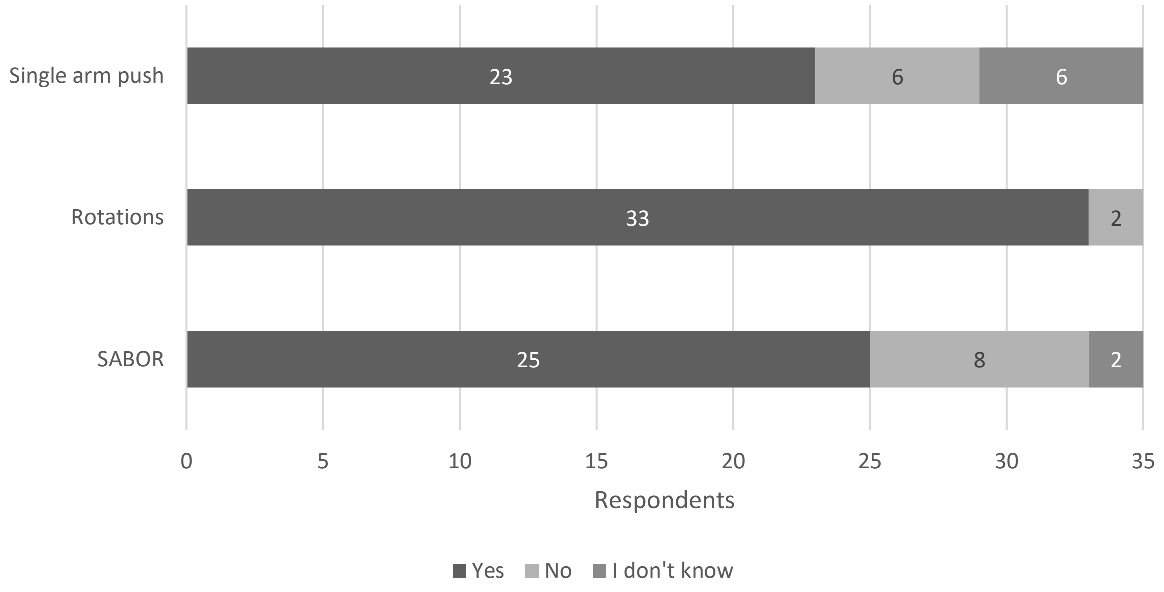


Figure 3.9. Upper body flywheel exercises amongst therapists working in sport. SABOR = Single arm bent over row. N = 35 for each statement.

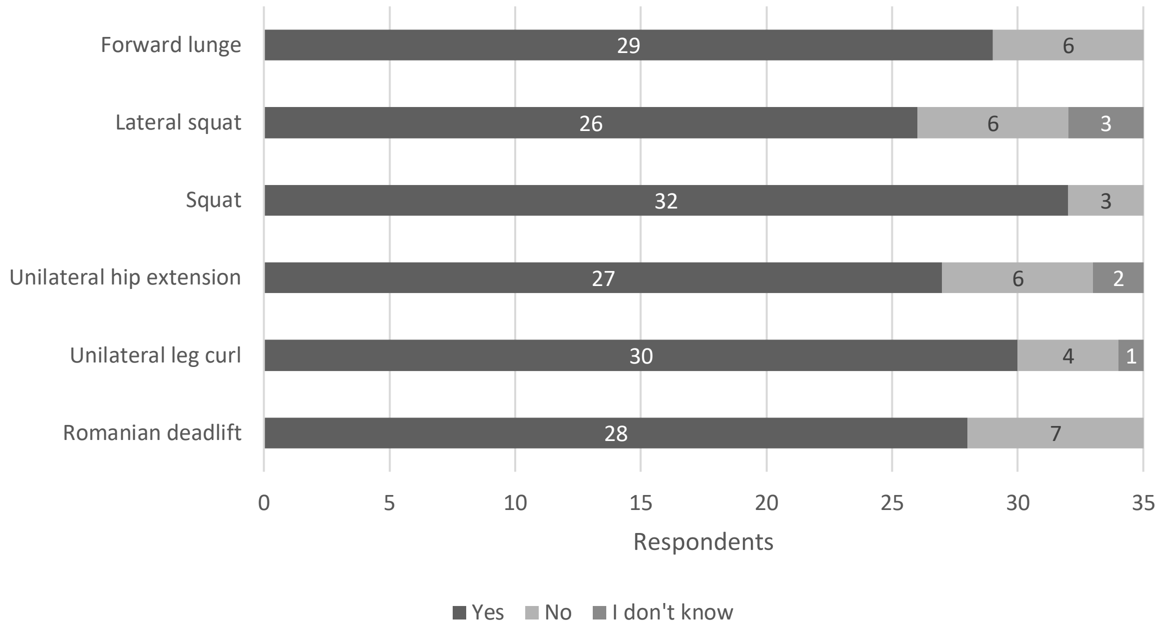


Figure 3.10. Lower body flywheel exercises amongst therapists working in sport. N = 35 for each statement.

Barriers to flywheel training

The biggest barriers to the use of flywheel training amongst therapists are equipment cost or space (*n*= 21/38). Although some therapists perceive there to be no barriers (n = 8/38), others perceive evidence and knowledge (*n*= 14/38), scheduling (*n* = 7/38), or safety (n = 1/38) to be barriers to use of flywheel training.

3.5. Discussion

The overarching aims of Chapter 3 are to describe current application and perception of flywheel-based resistance training. The chapter brings novel information on how the flywheel scientific literature is applied by practitioners. Importantly, the present chapter is the first to identify whether gaps in current knowledge and application of flywheel training exist and compare current perceptions to the literature reviewed previously in Chapter 2. Specifically, Chapter 2 identified that practitioners are aware that a familiarisation period is needed to optimize the performance and outcomes with flywheel training. The FIS questionnaire found a clear majority of practitioners are confident in the application of flywheel training for acutely enhancing performance through PAPE protocols. Although some uncertainty remained, most FIS questionnaire respondents believed that flywheel training is useful for chronically enhancing change of direction, sprint, and jumping performance. Similarly, although some practitioners remained uncertain, the FIS questionnaire identified that most practitioners believed that flywheel training is useful for decreasing injury likelihood. The TFT questionnaire also identified important differences between the perceived benefit and actual evidence for using flywheel training to reduce injury likelihood exist. The FIS questionnaire highlights that most respondents would prescribe flywheel training more in pre-season than the in-season period, which is in line with present guidelines and reflects key changes between tactical, technical and physical objectives throughout the soccer season. Most practitioners would program the flywheel squat and rotational exercises, while respondents remain more unsure about upper body (push, pull) and unilateral or split stance lower body exercises (hip extension, lateral squat) (Figure 3.4 and 3.10). Although a clear majority of practitioners are confident in the application of flywheel training for acutely and chronically enhancing strength, the FIS questionnaire highlights lacking confidence or awareness of flywheel training guidelines. The present chapter highlights that a lack of guidelines may systematically impact efficacy and application of flywheel training in field-based team sports, especially where evidence is even more limited – like with female athletes.

Prerequisites & Familiarisation to flywheel training

It is likely that if a training intervention is short in duration or limited in frequency, the initial few sessions would likely still involve some degree of familiarisation if athletes were naïve to flywheel training and thereby reduced the true response to training [205]. A majority of practitioners believe that an appropriate familiarisation process is necessary to enhance training outcomes (Figure 3.1 and 3.6). Following this, practitioners perceive a sufficient strength level and training age to be a prerequisite to the use of flywheel training (Figure 3.6). Little remains known about the impact of strength and training age on the efficacy of flywheel training [39]. The need for sufficient strength or training age prior to introduction of flywheel training may be particularly relevant with youth populations or athletes rehabilitating from surgery or long-term injuries [63,105,106], with almost all research limited to male populations. Although a relatively strong consensus seems to have been reached amongst the surveyed practitioners, the literature does not provide clear guidelines on how many sessions or which methodology is most appropriate to familiarise athletes with flywheel resistance training [17,39]. Previous studies have reported using either no sessions [74], one [34,38,40,51,73,81,97], two [22,49,52,84], three [8,35], 4–6 sessions [4], or participant dependent familiarisation [98].

Specific to the FIS questionnaire, a large portion of practitioners (n = 25) believe it is necessary to program two or three familiarisation sessions, which is in line with current recommendations [30,39]. Some practitioners (n = 9) believe one familiarisation session is sufficient, possibly due to the limited time for strength training [94] or in reflection of most of the literature which employs one session. An equal number of practitioners (n = 9) utilise 4 familiarisation sessions. Such sessions may be characterised by lower intensity or volume, as a strategy to mitigate any negative impact of initial flywheel training sessions on concurrent soccer training and performance – although this cannot be confirmed. Indeed, some practitioners are likely to familiarise athletes with flywheel training as a part of a micro-dosing strategy whereby other stimuli (with which the athletes are familiarised with) are utilised to provide a higher quality training session. Utilising four familiarisation sessions may not be feasible for practitioners working with athletes who have many commitments such as international team duty or congested fixture periods. In this case, it may be more practically viable to spend one or two sessions (at most) familiarising the athletes and utilising less complex and more commonly practised exercises (i.e., squat). Few (n = 5) practitioners believe familiarisation is dependent on the athleticism, coordination, and training age of the athlete. Although such an approach is sensible, little is published on the topic. Considering an athletes athleticism and training age may be particularly important when implementing flywheel methods with youth or novice athletes [51].

It is possible that some practitioners also view familiarisation as a ‘tick box activity’ even though it is a key part of utilising flywheel training efficiently. Although less explored in the literature, the combination of objective mechanical outputs (i.e., power) [18], qualitative feedback, and sufficient athlete confidence are likely to optimize familiarization and movement competency with flywheel training. A comprehensive and thorough approach to familiarisation should be considered by practitioners and researchers.

Flywheel training and PAPE

Most practitioners (n = 37) believed that PAPE protocols can acutely enhance performance, which is supported by the scientific literature [34,38,40]. Desirable neuromuscular responses elicited by flywheel PAPE protocols are related to effective activation of the musculature at a greater velocity and force, improving strength and task specific performance [30]. The integration of a flywheel PAPE protocol could provide a practical and effective option to enhance the intensity and training demands of a session. For example, if coaches are aiming to increase the intensity of their plyometric training, they could pair an appropriate dose of flywheel squats with sufficient rest and subsequently increase the training demands of the session.

Although the use of flywheel training has shown promise in the scientific literature, limited research on the effects of differing moments of inertia, volume, and exercises on PAPE performance may have impacted practitioners’ beliefs. Some practitioners reported they neither agreed nor disagreed (n =

11) and few others stating they disagreed (n = 3) that flywheel PAPE protocols acutely enhance sport performance. Nonetheless, comparisons between flywheel PAPE and traditional resistance PAPE squat protocols report similar positive outcomes [34] with comparisons of different moments of inertia [39] and movements [40] also attaining similar enhanced outcomes. These studies support practitioner confidence in application of flywheel PAPE protocols to enhance change of direction and jumping outcomes within a variety of contexts [39]. Nonetheless, conclusive evidence on speed performance (≥ 10 m) enhancement within a flywheel PAPE protocol is still needed. Although the long-term effects of this training methodology have not been studied nor compared to other approaches, coaches can be confident that flywheel PAPE protocols can significantly enhance sport performance.

Flywheel training for enhancing sport specific capacities

Chronic performance enhancement of jumping, sprinting, and change of direction have been achieved with 1–3 weekly training sessions over a 6–10-week period involving 3–6 sets of 6–10 repetitions [4,50,81,87,97]. Based on the FIS questionnaire, practitioners (n = 31) mostly agree that jumping, an important capacity in team sports [98], can be enhanced by flywheel training. Although flywheel training has improved jumping performance in highly trained youth [21,22,50,87,98], semi-professional, and professional male team sport players [49,74,80,81], some practitioners (n = 19) stated they neither agreed nor disagreed, while one practitioner disagreed with such statement (Figure 3.2). Some of the practitioners (n = 16) prescribing weekly training sessions during the in-season period may also be encouraged by the literature showing how such exposure can specifically enhance unilateral vertical and horizontal jumping ability after 7–10 weeks of training with youth soccer players [42,81]. Such a low dose approach may be a viable short-term alternative to precede more comprehensive and time demanding protocols [94] or as a long-term method to maintain vertical jumping performance over a 24-week period with an athletic population at risk of patellar tendinopathies [74].

Most practitioners (n = 31), responding to the FIS questionnaire, agreed that flywheel training can enhance sprint speed (Figure 3.2), with evidence supporting such an approach with male youth and professional soccer players and professional handball players [4,50,80]. Nonetheless, the rest of the practitioners (n = 20) stated they neither agreed nor disagreed, reflecting some inconsistency in the literature [22,42,49]. Interestingly, the weekly or bi-weekly exposure utilised in the flywheel soccer literature [4,22,49,50] has also been adopted by many practitioners in the present chapter (Figure 3.5) – even if such an approach has not always been successful in enhancing performance [22,42,49].

Specifically for the FIS questionnaire, a large portion of practitioners (n = 36) agree that flywheel training can improve change of direction performance, an important determinant of soccer match play performance [49]. Importantly, practitioner views are in line with evidence supporting flywheel training for enhancement of change of direction performance [4,22,42,49,50,52]. Eccentric strength, one of several factors associated with successful change of direction performance, can be improved by flywheel training [47]. Investigations lasting 6–11 weeks have enhanced change of direction performance with semi-professional male soccer players [49], athletes with limited training experience [22], and professional handball players [80]. Nonetheless, some practitioners (n = 14) neither agreed nor disagreed and one disagreed that flywheel training can enhance change of direction performance. Considering the evidence supporting the use of flywheel training for enhancing muscle activation and the ability to sustain greater intense deceleration and stabilisation with athletes [22,84] – it remains unclear why practitioners are lacking confidence in flywheel training for enhancing change of direction performance.

Flywheel training for reduction of injury likelihood

Injuries, especially hamstring muscular strains, are common occurrences amongst field-based team sports athletes during competitive in-season periods [106]. Strength training, such as flywheel training, is considered a key factor when aiming to reduce likelihood of injury [104]. The importance of appropriately dosed intense eccentric training throughout the competitive period is highlighted by the increased risk of muscle damage and injury associated with its prolonged absence (e.g., > 4 weeks) [73]. Indeed, 72% of practitioners believe that flywheel training is effective for reducing likelihood of non-contact muscular injury (Figure 3.1 and 3.7). Various forms of strength training with a particular emphasis on eccentric training has shown to reduce injury risk amongst athletes [17]. The use of flywheel training to reduce likelihood of muscular injury is also supported by a few investigations that have reported beneficial outcomes with male soccer players [4,50]. These studies prescribed flywheel squats and/or hamstring curl training protocols weekly or twice per week [4,50,96], which are among the more commonly prescribed exercises by practitioners (Figure 3.4 and 3.10). Although some evidence supports the integration of flywheel training for preventing muscular injury, the limited evidence supporting the use of flywheel training for prehabilitation of tendon or ligament injuries is reflected in the present chapter with fewer therapists utilizing it for such purposes (Figure 3.8). Nonetheless, flywheel training can effectively enhance the ability for muscles such as the quadriceps to control knee movement and thereby reduce rotation valgus stress on the knee ligaments, potentially playing a part in the reduction of injury likelihood to ligaments [206].

Flywheel training for rehabilitation

The TFT questionnaire reports that flywheel training is typically re-integrated at various stages of rehabilitation. The return to play (RTP) programme must follow a thorough and phased process where the athlete is progressively exposed to training which ultimately aims to involve sport specific movements in competitive, intense, and realistic demands that replicate competition [207]. The use of flywheel training within rehabilitation settings is supported by the enhanced neuromuscular capacity, musculotendinous stiffness, and connective tissue strength associated with maximal strength training during rehabilitation [100]. The findings of the TFT questionnaire suggest therapists would re-integrate intense eccentric training (i.e., flywheel training) during late-stage rather than early-stage rehabilitation (Figure 3.8), in line with traditional recommendations of progressive rehabilitation guidelines [100]. Nonetheless, a greater number of therapists would re-introduce flywheel training sooner when rehabilitating muscular injuries (37%) in comparison to tendon (29%) or ligament (18%) injuries (Figure 3.8). Such views are supported by the specific characteristics and advantages of flywheel training that may simultaneously reduce likelihood of re-injury and enhance performance [96]. Although published trials involving re-introduction of flywheel training within the early phase of rehabilitation are unavailable, evidence supporting the use of lengthening exercises earlier within rehabilitation with progressively increased eccentric load are promising [111,112]. Specifically, training with an eccentric emphasis significantly reduced time to return (28 [8- 58] days) in comparison to a conventional training protocol (51 [12-94] days) [111], supporting the use of flywheel training within rehabilitation. In support of the approach utilized by some therapists in the present chapter, re-introduction of lengthening exercises earlier in the rehabilitation of muscular injuries also quickened return to sport (23 days) compared to a typical “delayed lengthening” protocol (33 days) without negatively impacting re-injury rates between groups [112]. It is important to recognise that evidence available to support early integration of eccentric training is still limited and it would certainly depend on the type of injury and other circumstances present (competitive pressure, age, etc.) [95]. For example, the integration of delayed eccentric training has shown to be effective with hamstring intramuscular tendon injuries [208]. Overall, flywheel training allows for greater customisation of training by manipulation of exercise intensity, volume, and technique [101]. Indeed, flywheel training can also allow for the customisation of movement patterns to specifically target muscle groups that have been injured, to supplement training (by conditioning other muscles that are not injured), or to prepare movements that may be particularly relevant to the sport [95].

Differences between pre- and in-season prescription in soccer

The FIS questionnaire highlights that most practitioners prescribe flywheel training 2–3 times per week (n = 44) and 1–2 times per week (n = 46) during the pre- and in-season period, respectively (Figure 3.5). The reduced training frequency applied from pre- to in-season periods by practitioners is in line with present guidelines [46] and reflects key changes between tactical, technical and physical objectives throughout the soccer season [14,30]. Apart from athlete, coach, and environmental factors (e.g., team timetables), considerations for exercise choice, intensity, and volume are important for determining optimal training frequency [39,44,46]. The application of low volume flywheel protocols [22,35,38,42,74,81] may be particularly important during the initial stages of the in- season period if athletes are not accustomed to flywheel training. Careful consideration of training frequency and volume may be important for reducing injury risk [23,39] and for maintenance of muscle strength and sport performance in-season [42]. Similar to what was proposed previously, the micro-dosing of flywheel training may allow for greater volume without excessively taxing athletes during the initial in-season period. Similarly, the use of maximal isometric training as well as typical exposure on flywheel devices may be a valid method of increasing training volume and initially familiarising athletes with the device while reducing the likelihood of excessive fatigue. Nonetheless, the periodisation of flywheel training during the competitive period must be further explored as currently there are only few studies comparing the use of different strategies [136].

Upper body Flywheel training exercises

The present chapter is the first to investigate how upper body flywheel exercises are perceived and applied in field-based team sports. The FIS questionnaire identified that only 24% of practitioners working in soccer would use upper body and core exercises (Figure 3.4). Meanwhile the TFT questionnaire found that almost all therapists would use rotational exercises (94%) while most would consider using unilateral pull (71%) and push (66%) exercises (Figure 3.9). Evidence supporting the use of flywheel training with team sport athletes is limited and based solely on male athletes. Specifically, three weekly sessions over a 12-week period of unilateral pull and rotational flywheel exercises enhanced shoulder isometric strength and range of motion in comparison to a control condition (which also included strength training) with youth male tennis athletes [108]. Another bi-weekly program of either flywheel or pneumatic resistance training similarly enhanced isokinetic shoulder strength, hypertrophy, and throwing speed outcomes with professional male hand ball athletes [109].

Lower body Flywheel training exercises

Both questionnaires highlight that most (84%) practitioners would program the flywheel squat (Figure 3.4 and 3.10). The findings of the present chapter are in line with the flywheel literature which mostly consists of bilateral squat protocols [21,27,34,35,38,40,50,52,84,97]. The findings of the present chapter are also supported by a previous questionnaire amongst practitioners working in elite sport. Specifically, the questionnaire reported a similar trend, whereby most practitioners would also prescribe variations of eccentric squats more so than other typologies of eccentric exercises [14]. Since the flywheel squat is one of the most applied and researched exercises, an interest in practically enhancing its application has grown. Generally, interest in 'eccentric overload' and it's confirmation has grown in the flywheel literature [66,78,80]. More recently, a great deal of effort has been placed on finding innovative and practical ways to increase training intensity (and specifically the eccentric demands) of flywheel training, with a specific focus on the flywheel squat [209]. Previously, the manipulation of range of motion and moments of inertia selected were the most well-known and used methods to alter eccentric outputs relative to concentric outputs [83]. Nonetheless, a recent study showed that performing assisted squats (whereby athletes utilise assistance during the concentric phase) increases flywheel peak power outputs in comparison to traditional flywheel squats [209]. Indeed, a moderate to very large difference in eccentric peak power was obtained between assisted and unassisted squats. Although this provides a practical method to progressively overload the eccentric phase of the squat with excellent reliability, little remains known about other exercises and how to manage training intensity and eccentric overload.

In contrast to bilateral squats, few protocols within the flywheel literature have utilised lateral [22,42,52,87] squats. The lack of evidence supporting the use of lateral flywheel squats is reflected by the reduced reported use amongst TFT questionnaire respondents (Figure 3.10). Contrasting this, although few studies have investigated the use of Reverse [22] and forward lunges [42,81], a large amount of FIS questionnaire respondents reported utilising flywheel lunges in practice (59%). The limited evidence available suggests that bi- and uni-lateral eccentric capacity has been enhanced via flywheel multi-planar movements [22,52], supporting use of flywheel lunge and multi-directional training (Figure 3.4). The present chapter highlights that practitioners working in field-based team sports have a significant interest in using flywheel resistance training to strengthen the posterior chain, with a specific focus on the hamstrings (Figure 3.4 & 3.10). Based on the TFT questionnaire, as many as 86% of therapists would use the unilateral flywheel leg curl exercises in their practice. Amongst 89 practitioners included in the present chapter, more than half (57%) of practitioners would utilise open kinetic chain exercises (such as the unilateral hip extension), even though little evidence is available to support its use for enhancing strength amongst athletes. Additionally, the two unilateral hamstring exercises included in the TFT questionnaire were the lower body exercises practitioners were most unsure about prescribing (9%). Future investigations should study the effects of manipulating training variables (moment of inertia, volume, exercises) with open kinetic chain hamstring exercises that are relevant to field-based team sports to increase the efficacy of such training programmes.

Importantly, further research specific to exercises that are of interest to practitioners (*i.e.,* unilateral hamstring exercises) are needed to further enhance their application [66], as has been done with the flywheel squat [209]. Amongst TFT questionnaire respondents, only equipment cost and space (55%) was believed to be more of a barrier to application of flywheel training than evidence and knowledge (37%). Other factors that may influence exercise selection and use of flywheel training are training purpose, athlete compliance and experience [94,98]. Further high-quality investigations may reduce the impact of other barriers (scheduling, bias and culture, or safety) on the application of flywheel training[43]. Apart from research on specific exercises (unilateral hamstring exercises), further studies specific to female athlete populations are especially needed due to the under-representation present in the literature (Chapter 2) and in practice (Chapter 3).

Flywheel training enhances strength

A large majority of respondents between the two questionnaires (84%) believe that flywheel training can enhance strength. Amongst FIS questionnaire respondents, the overloaded eccentric phase is perceived to be crucial for most practitioners (n = 33) when applying flywheel training. Although some practitioners neither agreed nor disagreed (n = 16) and others disagreed (n = 2), the perceived importance of a high intensity eccentric muscle action can be attributed to the vast evidence supporting its use and well-established benefits [39,44,57]. Specifically, practitioners may be particularly attracted to the ability of high intensity eccentric training to preferentially recruit high threshold motor units and increase cortical activity – which may boost strength adaptations [23,97].

Specifically, 75% of TFT and 88% of the FIS questionnaire respondents believe that flywheel training can enhance strength (Figure 3.1 and 3.7). It is plausible that the evidence specific to soccer populations available may have increased confidence amongst practitioners working solely in soccer [71]. Indeed, although the need for strength and power training to reduce injury likelihood and rehabilitation is evident [100], 25% of therapists responding to the TFT questionnaire stated they were either neutral, disagreed, or didn't know whether flywheel training was effective for enhancing strength (Figure 3.7). The limited evidence within the realm of rehabilitation and sports therapy may limit confidence for use of flywheel training amongst therapists and may explain the differences between the TFT and FIS questionnaires findings [12,63,106]. The TFT questionnaire highlights an interesting novel finding that most physiotherapists working with competitive and national level female athletes reported not knowing or not believing that flywheel training can effectively improve strength outcomes. Like the bias present in the literature (see chapter 2 for more details), the present chapter is mostly represented by practitioners working with males, with only 15% of respondents working only with females between the FIS and TFT questionnaires. Since less is known about how effective flywheel training is for enhancing strength with female team sport athletes and little is known about how it is applied, further study into the effects of flywheel training on strength amongst female athlete populations is necessary. The perceptions of practitioners working in field-based team sports on the use of flywheel training to develop strength, although mostly biased towards practitioners working with male populations, are supported by the literature explored on flywheel training in Chapter 2 (please see Table 2.3 for more specific information).

Flywheel training vs traditional resistance training

The FIS questionnaire highlights that 27% of practitioners believed that flywheel methods were superior to traditional resistance training methods for increasing strength, while 55% neither agreed nor disagreed with the statement (Figure 3.3). Uncertainty amongst practitioners reflects the state of the research [39,44]. Primarily, a lack of evidence impacts the conclusions drawn [44], with largely contrasting findings also presented [39,44,51]. Comparisons of equipment practicality show practitioners remain more divided – with some (39%) agreeing, others neither agreeing nor disagreeing (37%), and fewer practitioners disagreeing (24%) that flywheel training equipment is more practical than traditional resistance equipment. An aspect that makes flywheel training more practical than traditional resistance training are the variety of easily accessible validated and reliable measures that can highlight changes in concentric and eccentric strength [17,21]. Indeed, only 11% of TFT questionnaire respondents suggested they wouldn't use output measures. In line with the literature [80], practitioners prefer power (55-63%) over velocity (42-47%) measures to manage flywheel training. It is possible that practitioners prefer the use of power measures because of the strong correlation shown previously in the literature [81]. Indeed, both concentric and eccentric peak power outputs during the flywheel squat showed *large* (Pearson correlation coefficients [r]) correlations with concentric knee extensor ($r = 0.53$ to 0.56) and eccentric knee flexor ($r = 0.52 – 0.50$) torques [81]. The similarity between muscle actions and neuromuscular demands is likely to explain this correlation. Although quantification of load requires little equipment or time [17,34], differences between devices and moments of inertia may present issues regarding reliability, potentially impacting its use for practitioners [39]. Although research dedicated to developing application and safety of flywheel training among athletes is growing [39], the present chapter clearly evidences a divide exists amongst practitioners regarding flywheel training practicality (Figure 3.3). Nonetheless, as devices become more commonplace, further evidence is disseminated, and flywheel training is further integrated into practice – it is likely that flywheel training will be considered more practical.

Flywheel training may also be perceived as a safer and more manageable method than traditional resistance training methods for practitioners working with populations less accustomed or willing to perform intense eccentric training, although opinions may differ between practitioners due to familiarity with flywheel devices [14]. There are many methods that can be used to overload flywheel training. For example, flywheel devices do not require third-party assistance (e.g., coach) or implements (e.g., chains) to create greater overload and manipulation of training - enhancing both practicality and safety [14]. In support of this, a majority of practitioners (73%) believe that flywheel devices provide an eccentric load that is difficult to achieve with traditional resistance training, which is in line with the literature [39]. Although evidence supports such a statement [8,34], several practitioners neither agreed nor disagreed (18%) or disagreed (10%). Differences between devices and techniques may alter eccentric load achieved – possibly swaying practitioners' opinions on this issue [8,14,39]. The continued use of evidence-based programmes involving multiple exercises are recommended for male sporting populations rather than relying solely on one exercise or training modality [49,71,84,93]. Although such recommendations may be practical for male sporting populations, the limited sample available for females limits conclusions on this topic. Further high-quality research is needed on the topic.

3.6. Limitations and future directions

This chapter is not without limitations. Firstly, this chapter may not allow for generalisations to all practitioners working in field-based team sport due to various types of bias (affecting respondent participation and responses given). Nonetheless, it increases awareness of perceived limitations and supports the need for further study (addressed in the subsequent chapters). It is likely that practitioners who are more confident or well versed with flywheel training may have been more likely to participate, thereby skewing the responses in the questionnaires to bias flywheel training. The present chapter is also mostly represented by practitioners working in soccer (85%), therefore may not thoroughly represent how flywheel training is applied and perceived in other field-based team sports. Another limitation related to the participation in the questionnaires is the lack of practitioners working with female athletes. Specifically, less than 10% of respondents worked only with female athletes – limiting conclusions drawn with this population. The present chapter highlights future investigations should aim to also provide further information on the use of metrics (such as power and speed/velocity) to guide training and rehabilitation (discussed in Chapters 4 and 5). Additionally, the use of unilateral hamstring exercises, which have received a lot of attention by practitioners should be further studied. It is crucial future studies investigate the efficacy of flywheel training in comparison to traditional resistance training amongst female athletes to better understand how flywheel training can be applied with an athletic female population.

3.7. Conclusion

This chapter is the first to provide valuable insight into the application and perception of flywheel training amongst practitioners working in sport. In total, 103 practitioners working across separate sports and from different disciplines were involved in the present Chapter. Most practitioners agree that flywheel training can improve strength and likelihood of non-contact injury outcomes. More specifically in soccer, flywheel training is typically applied twice per week and mostly consists of squats. Although the present chapter highlights that the most frequently prescribed exercise, a variety of exercises, including unilateral hamstring exercises are often prescribed but remain under investigated within the literature. Indeed, nearly half of all FIS questionnaire respondents (n = 24) stated they were not satisfied with the current guidelines for flywheel training within soccer (Figure 3.1). Specifically, little remains known about how modulation of training variables with specific exercises (*i.e.,* unilateral hamstring exercises) influences key training variables. As addressed within the chapter, further study is necessary to understand and quantify flywheel training. Nonetheless, FIS questionnaire respondents (mostly working in male soccer) perceive flywheel training to be effective for developing strength and performance outcomes, a finding that agrees with the current literature on male soccer highlighted in Chapter 2. Similarly, practitioners investigated in Chapter 3 perceive flywheel and traditional resistance training methods to similarly enhance strength, a statement the literature currently supports with male athletes (Chapter 2). Similar to the previous chapter, limited knowledge on the application and perception of flywheel training exists with female athletes. Overall, this Chapter highlights some interesting trends, concepts, and ideas that are very much biased towards male field-based team sport populations. The present chapter further emphasises that not only is there a limited amount of literature on flywheel training with female athlete populations (Chapter 2) but there is also limited evidence on how flywheel training is applied with female athletes. In line with this, future study should explore how traditional and flywheel resistance training may differ for enhancing strength with female athletic populations.

Chapter 4 - The effect of flywheel inertia on peak power and its inter-session reliability during two unilateral hamstring exercises: leg curl and hip extension.

Publication arising as a result of this chapter:

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4.1. Abstract

The present chapter investigated how alterations in flywheel moment of inertia (0.029, 0.061, and 0.089 kg·m^2) influenced concentric and eccentric peak power and the eccentric:concentric peak power ratio during two unilateral hamstring exercises (leg curl and hip extension). Furthermore, the inter-session reliability of peak power was analysed during both exercises. Twenty amateur male soccer athletes attended five visits – performing a protocol (three sets of eight repetitions for all inertias) of a unilateral leg curl or unilateral hip extension each session. There were no significant differences in any measure between moments of inertia ($p = 0.479$) but a greater eccentric than concentric peak power for all moments of inertia ($p < 0.001$) during the leg curl. Differences between moments of inertia were reported for all measures ($p < 0.05$) during the unilateral hip extension. Specifically, the lowest moment of inertia elicited the greatest concentric peak power ($p = 0.022$), there were no differences with the medium moment of inertia ($p = 0.391$), and the greatest moment of inertia obtained the greatest eccentric peak power ($p = 0.036$). Peak power measures obtained acceptable to excellent reliability while the reliability of the eccentric:concentric ratio was considered *unacceptable* to *good* for both exercises. Different moments of inertia can elicit similarly high eccentric knee flexor demands during unilateral leg curls, while higher moments of inertia are needed to obtain an eccentric-overload in peak power variables during unilateral hip extensions. Differences between exercises highlight that there is no universal inertia-power relationship between athletes or exercises. The concentric and eccentric peak power outputs could be used to prescribe and adjust training as necessary. The eccentric:concentric ratio should not be used within practice.

4.2. Introduction

The perception and application of flywheel training in field-based team sports highlights a clear gap in the literature, with lacking evidence-based guidelines, and high-quality research. Specifically, little remains known about how to manage and manipulate exercises of interest to practitioners or whether such exercises enhance key performance indicators (*i.e.,* power and strength). A key finding from the previous chapters is that little evidence supports the practices of practitioners utilising flywheel training in field-based team sports. For example, although a great deal of research has gone into the use of flywheel squats for testing and training [64,81,141], little is known about different unilateral flywheel exercises, such as hamstring exercises.

The demands of modern-day field-based team sports require enhanced strength and conditioning programmes to enhance long-term performance and strength while aiming to reduce injury likelihood [7,196]. The in-season period, with its prolonged duration, fixture congestion, and large travel demands can create challenges for managing training load and preparing elite athletes [140,210]. Among these issues, the high incidence and recurrence of muscular injuries, particularly hamstring injuries, are significant concerns in modern-day sport [7,211]. Various training methods have been applied to reduce injury likelihood and improve performance with field-based team sport athletes [61,132,141,212,213]. Fundamentally, such exercises (which often have a focus on the eccentric muscle action) elicit unique neuromuscular benefits [63,67]. Such exercises focus on the eccentric phase because it has been hypothesised that hamstring injuries occur during the eccentric phase of sprinting-type and closed-chain stretching-type movements – which require rapid eccentric muscle actions [95,114]. Traditional resistance training exercises, involving hip extension or knee flexion have been used to reduce likelihood of hamstring injury [214–216]. Evidence suggests that a large majority of injuries occur to the biceps femoris (84%) rather than the semitendinosus (11%) and semimembranosus (5%) muscles [217]. An appropriate strength training strategy focusing specifically on the proximal area of the biceps femoris is therefore likely to be beneficial to reduce likelihood of injury [95]. Therefore, the focus on appropriate training of the biceps femoris area is even more important as prolonged negative effects (*i.e.,* reduced neuromuscular activation) of injury can be prominent in this area [218,219]. While hip-dominant exercises (*i.e.,* single and double leg deadlift, 45° hip-extension exercise) have shown to activate the proximal area of the biceps femoris [214], the use of knee dominant hamstring exercises is very commonplace in practice and warranted according to guidelines [117]. Nonetheless, eccentric exercises still remain difficult to prescribe and integrate with athletic populations [56,220].

Flywheel training has shown promise in improving strength and key performance parameters in sporting populations [174,202]. Flywheel hamstring exercises have evolved considerably since the first investigation in 2003, which included a bilateral flywheel leg curl protocol [61]. Currently, flywheel hamstring exercises have evolved to involve unilateral flywheel exercises (as shown in chapter 3; Figure 3.10) and in the literature [95,221]. Although a flywheel device may allow for an eccentric overload (where eccentric output exceeds concentric output) [80] and the *Flywheel in soccer* questionnaire (in chapter 3) highlighted that achieving an eccentric overload is perceived to be of significant importance to practitioners [140], such outcomes are not consistently attained in the literature [80]. Variables such as moment of inertia, angular velocity, device type, and exercise selection largely dictate the ability to achieve an eccentric overload [80]. Previously, attempts have been made to quantify how changes in moments of inertia influence flywheel resistance training outcomes (such as peak power) to enhance training [83,172,221]. Altering moment of inertia (when analysed at group level rather than individually) did not influence peak power or trunk lean, but did impact velocity – highlighting differences between training variables for monitoring training intensity [71,222]. Further research into the topic must determine whether kinetic or kinematic variables can be used to determine intensity for different flywheel exercises. Hypothetically, intramuscular force-velocity-power relationships optimise force and velocity at greater and lower external resistance, respectively [223]. Power (force x velocity), on the other hand, would be optimised at a medium or moderate resistance [223]. Although such a theoretical relationship can be easily discussed, much remains to be investigated and many factors are likely to influence training [69,80]. Some factors that can influence training outcomes are participant characteristics (*i.e.,* training age), type of exercise, or inertia utilised. Such uncertainty highlights that arbitrary and pre-selected changes in inertia may result in unknown (and potentially sub-optimal) peak power outcomes [71].

While some guidelines exist for the implementation and management of flywheel training [69,136], Chapter 3 highlighted that it's systematic implementation may be limited due to a lack of evidence for periodization, training load management, or specific exercises (Figure 3.1) [80,83]. Although moments of inertia are often selected arbitrarily [65,134,141], the objective quantification of training has become more feasible for practitioners and researchers [173,221,224]. Parameters (*i.e.,* power, velocity, and force) have become more easily measurable (power, velocity, force), gaining significant interest amongst practitioners [69,140,220]. The use of higher rather than lower moments of inertia enhanced concentric and eccentric peak power for unilateral knee extensions [169], while bilateral squats and deadlifts with lower moments of inertia elicited higher peak power outputs than higher moments of inertia [83,221]. Additionally, eccentric overload was only obtained when higher moments of inertia were selected in some investigations [83,221], while others obtained eccentric overload regardless of the moment of inertia implemented [169,225]. The reliability and test-retest bias was inconsistent between flywheel exercises – highlighting the need for establishing reliability of different flywheel exercises before they can be used in practice [205]. For example, although the flywheel Romanian deadlift shows an *excellent* reliability for concentric and eccentric peak power measures (r = 0.92-0.93), the biceps curl and bent over row were lower (r = 0.69-0.82). The measurement of concentric and eccentric peak power (and it's ratio) is reported to be the most used training load parameter in field-based team sports (as reported in chapter 3) and more commonly investigated in the flywheel training literature in comparison to other training variables [80,220]. In line with such differences, previous research investigating different upper body exercises noted that significant differences existed in reliability for different mechanical outputs and exercises [205]. It is worth investigating how the leg curl and hip extension exercises uniformly respond to changes in moments of inertia. The leg curl and hip extension have been reported to elicit different activation patterns and occupy different parts of the hamstrings force-length curve [134,226]. No previous studies have determined how moment of inertia influences peak power output during unilateral leg curls. Additionally, it remains unclear whether altering moment of inertia during unilateral hip extension exercises impacts peak power and whether an eccentric overload is obtained [227]. Further investigation into the impact of altering training variables of flywheel resistance training, such as unilateral hamstring exercises, will improve flywheel training application [32].

This chapter aims to determine how altering flywheel moment of inertia (0.029, 0.061, and 0.089 $kg \cdot m^2$) would impact concentric and eccentric peak power and eccentric:concentric peak power ratio during unilateral flywheel leg curl and hip extension exercises. Better understanding how flywheel peak power responds to changes in moments of inertia with specific hamstring exercises may be useful for the monitoring and assessment of physical performance, management of training load prescribed for training, and to achieve specific training outcomes (training along the force-velocity curve). Similar to other assessments of function (*i.e.,* isometric strength), the assessment of peak power during hamstring testing, monitoring, and training may be valuable for practitioners (since the exercise is already commonly utilised in practice – see Chapter 3). Additionally, another objective of the present chapter was to analyse the inter-session reliability of concentric, eccentric, and the eccentric:concentric ratio of peak power during both exercises. It was hypothesised that lower moments of inertia would allow for greater peak power outputs and that eccentric overload would only be obtained with higher moments of inertia, as reported with bilateral and unilateral flywheel exercises [83,169,221].

4.3. Methods

Experimental approach to the problem

The present chapter utilised a cross-sectional design to determine the impact of different flywheel moments of inertia during unilateral flywheel leg curl and hip extension on concentric and eccentric peak power and it’s eccentric:concentric ratio. Each individual participant attended the laboratory five times over a 3-week period (as reported in Figure 4.1). An initial familiarisation session consisting of unilateral leg curl and unilateral hip extension exercises was performed with both legs. The next session consisted of either exercise (leg curl or hip extension) performed with their self-selected kicking leg, using all moments of inertia in each session (Figure 4.1). Exercise order and moment of inertia order was randomised. A 2-minute rest between sets was prescribed to minimize the effects of accumulated fatigue on performance. Testing was repeated using the same approach to allow for an analysis of inter-session reliability for both exercises (repeated a week later).

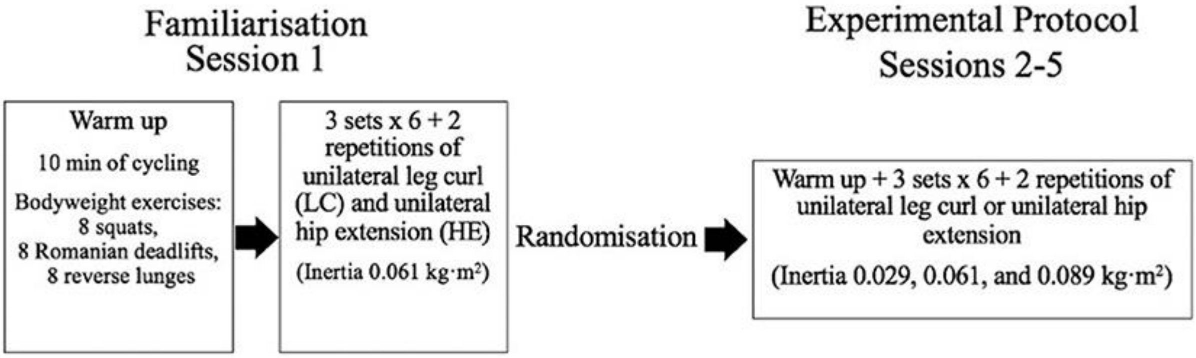


Figure 4.1. Experimental design. Min = minutes. 6 + 2 repetitions = 6 maximal repetitions with 2 initial repetitions utilized to initiate the movement.

Participants

Twenty healthy male university soccer athletes (age 22 ± 2 years, height 1.82 ± 0.04 m, body mass 83.4 ± 8.8 kg) voluntarily participated in this chapter. An a *priori* power analysis was conducted to determine the appropriate sample size using G*Power (version 3.1.9.3, Düsseldorf, Germany). Considering the present chapter design (1 group, 2 repeated measures), a medium effect size $f = 0.3$, a correlation between measurements of $r = 0.6$, an $\alpha = 0.05$, a required power $1- \beta = 0.80$, a non-sphericity correction $\varepsilon = 1$, a sample of 20 participants was required (actual power = 0.81). The present chapter was performed in the off-season period to avoid interfering with team-based training and competition. All participants were informed of the risks associated with procedures. Prior to participating, all participants were required to sign an informed consent form which was approved by the research ethics committee of the university of Suffolk in accordance with the declaration of Helsinki.

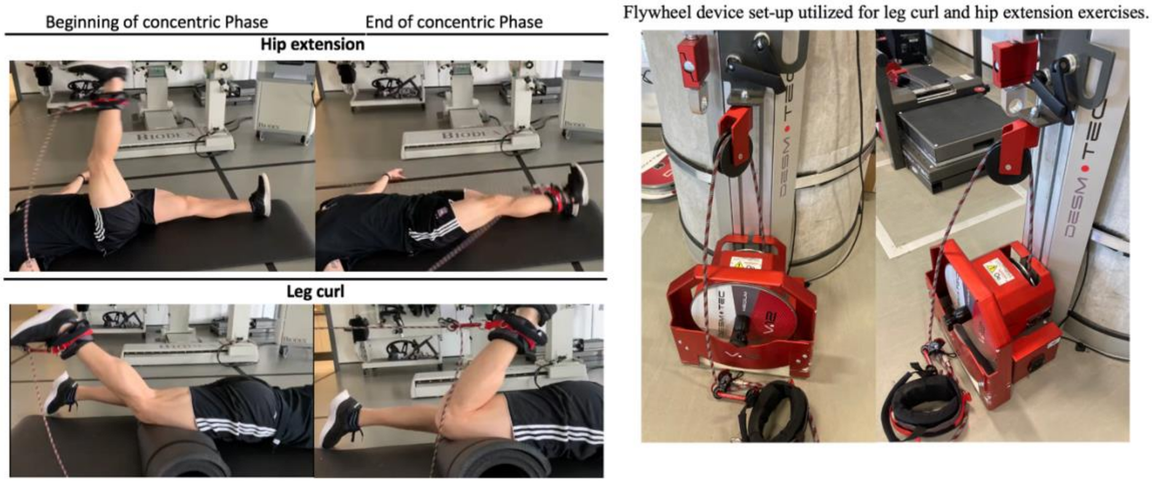
Procedures

Body mass and height were recorded by stadiometer (Seca 286dp; Seca, Hamburg, Germany). A standardized warm-up consisting of 10 min of cycling at 80-100 W (Wattbike, Nottingham, UK) and bodyweight lower body movements were performed prior to every session (Figure 4.1). Participants were requested not to take anti-inflammatory drugs or any form of supplementation (*i.e.,* caffeine) on testing day. Testing was replicated at roughly the same time of day for participants to maintain habitual diet and fluid intake for the duration of the intervention.

Leg curl and hip extension

The limbs range of motion was determined by the investigator before initiating each set. The knee was approximately ranging from 30° of knee flexion (beginning of concentric/end of eccentric) to 120° of knee flexion in the sagittal place (end of concentric/beginning of eccentric). In a similar fashion, the range of motion of the hip extension exercise (measured in anatomical position) ranged from roughly 90° of hip flexion/extension angle (start of concentric/end of eccentric) to 0-5° of hip extension angle in the sagittal plane (end of concentric/start of eccentric). Initially, a manual goniometer was utilised to set the initial range of motion. Following this, range of motion was assessed qualitatively by the same researcher during familiarization and testing for both exercises. The moments of inertia selected for the present chapter were 0.029, 0.061, and 0.089 kg·m^2. These moments of inertia were selected based on the large variety previously reported in the flywheel hamstring literature [225]. The specific moments of inertia utilized different (flywheel) discs and are specified here: 0.029 kg·m^2 [1 large disc (diameter = 0.285 m; mass = 1.9 kg; inertia = 0.02 kg·m^2) and 1 medium disc (diameter = 0.240 m; mass = 1.1 kg; inertia = 0.008 kg·m^2)]; 0.061 kg·m^2 [1 pro disc (diameter = 0.285 m; mass = 6.0 kg; inertia = 0.060 kg·m^2)]; and 0.089 kg·m^2 (1 pro, 1 large, and 1 medium disc). The inertia of the ergometer was estimated as 0.0011 kg·m^2 and has already been considered in the reported moments of inertia (Figure 4.1).

Participants were always encouraged to perform a maximal concentric phase and a delayed braking phase. This delayed eccentric phase is a common instruction prescribed to obtain greater eccentric peak power outputs [67]. Concentric and eccentric peak power were recorded *via* an in-built rotational encoder (V11Full, Desmotec, Biella, Italy). The peak power of 3 sets was averaged over all experimental sessions (session 2-5) and subsequently analysed. The rotary encoder is a position sensor that can measure angular position of the flywheel's shaft. The encoder converts the rotational position and speed into electrical signals and with the monitored pulse string that is based on the mechanical displacement then provides mechanical outputs performed during flywheel training. Those mechanical outputs are then combined with other variables of interest (*i.e.,* angular moment of inertia and shaft radius) to provide peak and average power, velocity, and force outputs for practitioners to utilise. The rationale for determining peak power in relation solely to the exercise is similar to the rationale behind what has been done in previous attempts to quantify and monitor resistance training. For example, with barbells, testing of a physical quality (strength) can be done via a standardised protocol (*i.e.,* warm up, familiarisation, instructions, 3-RM) where key metrics are considered (*i.e,* kilograms lifted). The rationale of such assessments is to provide feedback on the athlete's current training status and guide future training amongst other factors. Specifically, these two exercises were considered because they are commonly being used in practice (Chapter 3) and little information is available on them. The bilateral leg curl for example is also utilised frequently but is well supported by literature from over 20 years ago [61]. Therefore, to enhance the use of flywheel training in team sports, this Chapter aims to provide more information on these exercises specifically. Similarly, the use of peak power is the most common method utilised to monitor and assess performance of flywheel exercises and therefore is the focus of the present chapter. Peak power has shown to be correlated during bilateral squatting with quadriceps concentric and eccentric isokinetic torque and may therefore be a practical method to assess changes in performance that are associated with isokinetic strength. Additionally, the intention of flywheel training is to produce the most amount of force at the greatest velocity possible and therefore power (a byproduct of force and velocity) is a useful measure. Like with any other measurement, there are some limitations to the current measurement of peak power. Firstly, the measurement of both movements is completely reliant upon the effort of the participant (which is intended to be maximal but may vary in every repetition). Additionally, the output measure can be affected by the technique utilised. Although the technique utilised should remain consistent after a thorough familiarisation period and warm-up, it is possible that some participants are unable to maintain technique efficiently due to a variety of factors (*i.e.,* as they fatigue during the protocol). These inherent limitations are not specific solely to assessments on flywheel devices but have been acknowledged here to highlight the inherent limitations of such testing.



Flywheel device set-up utilized for leg curl and hip extension exercises.

Figure 4.2 The equipment utilised for the unilateral leg curl and hip extension.

Statistical Analysis

All statistical analyses were performed using JASP software version 0.13.1 for Mac (Amsterdam, Netherlands). Data was assessed for normality using the Shapiro-Wilk test and are presented as mean ± standard deviation (SD). A repeated measures analysis of variance (ANOVA) was performed to analyse potential within condition (flywheel moment of inertia) differences for the unilateral leg curl and hip extension. Sphericity was checked using Mauchly's test, and if violated ($p > 0.05$), the Greenhouse-Geisser correction was applied. Statistical significance was set at $p < 0.05$. When significant F-values were reported, *post-hoc* analyses were performed (with Bonferroni correction applied to the alpha value). Paired-samples *t*-tests were performed to analyse differences between concentric and eccentric peak power outcomes. Robust estimates of 95% confidence intervals (CI) and heteroscedasticity were calculated using the bootstrapping technique (1,000 randomly bootstrapped samples). Effect size based on the Cohen's *d* principle was interpreted as: *trivial* < 0.2; 0.2 ≤ *small* < 0.6; 0.6 ≤ *moderate* < 1.2; 1.2 ≤ *large* < 2.0; *very large* ≥ 2.0 [228]. All statistical analyses were performed using JASP (version 0.9.4; JASP, Amsterdam, the Netherlands). The reliability of the measures was assessed through a two-way mixed model intraclass correlation coefficient (ICC) and interpreted as: *excellent* > 0.9; 0.9 ≥ *good* > 0.8; 0.8 ≥ *acceptable* > 0.7; 0.7 ≥ *questionable* > 0.6; 0.6 ≥ *poor* > 0.5; and *unacceptable* < 0.5 [229]. The ICC interpretation is based on point estimates and confidence intervals. Standard error of measurement (SEM) was also calculated as shown here:

$\text{SEM} = \text{pooled SD}\sqrt{(1\text{-ICC})}$

Results

Unilateral Flywheel Leg Curl

All data were normally distributed (*p* > 0.05). Repeated measures ANOVAs detected no difference in peak power between moments of inertia for concentric (*F* = 0.62; *p* = 0.479), eccentric (*F* = 0.50; *p* = 0.564), or eccentric:concentric ratio (*F* = 0.07; *p* = 0.934), therefore a *post-hoc* analysis was not performed. Significant differences (*p* < 0.001) between eccentric peak power and concentric peak power measures were reported for all moments of inertia (Figure 4.3). Specifically, differences between concentric and eccentric peak power (greater eccentric power) were found at 0.029 kg·m^2 [68 W (47-90); *d* = 1.46 (0.82-2.09)], 0.061 kg·m^2 [70 W (53-87); *d* = 1.92 (1.61-2.66)], and 0.089 kg·m^2 [69 W (49-88); *d* = 1.68 (0.98-2.36)].

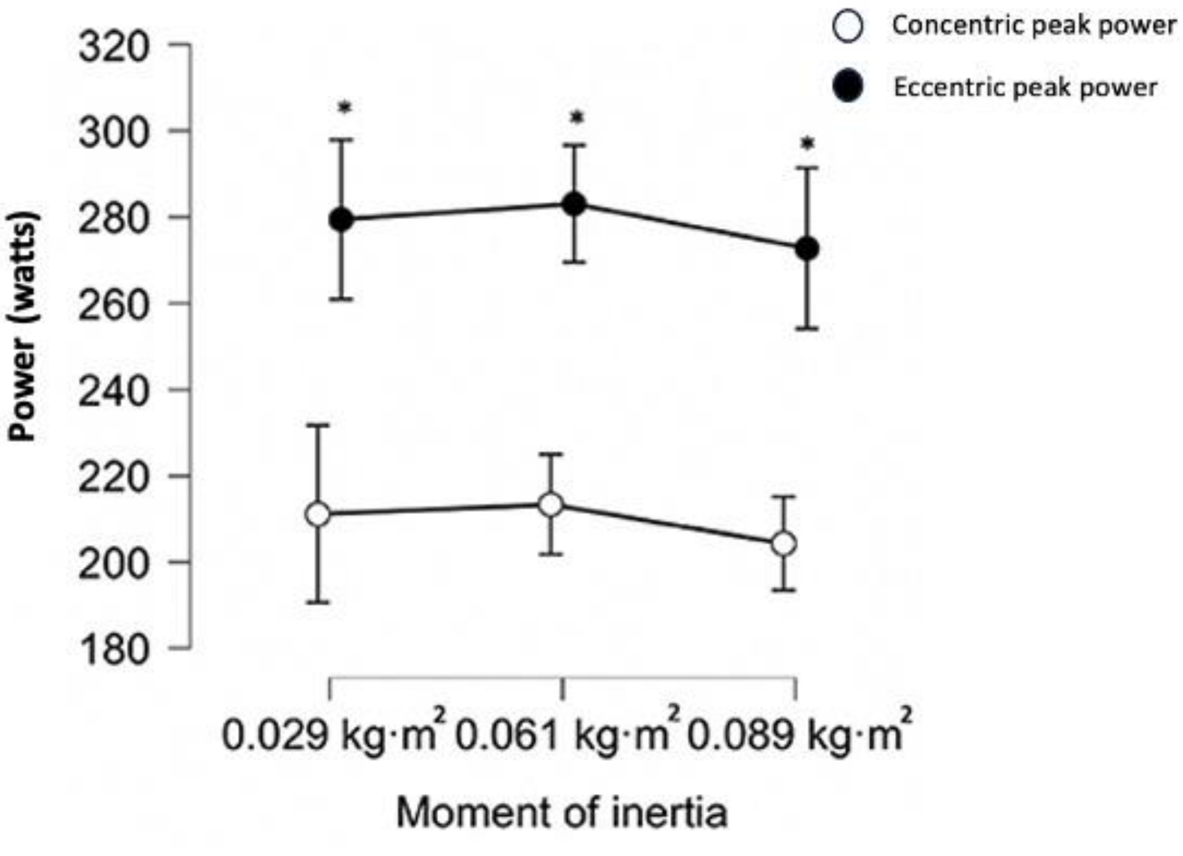
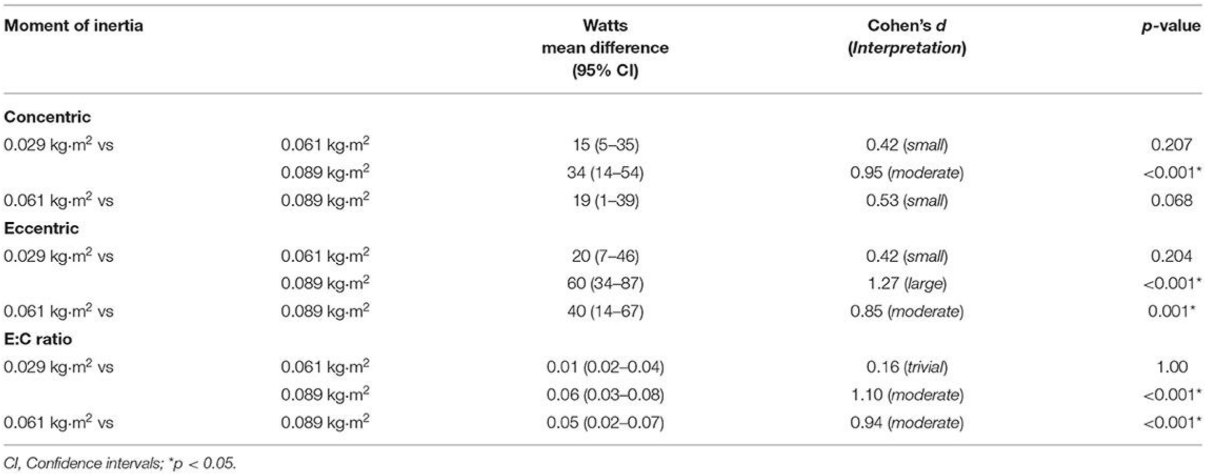


Figure 4.3. Concentric and eccentric peak power during unilateral flywheel knee flexion. *= Statistically significant (p < 0.05) difference between concentric and eccentric peak power. N = 20.

Table 4.1. Flywheel unilateral hip extension *post-hoc* tests for the repeated measures ANOVAs. N = 20.



Moment of inertia		Watts mean difference (95% CI)	Cohen's *d* (*Interpretation*)	*p*-value
Concentric				
0.029 kg·m^2 vs	0.061 kg·m^2	15 (5–35)	0.42 (*small*)	0.207
	0.089 kg·m^2	34 (14–54)	0.95 (*moderate*)	<0.001*
0.061 kg·m^2 vs	0.089 kg·m^2	19 (1–39)	0.53 (*small*)	0.068
Eccentric				
0.029 kg·m^2 vs	0.061 kg·m^2	20 (7–46)	0.42 (*small*)	0.204
	0.089 kg·m^2	60 (34–87)	1.27 (*large*)	<0.001*
0.061 kg·m^2 vs	0.089 kg·m^2	40 (14–67)	0.85 (*moderate*)	0.001*
E:C ratio				
0.029 kg·m^2 vs	0.061 kg·m^2	0.01 (0.02–0.04)	0.16 (*trivial*)	1.00
	0.089 kg·m^2	0.06 (0.03–0.08)	1.10 (*moderate*)	<0.001*
0.061 kg·m^2 vs	0.089 kg·m^2	0.05 (0.02–0.07)	0.94 (*moderate*)	<0.001*

*CI, Confidence intervals; *p < 0.05.*

Unilateral Flywheel Hip Extension

The repeated measures ANOVA detected an effect between moments of inertia for concentric peak power ($F = 9.07$; $p = 0.002$), eccentric peak power ($F = 16.85$; $p < 0.001$), and eccentric:concentric ratio ($F = 14.17$; $p < 0.001$). *Post-hoc* results are presented in Table 4.1.

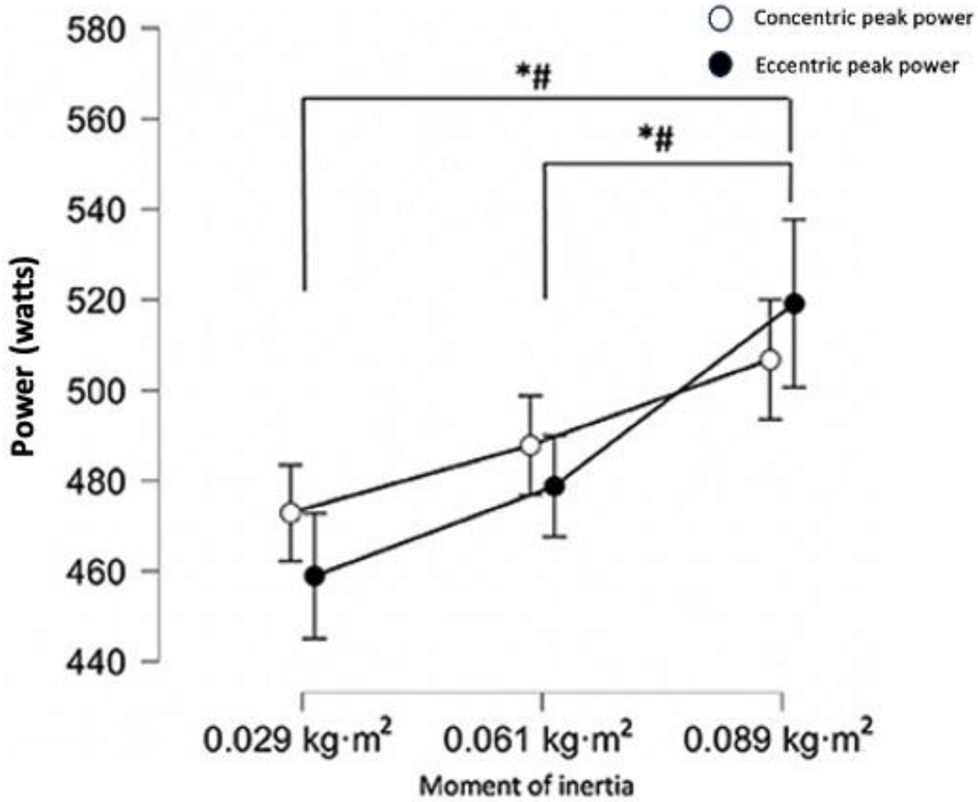


Figure 4.4. Concentric and eccentric peak power output during unilateral flywheel hip extension. *Statistically significant ($p < 0.05$) difference between concentric peak power. #Statistically significant

($p < 0.05$) difference between eccentric peak power. Black dots = eccentric peak power output. White dots = concentric peak power output. N = 20

Significant differences between concentric and eccentric peak power were reported for 0.029 kg·m^2 [$p = 0.022$; 14 W (2-26); $d = 0.56$ (0.08-1.03)] and 0.089 kg·m^2 [$p = 0.036$; 12 W (1-23); $d = 0.50$ (0.31-0.96)], but not for 0.061 kg·m^2 [$p = 0.391$; 9 W (2-20); $d = 0.39$ (0.07-0.84)], as presented in Figure 4.3. Figure 4.5 highlights the larger eccentric peak power demands (represented as eccentric:concentric ratio) of the unilateral leg curl in comparison with the unilateral hip extension. N = 20.

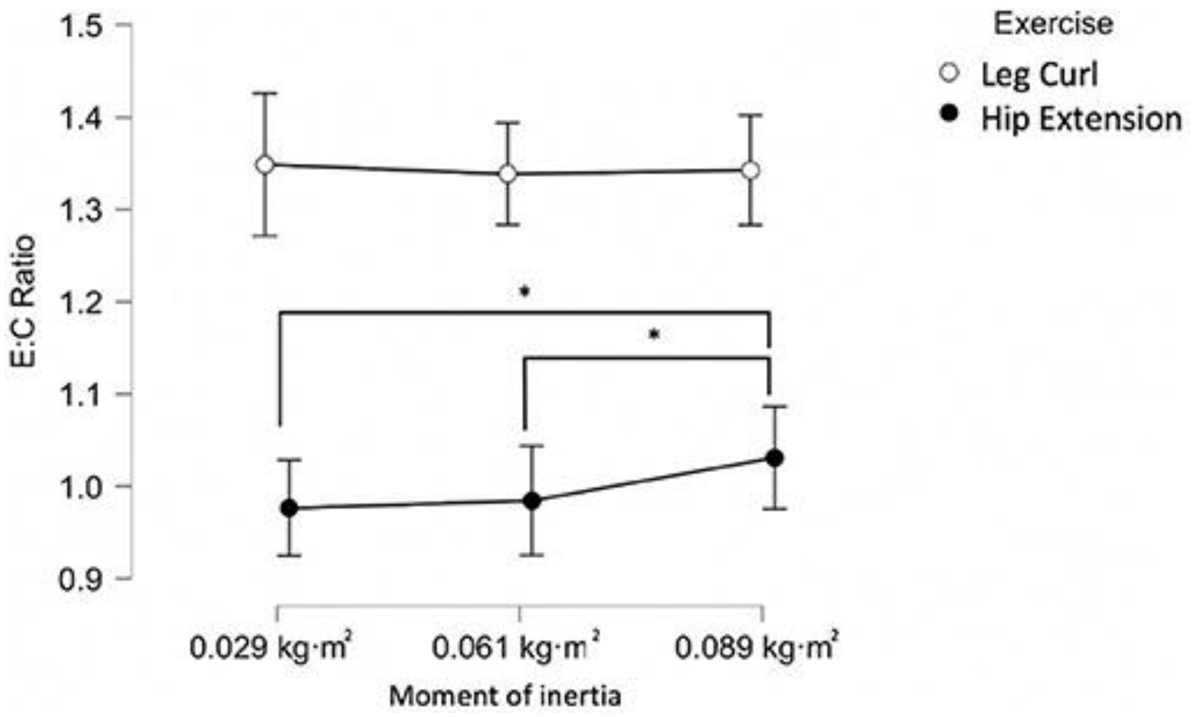
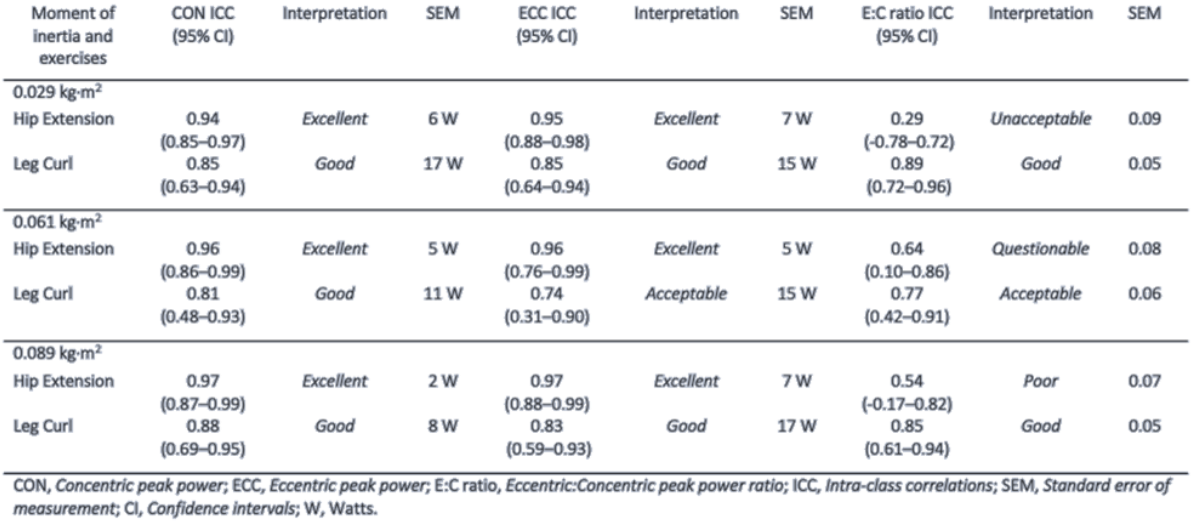


Figure 4.5. The eccentric:concentric (E:C) ratio for unilateral flywheel leg curl and hip extension exercises.* = Statistically significant ($p < 0.05$) difference between E:C ratio. N = 20.

Table 4.2 Unilateral flywheel leg curl and hip extension reliability.



Moment of inertia and exercises	CON ICC (95% CI)	Interpretation	SEM	ECC ICC (95% CI)	Interpretation	SEM	E:C ratio ICC (95% CI)	Interpretation	SEM
0.029 kg·m^2									
Hip Extension	0.94 (0.85–0.97)	*Excellent*	6 W	0.95 (0.88–0.98)	*Excellent*	7 W	0.29 (-0.78–0.72)	*Unacceptable*	0.09
Leg Curl	0.85 (0.63–0.94)	*Good*	17 W	0.85 (0.64–0.94)	*Good*	15 W	0.89 (0.72–0.96)	*Good*	0.05
0.061 kg·m^2									
Hip Extension	0.96 (0.86–0.99)	*Excellent*	5 W	0.96 (0.76–0.99)	*Excellent*	5 W	0.64 (0.10–0.86)	*Questionable*	0.08
Leg Curl	0.81 (0.48–0.93)	*Good*	11 W	0.74 (0.31–0.90)	*Acceptable*	15 W	0.77 (0.42–0.91)	*Acceptable*	0.06
0.089 kg·m^2									
Hip Extension	0.97 (0.87–0.99)	*Excellent*	2 W	0.97 (0.88–0.99)	*Excellent*	7 W	0.54 (-0.17–0.82)	*Poor*	0.07
Leg Curl	0.88 (0.69–0.95)	*Good*	8 W	0.83 (0.59–0.93)	*Good*	17 W	0.85 (0.61–0.94)	*Good*	0.05

CON, *Concentric peak power*; ECC, *Eccentric peak power*; E:C ratio, *Eccentric:Concentric peak power ratio*; ICC, *Intra-class correlations*; SEM, *Standard error of measurement*; CI, *Confidence intervals*; W, Watts.

Table 4.2 reports *good* to *excellent* reliability for most concentric and eccentric measures and the large variations in reliability (*unacceptable* to *good*) of the eccentric:concentric ratio for both exercises. Additionally, the standard error of measurement is reported for each measure.

4.5. Discussion

The present chapter's main objectives were to investigate how manipulating flywheel moment of inertia (0.029-0.089 kg·m^2) influences exercise parameters: concentric and eccentric peak power, and eccentric:concentric ratio during two unilateral hamstring exercises. Additionally, the chapter aimed to investigate the inter-session reliability of such exercises. The inter-session reliability of the leg curl exercise ranged from *acceptable* to *good*, while the reliability between sessions for both concentric and eccentric peak power was considered *excellent*. Of interest, the eccentric:concentric peak power ratio was rated as *acceptable* to *good* and *unacceptable* to *questionable* for leg curl and hip extension, respectively (Table 4.2). Contrary to the hypothesis, peak power values were higher with lower moments of inertia when utilising the hip extension exercise while no differences were seen between moments of inertia for the leg curl. When using the hip extension exercise, a greater eccentric:concentric ratio was reported with the highest moment of inertia, in agreement with the hypothesis that higher moments of inertia would obtain greater eccentric overload (Figure 4.4), while all moments of inertia achieved similar eccentric overload during unilateral leg curl (Figure 4.3).

The implementation of flywheel leg curl exercises in team sports (and specifically soccer) has been previously investigated and reported favourable outcomes – warranting further investigation [61,225]. Specifically, little is known about the unilateral variation of the flywheel leg curl exercise. In fact, the present chapter is the first to highlight that unilateral leg curl peak power does not differ significantly when a range of moments of inertia are used (0.029-0.089 kg·m^2) (Figure 4.3). The concentric force-velocity-power relationships theoretically suggest that maximal power occurs at an intermediate resistance [223], although some previous studies into the moment of inertia-power relationship during flywheel training do not support such a theory [83,169,225]. Specifically, a large majority of previous studies have reported that higher peak power outputs occur when lower moments of inertia are utilized [83,221,225]. It is important to consider that the aforementioned relationship is one that exists for the typical prescription of flywheel training in practice [169,230], rather than an exhaustive description of the relationship between peak power and all potential moments of inertia. The present findings suggest that the relationship between moment of inertia and peak power is affected by many factors. In agreement with this, previous research has suggested that other factors (*i.e.,* exercise selected, athlete characteristics) influence this relationship and therefore it cannot be generalised that lower moments of inertia elicit higher peak power outputs [71,227]. When attempting to quantify the impact of altering moment of inertia on groups (or individuals), it is also worth considering that outcomes or measures (*i.e.,* velocity, force, and peak power) will not respond uniformly [80]. In this specific investigation, only power outputs were readily available through the software. As discussed in the limitations, future research should look to investigate a variety of different training load variables to further explore flywheel resistance training. For example, something that may increase peak power may not necessarily do so for peak velocity or force. Although this may sound logical, it therefore becomes imperative to plan flywheel sessions according to the desired aims and objectives with the moment of inertia, exercise, and athlete's experience in mind. Additionally, considering the unclear moment of inertia-power relationship presently reported at the group level, it is recommended that practitioners utilize peak power with caution to determine which moment of inertia to utilize (as a measure of exercise intensity) during the unilateral leg curl exercise.

The present chapter reports that eccentric peak power is significantly greater than concentric peak power during the unilateral leg curl (Figure 4.5). In agreement with the present findings, bilateral flywheel leg curl training elicited high eccentric peak power outputs using a variety of moments of inertia [225,230]. The present findings highlight that eccentric overload must be confirmed, as it is not always obtained between exercises [80]. The high eccentric outputs obtained during flywheel training are perceived to be important to surveyed elite soccer practitioners [140]. High eccentric outputs may also be important for improving eccentric strength and inducing morphological adaptations with athletic populations [134,162,202]. Previously, bilateral flywheel hamstring leg curls did not enhance morphological adaptations, whereas eccentric-biased flywheel leg curls improved fascicle length and strength [134]. The present findings suggest that unilateral flywheel leg curls are an effective and reliable method for obtaining eccentric overload and may therefore be effective for inducing desirable morphological and strength adaptations with athletic populations. In exercises that are more "knee dominant" (with the hip at 0-15°), the hamstring operates only at optimal lengths as the knee rotates from 45° to 0° knee flexion [113]. This range is difficult to achieve with traditional eccentric exercises such as the Nordic hamstring curl [113] - but can be more specifically targeted with a unilateral flywheel leg curl (Figure 4.2). The present findings also highlight that flywheel unilateral leg curls can reliably be used as assessment tools to monitor and assess athletes in an easy and practical manner, as suggested with other flywheel exercises (*i.e.,* flywheel squat) [81]. Further investigation into whether flywheel testing can be incorporated into testing, monitoring, and screening batteries in sport is needed. Specifically, a greater focus must be placed on standardising protocols and procedures.

Contrasting the present findings, other studies reported that no eccentric overload occurred when using a unilateral [231] or bilateral flywheel leg curl [230]. Although the moment of inertia (0.072 kg·m^2) previously used in unilateral protocols is within the range of the present chapter (0.029 – 0.089 kg·m^2), other factors may have influenced the outcomes between investigations. For example, the participants flywheel training experience may be a factor that influenced outcomes. Indeed, it has been consistently reported in the literature that a sufficient and thorough familiarisation is necessary to optimise outcomes [83]. Some evidence suggests that specifically for eccentric peak power outputs, a maximal and prolonged familiarization may be especially necessary [83,225]. Nonetheless, the previous study only utilised a submaximal familiarization (2 sets of 6-8 repetitions) and therefore may have influenced the eccentric peak power obtained [231]. Meanwhile, in the present chapter, a familiarisation session involving both limbs performing both unilateral exercises maximally was performed. Eccentric overload of peak power may therefore be achieved regardless of moment of inertia utilized with unilateral flywheel leg curl after sufficient familiarization (Figure 4.5). Another factor that may have had an impact on whether eccentric overload is obtained are the machine characteristics. A flywheel device with a narrower axis requires a higher torque than a wider axis to obtain an identical angular velocity during flywheel training [78]. Similarly, differences in shape of the pulley may also have a significant impact on mechanical outputs during flywheel training [80]. For example, conical pulleys allow for higher angular velocities but lower vertical force when compared to cylindrical pulleys [78]. Such differences between flywheel devices (axis size and shape) in the literature may therefore have had an influence on outputs obtained [78]. Finally, another key aspect is the technique utilized when performing training that can largely determine whether eccentric overload is obtained [67]. Some differences between investigations with regards to instructions and participant adherence to guidance may have had an impact on the mechanical outputs obtained [32]. Although the aforementioned reasons may explain why different investigations have reported different outcomes in eccentric overload, it is also possible that differences in analysis methods (group rather than individual) of how moments of inertia influence eccentric overload may also play a role. Analysing how moments of inertia impact an individual's outputs rather than a group's outputs may enhance understanding and utilization of moment of inertia-power relationships. Therefore, if practitioners wish to optimize training prescription, it is worth investigating whether it would be preferable to individually verify if there are optimal moments of inertia to develop peak power with their athletes [225,231]. It is worth noting that such a process may be very time consuming and unlikely to be feasible amongst practitioners who do not have time to perform such protocols [140]. Considering no strong evidence currently exists with regards to whether an individualised approach should be taken, future investigations should study this.

Only the highest moments of inertia selected in the present chapter obtained an eccentric overload during the flywheel hip extension exercise (Figure 4.3). In contrast to the present findings, altering moment of inertia (0.075-0.100 kg·m^2) did not affect eccentric overload obtained during unilateral hip extension exercises with healthy young males [227]. Considering protocols utilized between studies are quite similar, it is possible that study limitations (limited sample size, study design) biased the results and impacted conclusions [227]. With regards to study design, the flywheel machine (horizontal cylindrical pulley) utilized for the hip extension exercise was not one that (according to the description and figures provided) was likely to allow for optimal technique. In agreement with the present findings, previous investigations have found that higher moments of inertia elicit higher eccentric overload of peak power during flywheel training [80]. It is nonetheless not a practical recommendation to aimlessly increase moment of inertia. In fact, blindly increasing moment of inertia used may negatively impact eccentric overload obtained – highlighting the importance of objectively quantifying outputs [221]. Specifically with flywheel Romanian deadlifts, no significant difference was reported between the eccentric overload obtained between higher moments of inertia (0.050 – 0.100 kg·m^2) [221]. Among the important changes in the mechanical outputs that are being measured with changes in moments of inertia, it is recommended that practitioners also consider how other factors they may not be measuring (*i.e.,* rate of perceived exertion, movement velocity) may be influenced.

The unilateral flywheel hip extension exercise has been investigated less than the leg curl exercise, however it is often utilized by practitioners to strengthen the hamstrings [84,220,231]. It is also considered an exercise that can be practically integrated within injury prevention programmes for team sport athletes [136]. The current findings highlight that the greatest moments of inertia elicited higher concentric (*small* to *moderate*; *d* = 0.53-0.95) and higher eccentric (*moderate* to *large*; *d* = 0.85-1.27) peak power outputs during the unilateral flywheel hip extension exercise than with lower moments of inertia (Table 4.1). Contrasting the present findings, lower moments of inertia (0.025-0.050 kg·m^2) obtained higher peak power outputs when compared to higher moments of inertia (0.075-0.100 kg·m^2) during flywheel Romanian deadlifts [221]. The moment of inertia-power relationship between the two exercises may differ due to the biomechanical differences of the exercises (supine unilateral open kinetic chain vs. standing bilateral closed kinetic chain) and muscle recruitment involved in the two exercises [221]. There are a few biomechanical considerations to make when comparing the two exercises. In a supine unilateral open kinetic chain exercise the athlete is lying on the floor with one leg working and the other limbs remaining stationary and aiming to provide balance and stability (Figure 4.2). The flywheel unilateral hip extension exercise allows for isolation of the hamstrings in a stable environment, a specific and targeted movement pattern that is easy to learn and focalises the demands on the hamstrings. It is likely that the knee and hip joint angles experienced during this exercise involve greater force production at longer lengths (>45° hip flexion) and of knee flexion of up to 10-30° for the biceps femoris long head with the semimembranosus contributing significantly throughout the range of motion [113]. Indeed, during "hip-dominant" exercises, the limited evidence available suggests that the hamstrings operate at optimal lengths for force generation at angles of 45-90° of hip flexion [232]. The isolation of the muscle groups allows for this exercise to be progressed and monitored and may be of use if an athlete has a pronounced asymmetry that needs to be targeted or during rehabilitation [95,102]. Although a greater focus can be placed on the hamstrings during unilateral flywheel hip extension, the hamstrings must still work synergistically with other muscles such as the gluteus maximus and adductor magnus during hip extension [113]. The range of motion of the unilateral flywheel exercise ranges from roughly 90° of hip flexion/extension angle (start of concentric/end of eccentric phase) to 0-5° of hip extension angle in the sagittal plane (end of concentric/start of eccentric phase). Although the range is specified and aimed to occur only in the sagittal plane, it is possible that as athletes apply maximal effort, fatigue, or just due to variability of exercise execution a degree of movement in multiple planes may occur simultaneously. Although the familiarisation phase aimed to focus on maximal effort and development of appropriate technique, it is possible that the hip may experience movement in the frontal plane (adduction/abduction) or more subtle internal/external rotation of the hip in the transverse plane regardless of familiarisation. Future study should aim to confirm if such movement is an issue specifically for open-kinetic chain hip extension exercises (where the foot is able to move).

Alternatively, a standing bilateral closed kinetic chain hamstring exercise, such as the Romanian deadlift, differs biomechanically and in complexity [134,221]. Firstly, both feet are firmly placed on the ground with the movement involving the whole body to a greater degree. Such exercises involve multiple joints and engage a variety of muscle groups (*i.e.,* core, lower back) and can often be heavily limited by training experience/age [233,234]. Indeed, the movement patterns are more challenging and require a greater amount of coordination and technique to perform the dynamic movement with balance, form, and desired intent. Specifically with flywheel devices, a variety of bilateral and unilateral hip extension exercises can be performed with technique and outcomes varying significantly as technique and intensity are altered [132,235]. Some evidence suggests that exercises like the unilateral flywheel leg curl preferentially recruit the Semitendinosus whereas exercises like the unilateral hip extension preferentially recruit the Biceps femoris long head and Semimembranosus [216]. Such differences between exercises are likely to be due to the bi-articular function of the hamstrings, potential recruitment in rotation movements, and movement velocity. These differences may therefore influence force and activation as well as greater BFlh moment arm and thereby torque generation at the hip than at the knee [113]. Previous research into the importance of training the hamstrings at fast-velocities and slow-velocities has been raised [236,237], with a mixture of the two methodologies warranted in practice. Although the application of flywheel training may be an effective tool to target and elicit high-velocity hamstring strength or power, little is currently known about whether these exercises would be effective for this. Further research into the differences between exercises is needed to understand how they differ biomechanically and how these differences may influence practice.

The present and aforementioned findings support the theory that different exercises (considering equipment and execution) may alter moment of inertia-power relationships [71,83,169,222,227]. In contrast to the present findings, previous investigation into unilateral hip extensions supports the notion that altering moments of inertia (0.075-0.100 $kg \cdot m^2$) did not impact peak power [227]. Differences in flywheel device characteristics utilized in the two protocols (vertical vs. horizontal cylindrical shafts varying in radius and disc diameter) may explain the differences between studies. Similarly, differences between participant characteristics (training age, familiarisation) may also partly explain disagreement between investigations.

Although concentric and eccentric peak power have become frequently applied as measures of intensity during flywheel training [69], such measures do not summarize the intensity of the eccentric component in comparison to the concentric component [177]. The eccentric:concentric ratio has become a practical method to monitor the demands of flywheel exercise in a single measure [177]. The eccentric:concentric ratio is a ratio made of the eccentric and concentric outputs (*i.e.,* power) measured during flywheel exercise [177]. Although ratios have been deemed to be problematic and easily misused [238], the eccentric:concentric ratio is still commonly researched and utilized [80]. The eccentric:concentric ratio may facilitate the discussion of training aims and helps to clarify objectives with athletes as it is a simple number (*i.e.,* 1.1 or 0.8) that athletes can understand. Previously, participants who were experienced with bilateral flywheel leg curl attained higher eccentric:concentric ratios than inexperienced participants [230]. The eccentric:concentric ratio has therefore been proposed as a method sensitive enough to determine flywheel resistance training experience [230]. This ratio may also allow for an easier and quicker analysis of exercise demands, allowing practitioners to alter intensity, technique, or volume with greater clarity [177]. Considering the difficulties associated with monitoring flywheel training, the eccentric:concentric ratio has been adopted by many practitioners and is also considered within the flywheel training literature. In support of the use of the eccentric:concentric ratio, more recent evidence has suggested that when inexperienced participants performed bilateral flywheel leg curls, the ratio obtained was not reliable [225]. The present findings suggest that the eccentric:concentric ratio generally has poorer reliability than its derivatives (in this case peak power). Specifically, the reliability of the eccentric:concentric ratio was consistently worse than concentric and eccentric peak power. Therefore, although the eccentric:concentric ratio may be considered a practical tool, it should not be utilised to monitor training intensity or to confirm familiarisation. Instead, practitioners should continue to use concentric and eccentric peak power parameters as reliable metrics for monitoring flywheel training (Table 4.2). Overall and until further investigation, the eccentric:concentric ratio should be considered an unreliable parameter and should not be utilized [69,225].

4.6. Limitations and future directions

This chapter has several limitations – firstly, the sample enrolled (amateur male soccer players) may not represent how other populations (*e.g.,* female or elite male soccer players) respond to changes in moments of inertia. Secondly, the group level analysis performed may have masked differences at the individual level, with future investigations potentially warranting individual analyses of responses rather than group-based analyses. Finally, this chapter did not investigate the moment of inertia-velocity relationship. Future research could evaluate if velocity can be used to prescribe appropriate moments of inertia. Future study should look to assess how different output measures compare when changes to moments of inertia are made. Furthermore, study into females and comparing group-based and individualised moment of inertia-power profiles are of interest to practitioners and researchers alike.

4.7. Conclusions

The present chapter reports that leg curl reliability ranged from *acceptable* to *good*, while all hip extension reliability scores for concentric and eccentric peak power were rated as *excellent* – highlighting that such parameters can be used by practitioners. The eccentric:concentric ratio should not be utilised for monitoring training outcomes. The present chapter is the first to determine that moments of inertia impact training parameters differently (concentric and eccentric peak power) between two unilateral flywheel hamstring exercises with the same population. Greater peak power values were obtained with higher rather than lower moments of inertia during the hip extension exercise. Nonetheless, similar peak power measures were seen between moments of inertia during the leg curl exercise. The moment of inertia-power relationship between the two hamstring exercises may differ due to biomechanical differences between the exercises. Accordingly, such differences must be considered by practitioners when periodizing and planning training, possibly warranting individualization of moment of inertia to optimize peak power.

Practical Applications

The present chapter provides novel insight and recommendations for the prescription of flywheel training. Specifically, a variety of moment of inertia (0.029, 0.061, and 0.089 kg·m^2) can be prescribed during unilateral flywheel leg curl to achieve high eccentric knee flexor demands. With regards to unilateral hip extension, practitioners are recommended to utilize higher moments of inertia (*e.g.,* 0.089 kg·m^2) to obtain greater eccentric peak power outputs. Different exercises may have different moment of inertia-power relationships because of the biomechanical differences between exercises – warranting careful consideration for training prescription as discussed in the chapter. Although this chapter demonstrates that peak power can be a useful parameter to use in daily practice, practitioners may also wish to measure other parameters (*e.g.,* velocity) to further characterize training demands and outcomes. Specifically, focusing on the use of unilateral hamstring exercises to develop low and high velocity strength is of interest and should be considered in future research. Overall, practitioners must consider that obtaining high peak power outputs are not the sole objective in physical preparation, whereby many different considerations must be made to optimize performance (*e.g.,* focus on high velocity movements with lower moments of inertia). If practitioners are unable to obtain individual moment of inertia-power relationships or monitor training load objectively with a group of athletes, the present findings can be used to guide basic flywheel hamstring training prescription.

Finally, this chapter suggests avoiding the use of the eccentric:concentric ratio as a parameter with flywheel training.

A variety of methods exist to integrate flywheel training into monitoring and testing processes to create ‘invisible processes’ that may reduce burden and stress placed upon athletes. For example, the use of flywheel squat or unilateral hamstring exercises can be utilised as a part of training and testing. Although such mechanical outputs can be useful and easily integrated within practice, how much value they hold for monitoring fatigue or whether they are valid measures of performance are key considerations to make. Ultimately, peak power provides a mere singular discrete value and if used in isolation provides no real kinetic or kinematic information regarding the rest of the movement. Therefore, although peak power can still be utilized as a basic method for prescribing exercise intensity during unilateral flywheel hamstring exercises at the group level, future investigation must confirm how to optimise such practice. Other mechanical outputs, such as velocity measures, may be more appropriate when monitoring flywheel training and determining the effect of altering moment of inertia on training. Further study into this is also needed to clarify if there is an ‘optimal’ method to determine flywheel training intensity.

Chapter 5 -The effects of 6 weeks of unilateral flywheel hamstring training on flywheel, isokinetic, and isometric strength outcomes.

Publication arising as a result of this chapter:

de Keijzer, K. L., McErlain-Naylor, S. A., & Beato, M. (2023). Six Weeks of Unilateral Flywheel Hip-Extension and Leg-Curl Training Improves Flywheel Eccentric Peak Power but Does Not Enhance Hamstring Isokinetic or Isometric Strength. International Journal of Sports Physiology and Performance, 1, 1-10.

5.1. Abstract

This chapter investigated how 6-weeks of unilateral flywheel hamstring training impact isokinetic, isometric, and flywheel strength and power outcomes. The chapter involved 11 male university athletes (age 22 ± 2 years; body mass 77.2 ± 11.3 kg; height 1.74 ± 0.09 m) with one leg randomly allocated to flywheel training and one leg to control. Unilateral eccentric knee flexion torque ($60^{\circ}\cdot s^{-1}$), isometric torque (30° of knee flexion), and flywheel unilateral leg curl and hip extension concentric and eccentric peak power were measured before and after training. Training involved progressive increase in volume or intensity of knee flexion and hip extension exercises. The intervention enhanced hip extension concentric ($p < 0.01$, $d = 1.76$, *large*) and eccentric ($p < 0.01$, $d = 1.33$, *large*) peak power more so than the control (significant interaction effect). Similarly, eccentric ($p = 0.023$, $d = 1.05$, *moderate*) peak power was enhanced for the leg curl. No statistically significant differences between conditions were found for isokinetic eccentric ($p = 0.086$, $d = 0.77$, *moderate*) and isometric ($p = 0.431$, $d = 0.36$, *small*) knee flexor strength or leg curl concentric peak power ($p = 0.339$, $d = 0.52$, *small*). Statistical parametric mapping analysis of torque-angle curves also revealed no significant ($p > 0.05$) time-limb interaction effect at any joint angle. Six weeks of unilateral flywheel hamstring training improved eccentric peak power during unilateral flywheel exercise but not isokinetic eccentric or isometric (long-lever) knee flexor strength.

5.2. Introduction

Hamstring strain injuries, such as those occurring to the biceps femoris long head during high-speed running actions, have affected team sports for decades [211]. The likelihood of re-injury to the hamstrings also increases after initial injury, with such issues persisting for years with some athletes [239]. With these injuries costing teams on and off the pitch, a concerted effort through testing, monitoring and training interventions has been made to curb their negative financial, performance, and health-related effects [240]. Several injury risk factors are older age, shorter biceps femoris long head fascicles, and poor eccentric hamstring strength amongst soccer players [7,216]. Although a gold-standard method to prevent hamstring strain injuries remains unknown and would likely be multifactorial [7,240], eccentric strength is amongst the most easily and frequently tested and trained capacities. Additionally, the use of isometric testing has gained traction and may play a role in better understanding hamstring capacity [241]. Although isokinetic dynamometers are considered the gold standard assessment for eccentric hamstring strength [242], they could be adopted alongside more practical testing methods by practitioners (*e.g.,* isometric, bodyweight strength-endurance or flywheel testing) to monitor hamstring strength and capacity [81,130,224].

Several resistance training methods have been proposed to improve hamstring strength and reduce likelihood of hamstring injury [7]. Specifically, the incorporation of knee-dominant (such as the Nordic hamstring exercise [NHE]) or hip-dominant (hip extension) exercises have improved hamstring eccentric strength [61,214,243]. Hip extension exercises performed on the 'glute-ham raise' machine enhanced isokinetic eccentric knee flexor strength of healthy males and 3-RM hip extension strength of recreationally active men [130,214]. Greater improvements in eccentric strength following eccentric training interventions (such as the NHE) in comparison to traditional resistance training or concentric-only isotonic exercises may be due to greater cortical activity, preferential recruitment of high threshold motor units, upregulation of satellite cell activity and transcriptional pathways in fast-twitch muscle fibres [125,244]. Nonetheless, the application of such interventions are not reducing hamstring strain injury incidence [211]. The efficacy of current interventions, such as the NHE, may be limited by their actual capability to reduce injury likelihood [39]. Additionally, eccentric hamstring exercises like the NHE remain severely underused in elite field based team sports [106], with evidence suggesting that traditional eccentric training such as the NHE remains difficult to program during competitive periods [56]. Another consideration is the limitation of standardised progression and individualisation with the NHE, which is typically limited to being executed with just a participants bodyweight [245]. The NHE is also most difficult at the beginning of the concentric phase (ascending portion) and is therefore typically performed purely as an eccentric-only exercise [246]. With traditional resistance training the constant external load is limited by what the athlete can lift on the very last repetition. Amongst other factors that contribute to reduced loads selected, this typically leads to the majority of training executed with a load that is far from maximal [62].

The maximal effort allowed throughout the range of motion of every flywheel exercise repetition may induce a greater neuromuscular demand and adaptations [64]. In support of this, flywheel leg extension resistance training induced similar significant improvements in muscle hypertrophy, power and strength with 22% fewer repetitions than traditional weight stack leg extension resistance training [65]. More recently, a greater effort has been placed into understanding how flywheel hamstring exercises may differ from each other and enhance strength amongst athletes [132,231,235,247]. Evidence suggests that eccentric overloaded flywheel leg curls can increase Biceps Femoris long head fascicle length amongst healthy males (*d* = 1.98; 14 ± 5%) [134]. Unilateral flywheel leg curls generated a significantly different transverse relaxation time (T2) shift between pre- and post-exercise for the four hamstring muscles in comparison to unilateral flywheel hip extensions [231]. Specifically, less-experienced soccer players were unable to generate an eccentric overload (of power) and selectively increased activity specifically for the Biceps Femoris short head and semitendinosus [231]. Meanwhile, the unilateral hip extension (performed on a conical pulley) led to greater T2 shifts and preferentially targeted the proximal and medial regions of the Biceps Femoris long head [231]. When flywheel and 80% 1RM traditional Romanian deadlift (RDL) protocols were completed twice per week over a 6-week period with male youth soccer players, both methodologies enhanced RDL 3-RM (18-28%) [248]. Nonetheless, only the flywheel RDL protocol improved NHE eccentric (13%) strength significantly [248]. Bilateral flywheel leg curls or deadlifts have improved strength of male professional and youth team sport athletes [61,131,133]. For example, a 10-week intervention involving 16 sessions of bilateral flywheel leg curl training significantly enhanced concentric (Hedges *g* = 0.79, moderate) and eccentric (Hedges *g* = 1.14, *moderate*) knee flexor peak torque of professional Swedish soccer players [61]. Evidence suggests that hip extension and leg curl exercises elicit different responses within muscles and are both warranted for a holistic training programme of the hamstring musculature [216,231]. One key benefit of flywheel training over traditional eccentric-only exercises such as the NHE is that they involve the stretch-shortening cycle and a maximal concentric phase [58,245,249]. The inclusion of a maximal concentric phase and the stretch shortening cycle are likely to increase transfer to training and greater benefit to both concentric and eccentric strength [3,17,250]. Additionally, flywheel training can be progressed and individualized to a greater degree in comparison to the NHE [245]. The use of flywheel hamstring exercises is likely to allow for more work to be performed at longer hamstring muscle lengths than NHE since the participant is able to control the exercise to a greater degree and may therefore be more beneficial than the NHE [214,245]. Knee- and hip-dominant strength training interventions based on alternative equipment (*e.g.,* flywheel devices) have therefore become of interest recently for improving strength and may help reduce hamstring injury likelihood [61,130,131,133,214]. Although it is beyond the scope of the present investigation it is important to address that hamstring strain injuries are complex and multi-factorial (*i.e.,* previous injury, age) but one of the practical modifiable risk factors is eccentric strength and are typically targeted with resistance training interventions [115,239].

Although chapter 3 and 4 highlight some interesting information on the use and reliability of unilateral flywheel hamstring training, chapter 2 emphasizes that little is known about the unilateral flywheel hamstring exercises. Currently, the only application of unilateral flywheel leg curl training in the literature did not improve hamstring strength in healthy males [134]. Such findings slightly contrast the limited unilateral hip extension and knee flexion training literature available [130,214]. Further investigation into the efficacy of a combined flywheel-based hip and knee dominant unilateral hamstring training programme should be performed to support integration of such training. The aim of the present chapter was therefore to determine whether unilateral flywheel hamstring training (a combination of hip extension and knee flexion exercises) enhances isokinetic knee flexor strength more than a control condition. A secondary aim was to determine the effect on concentric and eccentric peak power during the flywheel exercises. It was hypothesised that 6 weeks of unilateral hip extension and knee flexion flywheel hamstring training would improve peak eccentric and isometric knee flexion torques as well as concentric and eccentric peak power during the unilateral flywheel hip extension and leg curl exercises.

5.3. Methods

Experimental design

A randomised controlled trial design was used to determine the effects of a 6-week unilateral flywheel hamstring training protocol on isokinetic and isometric hamstring strength and flywheel peak power in amateur male university athletes. This trial was pre-registered on the Open Science Framework registry prior to data collection.

The protocol consisted of one familiarisation session, two testing sessions (baseline and post-training), and twelve training sessions (unilateral training performed twice per week for six weeks). During the first visit, participants' body mass and height were recorded using a stadiometer (Seca 286dp; Seca, Hamburg, Germany) and participants were familiarised with the lower limb tests (isokinetic, isometric and unilateral flywheel assessments) and flywheel training. In the subsequent session, participants performed the isokinetic eccentric and isometric knee flexor testing, as well as the two unilateral flywheel assessments (hip extension and knee flexion). All sessions were performed on weekdays and separated by 2 days from other intense activities (training or competition). All isokinetic, isometric and flywheel testing protocols were performed at baseline (week 1 / session 2) and post-training (week 8 / session 15) in the laboratory (19-21 °C) at a similar time of day to reduce the impact of circadian rhythms on performance. Participants were required to maintain their habitual nutritional intake during the experimental period. Depressants (*i.e.,* alcohol) and stimulants (*i.e.,* caffeine) were not permitted within 12 hours prior to the experimental sessions but participants were encouraged to hydrate themselves with water as necessary during all sessions. All sessions were evaluated qualitatively by a qualified strength and conditioning coach (NSCA) to ensure appropriate technique, offering kinematic feedback to participants during the familiarisation period.

Participants

An *a priori* power analysis was conducted to determine the appropriate sample size using G*Power (version 3.1.9.3, Düsseldorf, Germany). Considering the design (one limb per participant was randomly assigned to the experimental and the other to the control condition), a two-way analysis of variance (ANOVA) analysing time (pre-post) and within-participant (between limbs) effects, a moderate effect size of $f = 0.35$, an α-error of 0.05, and a required power ($1-\beta$) of 0.80, a total sample size of 10 participants was required (actual power = 0.84). Eleven male participants (age 22 ± 2 years; body mass 77.2 ± 11.3 kg; height 1.74 ± 0.09 m) were enrolled and each completed all training, with their limbs randomly allocated (http://www.randomizer.org/) to either experimental or control condition (n = 22).

Inclusion criteria were the absence of any injury or illness confirmed by completion of a physical activity readiness-questionnaire (PAR-Q); participation in a minimum of 2 resistance training sessions per week; and at least 6 months of resistance training experience. All participants completed a written informed consent form after a verbal and written rationale of the experimental procedure was given. The Ethics Committee of the University of Suffolk (UK) approved this design (RETH(S)21/015). All procedures were conducted in line with the Declaration of Helsinki for studies involving human participants.

Standardised warm-up

Prior to each session, a standardised warm-up was performed including 10 min of cycling at a constant power (1 $W{\cdot}kg^{-1}$ body mass) on a Watt bike (Trainer, Nottingham, United Kingdom) and dynamic mobilization (8 repetitions of each of squats, Romanian deadlifts, and reverse lunges).

Isokinetic testing

An isokinetic dynamometer (Bide Medical Systems, Shirley, NY, USA) was used to measure eccentric knee flexion torque at $60°{\cdot}s^{-1}$. Participants were seated on the dynamometer chair, with an internal hip angle of 95° and the crank axis aligned with the tested knee joint centre of rotation. The trunk, hip, and thigh were firmly strapped to the seating during all isokinetic and isometric testing. Participants performed three maximal eccentric knee flexion repetitions at $60°{\cdot}s^{-1}$. Isokinetic measures were sampled at 100 Hz, with the device calibrated (with peak torque gravity corrected) according to manufacturer's guidelines. Specifically, prior to each assessment the gravity correction firstly involved a passive measurement to determine a range of motion. Following this, using the software, the torque caused by gravity acting on the limb and dynamometer is accounted for. This value is taken into consideration by the software and thereby for each test, the isokinetic dynamometer more accurately assesses the torque produced by the participant. The data were then processed via open-source (http://www.ikd1d.org/) MATLAB (v 2022b, MathWorks, Natick, MA) script. Torque and crank angular velocity data were filtered using a recursive second-order digital low-pass Butterworth filter with a cut-off frequency of 5 Hz and a torque threshold of 0.1 $Nm{\cdot}kg^{-1}$ applied, again in line with the manufacturer's guidelines. Data points were only considered for further analysis if crank angular velocity was within 5% of the target angular velocity. Crank angle was consistently considered as joint angle (although this likely changes somewhat at smaller knee flexion values). For continuous analysis of the one-dimensional torque-angle data, all trials were normalized via linear length normalization to one value per degree of range of motion within the range common to all participants [251]. The three trials per participant-condition combination were ensemble averaged to produce a single representative normalized torque-angle curve per participant and condition. For discrete analyses, peak torque of the singular best trial was taken. The reliability of the isokinetic discrete analysis was performed with all participants prior to testing and was considered *good* (ICC = 0.85 [0.71;0.92]).

Isometric testing

The same isokinetic dynamometer was used to measure maximal voluntary isometric contraction (MVIC) at 30° of knee flexion (crank angle), with the dynamometer configured as for isokinetic testing. A maximal familiarisation session was completed prior to testing for all participants. For each testing session, participants performed two 3-second practice trials at 50% of perceived maximal effort before performing two 3-second MVICs separated by 30 s rest. Peak torque of the singular best trial was considered for further analysis. The reliability of the isometric testing was performed with all participants prior to testing and was considered *excellent* (ICC = 0.90 [0.81;0.95]).

Flywheel testing

Flywheel testing and training protocols were performed on a commercial flywheel ergometer (V11 Full, Desmotec, Biella, Italy). The flywheel testing protocol consisted of both unilateral knee flexion and unilateral hip extension. Participants performed 2 sets of 2+6 repetitions (2 submaximal repetitions to attain rhythm followed by 6 maximal repetitions) with a moment of inertia of 0.061 $kg{\cdot}m^2$ and 120 s of inter-set rest. Hip extension was initiated at approximately 80-90° of hip flexion and ended at 0-5° hip flexion. Knee flexion range of motion was established prior to each set as beginning at approximately 20° of knee flexion and ending at approximately 150° knee flexion, as described previously [224]. Range of motion for each participant was initially determined with a manual goniometer and subsequently assessed qualitatively by the same researcher during familiarisation and testing. A built-in rotational encoder recorded concentric and eccentric peak power. Strong standardised verbal encouragements were provided to maximise performance throughout all testing and training.

Flywheel training

The training protocol consisted of knee flexion and hip extension exercises, with a training frequency of two sessions per week over a 6-week period. The volume and moments of inertia (intensity) prescribed were progressively incremented during the training period (presented alongside results in Figures 5.2 and 5.3). The mean of all peak power outputs was recorded separately for each session and each of concentric and eccentric phases.

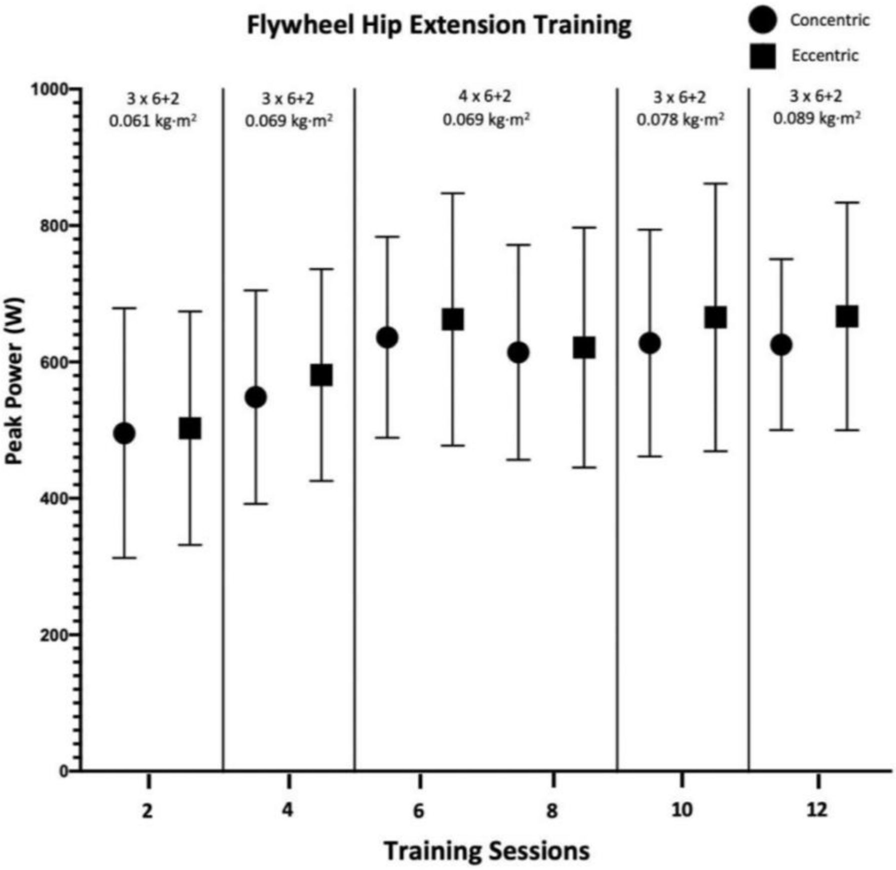


Figure 5.2. Peak power during flywheel hip extension training reported every other session.

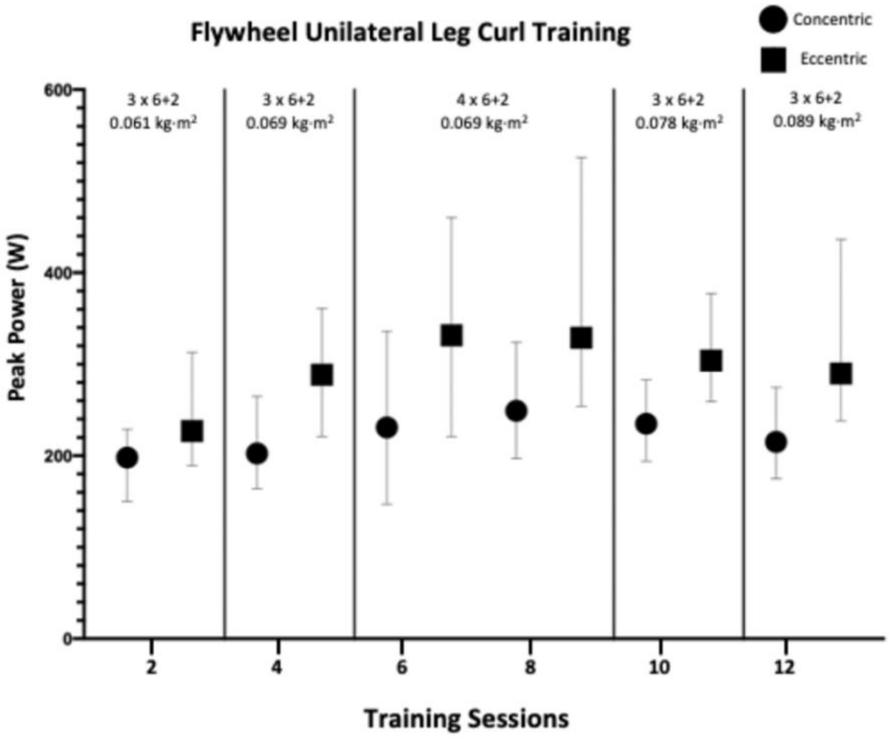


Figure 5.3. Peak power during flywheel unilateral leg curl training reported every other session.

Statistical analyses

The Shapiro-Wilk test was used to determine normality of distributions for all discrete values. Data were presented as mean ± standard deviation (SD). Inter-session reliability of peak power measures were assessed via intraclass coefficient correlation (ICC) (two-way mixed model) as: *excellent* ≥ 0.9; 0.9 > *good* ≥ 0.8; 0.8 > *acceptable* ≥ 0.7; 0.7 > *questionable* ≥ 0.6; 0.6 > *poor* ≥ 0.5; *unacceptable* < 0.5 [229]. The ICC interpretation is based on point estimates and confidence intervals. A two-way repeated measures ANOVA reporting f values was used to detect possible between and within condition (control *vs* intervention) effects and time-limb effects for knee flexion eccentric and isometric peak torque, and hamstring concentric and eccentric peak power during unilateral flywheel exercises. The between-effect of the training intervention was assessed by analysis of covariance (ANCOVA) with baseline values used as covariate. Delta difference with 95% confidence intervals (CI) were reported, with significance set at $p < 0.05$ throughout. If a significant difference was reported, post hoc tests (using the Bonferroni correction) were performed. The effect size based on Cohen's d principle was calculated and interpreted as: *trivial* < 0.2; 0.2 ≤ *small* < 0.6; 0.6 ≤ *moderate* < 1.2; 1.2 ≤ *large* < 2.0; *very large* ≥ 2.0 [228]. All discrete value statistical analyses were performed using JASP (version 0.9.4; JASP, Amsterdam, the Netherlands). Normalised one-dimensional isokinetic torque-angle waveforms were compared between limbs (control and intervention) and time-points (pre- and post-intervention) via a statistical parametric mapping two-way repeated measures ANOVA (main and interaction effects as above for the discrete ANOVA) using open-source (https://www.spm1d.org) MATLAB script. The critical test statistic and supra-threshold cluster were to be reported if the test statistic field exceeded the critical threshold.

5.4. Results

After 6 weeks of training, the two-way repeated measures ANOVA reported no statistically significant within group differences in eccentric isokinetic ($F = 4.578$, $p = 0.058$) or isometric ($F = 3.256$, $p = 0.105$) knee flexor strength (Figure 5.4). The same pattern of results occurred across the range of motion, with the statistical parametric mapping ANOVA reporting no significant interaction effect between time and limb at any joint angle (Figure 5.5). The greatest (non-significant) interaction effect size ($F = 2.51$, $p > 0.05$) occurred at 87° of knee flexion. An ANCOVA (with baseline values as covariates) reported no significant differences between intervention and control for isokinetic eccentric ($F = 3.27$; $p = 0.086$; $d = 0.77$ [-0.16; 1.70], *moderate*) or isometric ($F = 0.65$; $p = 0.431$; $d = 0.36$ [-0.59; 1.32], *small*) knee flexor strength.

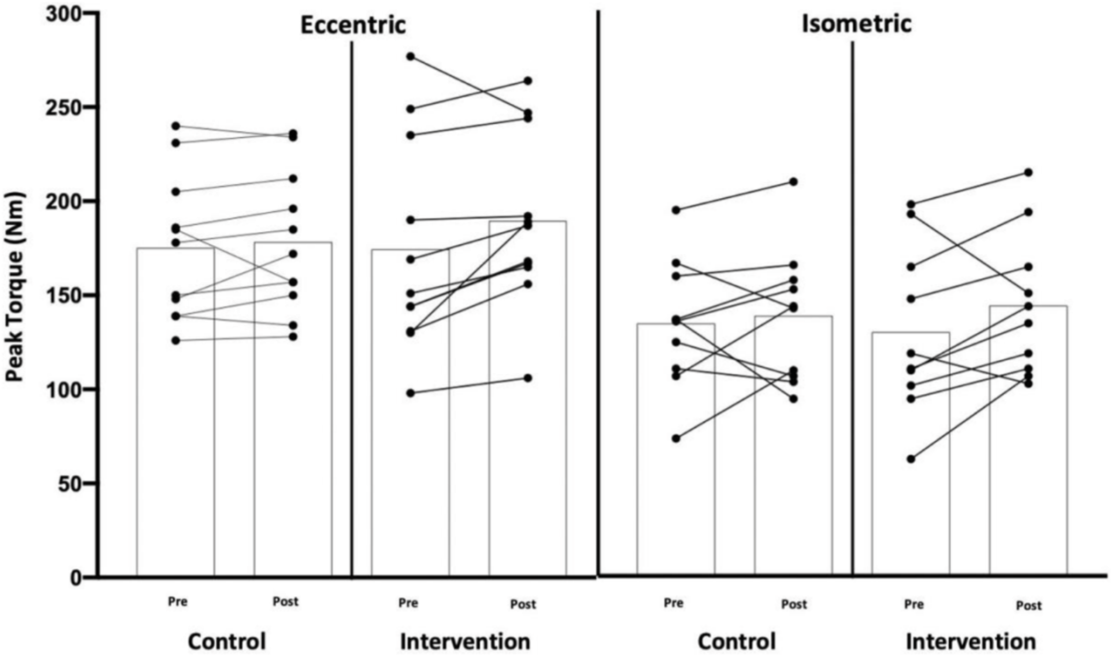


Figure 5.4. The time-effects of 6-week flywheel hamstring training on knee-flexor eccentric and isometric peak torque (N=11, limbs tested =22).

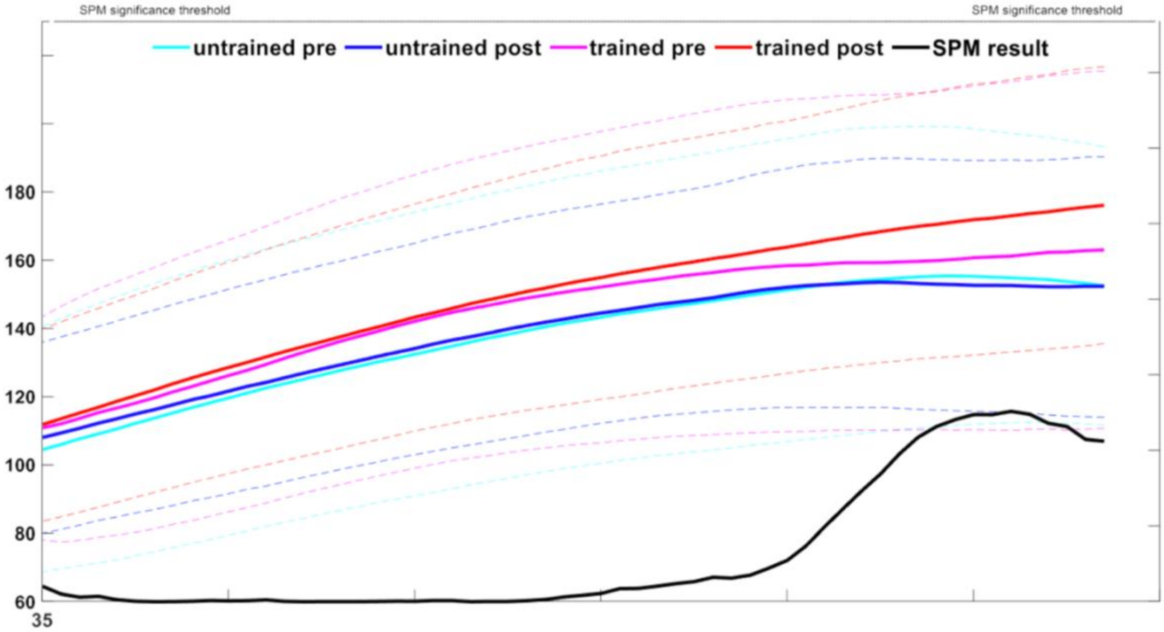


Figure 5.5. Mean (solid lines) ± SD (dashed lines) isokinetic eccentric knee flexion torque at pre and post six weeks of unilateral flywheel hamstring training (trained) or control (untrained). The thick black line and right-hand axis represent the statistical parametric mapping two-way repeated measures ANOVA time-limb interaction effect. Statistical significance ($p < 0.05$) would be indicted by the crossing of the thin dashed black line (critical threshold) at the top of the figure.

Statistically significant within group differences was reported for flywheel hip extension concentric ($F = 18.343$, $p = 0.002$) and eccentric ($F = 13.032$, $p = 0.005$) peak power (Figure 5.6) and leg curl eccentric

(*F* = 12.593, *p* = 0.005) but not concentric (*F* = 2.469, *p* = 0.147) peak power (Figure 5.6). Post hoc tests for flywheel hip extension and leg curl testing are reported in Table 1, with significant *moderate* changes in peak power occurring only in the intervention limb and not in the control limb.

The ANCOVA also reports that training enhanced hip extension concentric (*F* = 107.21; *p* < 0.001; *d =* 1.76 [0.69; 2.83], *large*) and eccentric (*F* = 95.98; *p* < 0.001; *d =* 1.33 [0.33; 2.33], *large*) peak power more than the control did. Leg curl eccentric peak power significantly improved after training (*F* = 6.08; *p* = 0.023; *d* = 1.05 [0.09; 2.01], *moderate*) but not concentric (*F* = 9.75; *p* = 0.339; *d* = 0.52 [-0.39; 1.43]*, small*) peak power.

5.5. Discussion

This chapter is the first to study the effects of unilateral flywheel knee flexion and hip extension training on hamstring strength and power. Six weeks of unilateral flywheel hamstring training, performed twice per week, significantly improved eccentric peak power assessed with a flywheel device (Table 5.1). Such training does not significantly enhance isokinetic eccentric or isometric (long-lever) hamstring strength within that time period (Figure 5.4 and 5.5). Additionally, the present chapter confirms previous evidence that unilateral flywheel leg curl training obtains a large eccentric overload of peak power while such overload is not as pronounced for unilateral flywheel hip extension exercises (Figure 5.2 and 5.3).

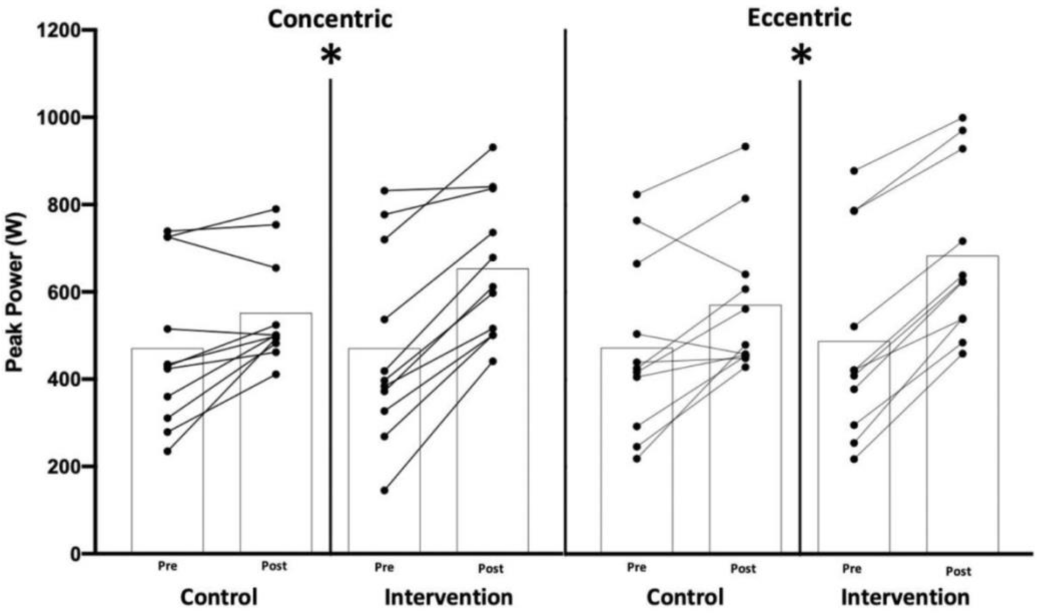


Figure 5.6. The time-effect of 6-week flywheel hamstring training on peak power during unilateral flywheel hip extension. (N = 11, limbs tested = 22). * = $P < 0.05$.

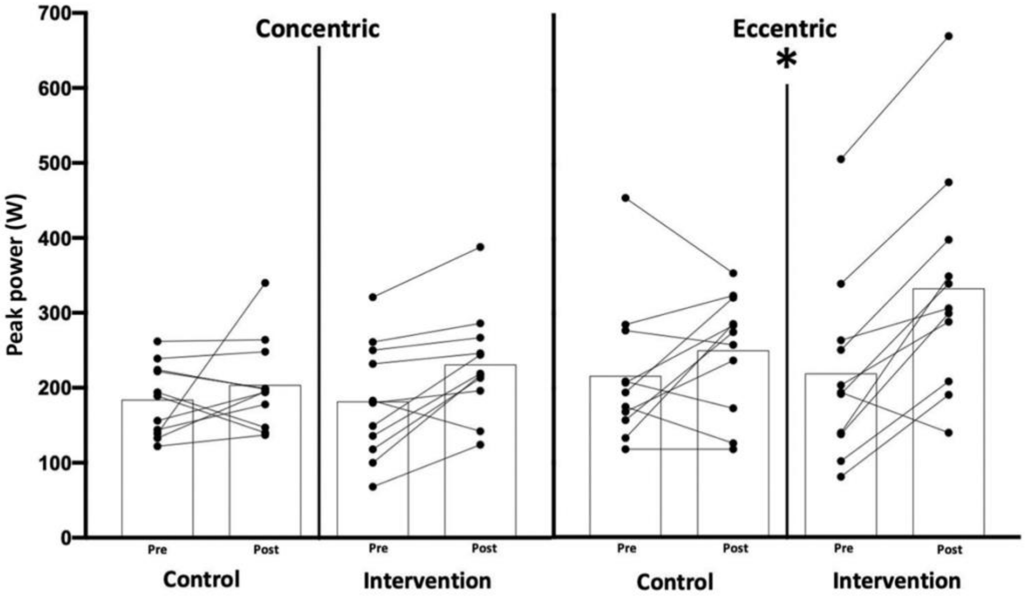


Figure 5.7. The time-effect of 6-week flywheel hamstring training on peak power during unilateral flywheel leg curl. (N = 11, limbs tested = 22). * = $P < 0.05$.

Table 5.1. Post Hoc tests for flywheel leg curl and hip extension tests. CI = Confidence interval, $p < 0.05$.

Parameter	Condition	Pre vs Post Mean Difference (95% Lower to Upper)	Cohen's d (95% CI) *Interpretation*	*p* value
Leg Curl Eccentric Peak Power (w)	Control	34 (-36 to 104)	0.30 (-0.34 to 0.95) *Small*	0.946
	Intervention	115 (45 to 184)	1.01 (0.09 to 1.92) *Moderate*	< 0.001*
Hip Extension Concentric Peak Power (w)	Control	81 (-1 to 163)	0.46 (-0.11 to 1.03) *Small*	0.052
	Intervention	183 (101 to 265)	1.04 (0.17 to 1.90) *Moderate*	< 0.01*
Hip Extension Eccentric Peak Power (w)	Control	98 (18 to 179)	0.50 (0.05 to 1.04) *Small*	0.012*
	Intervention	197 (116 to 277)	0.98 (0.18 to 1.79) *Moderate*	< 0.01*

Several factors including training duration, intensity, and exercise modality are likely to play a key role in the effectiveness of a hamstring strength training programme. Only one previous investigation used unilateral flywheel hamstring training, performing 6 weeks (392 repetitions) of either conventional unilateral flywheel leg curls (with 0.05 kg·m^2) or eccentrically biased (2 legs during concentric, 1 leg during eccentric) flywheel leg curls (with 0.10 kg·m^2) [134]. Similar to the lack of eccentric knee flexor torque enhancement in the present chapter (Figure 5.4, $p = 0.086$; $d = 0.77$), no enhancements in eccentric strength were seen after either conventional (*p* = 0.171; *d* = 0.52) or eccentrically biased (*p* = 0.329; *d* = 0.33) unilateral flywheel leg curl training. In agreement with the present unilateral hamstring flywheel literature, a variety of resistance training interventions involving the Nordic hamstring exercise (NHE) [252], Romanian deadlifts (75% 1-repetition maximum [1RM]) [244], or unilateral isometric weighted hip extensions did not enhance eccentric hamstring strength [130]. In contrast to unilateral flywheel hamstring interventions, bilateral flywheel leg curl training over a longer duration (10 weeks, 512 repetitions) significantly enhanced eccentric hamstring peak torque (Hedges *g* = 1.14, *moderate*) of professional Swedish soccer players [61]. Similarly, other resistance training interventions based on the NHE [124,213,244], isotonic (60-80% 1RM) and eccentric (only) weighted hip extensions [130,214] have also enhanced eccentric hamstring strength. Specifically, NHE protocols prescribed over 10 weeks (340 - 726 repetitions) elicited significant (11-15%) increases in isokinetic eccentric strength [124,213] and NHE eccentric strength (*p* < 0.005; *d* = 2.07) [214]. Additionally, a six week unilateral eccentric hip extension intervention (involving only 120 weighted repetitions [5 seconds per repetition]) also enhanced isokinetic eccentric knee flexor strength of healthy males (p = 0.003; *d* = 0.66) [130], contrasting the present findings.

The present chapter included isometric testing due to its perceived clinical value and increasing interest within performance and rehabilitation [134]. The findings suggest that isometric knee flexor strength at 30° knee flexion also does not increase after 6 weeks of flywheel unilateral hamstring training (Figure 5.4). Similarly to these findings, neither unilateral flywheel knee flexion (*p* = 0.77) nor eccentric Roman chair hip extension training previously enhanced isometric hamstring strength [130,134]. In contrast to the present findings, 6 weeks of isometric hip extension training enhanced isometric knee flexion torque (*p* < 0.01; *d* = 0.54) and hip extension force (*p* = 0.04; *d* = 0.41) [130]. Similarly, NHE training protocols enhanced isometric knee flexion torque at 30° (7%; 8Nm) [124]. The effects of unilateral flywheel hamstring training, alongside other strength training interventions, remain unclear on isometric strength and should be further analysed alongside other strength parameters in future investigations.

The present literature highlights some inconsistency between resistance training interventions but highlights that both knee and hip dominant exercises with varying volume and intensity can effectively enhance eccentric and isometric knee flexor strength. Several factors may explain why the present flywheel training intervention, involving unilateral hip extension (320 repetitions) and unilateral flywheel knee flexion (320 repetitions) training over 6 weeks, did not enhance eccentric or isometric hamstring strength. Firstly, it is possible that a greater training duration (*e.g.*, 10 weeks; 16 sessions) rather than a shorter intervention (6 weeks; 12 sessions) [134] may be necessary to enhance eccentric hamstring strength [61]. Further investigation (> 6 weeks) is necessary to confirm this. Secondly, it is well acknowledged that appropriate intensity and progressive overload are key to effectively increasing peak forces during training and eliciting strength adaptations with flywheel training [7,80]. Indeed, it is possible that the low initial moment of inertia previously (0.05 kg·m^2) and presently (0.041-0.061 kg·m^2) used during unilateral leg curl training did not allow for maximal strength enhancement [134]. Although the present chapter progressively increased the moments of inertia from 0.041 to 0.089 kg·m^2 in line with current guidelines [32,134], the present (< 0.069 kg·m^2 for 4 weeks) and previous (0.05 kg·m^2 for 6 weeks) designs may have progressed intensity insufficiently for eliciting maximal strength adaptations. Thirdly, it is possible that the volume prescribed per flywheel training session may have played a role. The only previous investigation which enhanced isokinetic eccentric hamstring strength after flywheel training performed 24 repetitions per session (after warm up) [61]. This differs to the prescription of 48-64 repetitions per session in the present chapter and >30 repetitions per session (for 4 out of 6 weeks) in a previous study which also did not enhance eccentric hamstring strength [134]. It is possible that the higher volume prescribed per session may have increased inter-set fatigue, reducing peak force during sessions and therefore reducing maximal strength adaptations in the present and previous unilateral flywheel hamstring intervention [7,80]. The present chapter recorded mechanical outputs (concentric and eccentric peak power) during training and highlights greater variability during leg curl training when volume was increased (64 repetitions per session) between sessions 6-8 (Figure 5.2 & 5.3). Greater variability in such parameters with greater volume supports the notion that excessive volume may have negatively impacted strength outcomes. In agreement with this, it has been previously reported that intensity was of greater importance than volume when prescribing NHE training for enhancing eccentric strength [253]. Such findings highlight the importance of better understanding the effects of flywheel training prescription (volume and intensity) and periodization [224].

Although the high-volume approach presently utilised may not have stimulated greater maximal strength (Figure 5.4 & 5.5), it may have developed other neuromuscular capacities. Flywheel eccentric peak power was increased for both leg curl (115 W; d = 1.01) and hip extension (194 W; d = 0.98) exercises (Figure 5.6 and 5.7). It is possible that the higher volume per session allowed for greater adaptation in the flywheel specific tests involving 32 repetitions than the isokinetic eccentric test that only involve 3 repetitions. Testing involving more repetitions may provide insight into the hamstrings' ability to maintain maximal power and resist fatigue – potentially warranting its inclusion within a hamstring testing battery. Some previous studies have reported similar findings of improvement in one hamstring specific test, but not another [130,254]. For example, Carmichael and colleagues [130] performed a low volume (120 repetitions) 6 week unilateral hip-extension protocol that enhanced isokinetic eccentric strength but not bodyweight hamstring strength endurance capacity or isometric strength [130]. It is also possible that enhancement of knee flexor capacity (measured as strength or power) is more likely to be significant if testing is performed on the training apparatus utilised. In agreement with this, 16 sessions of NHE or isokinetic eccentric knee flexor training were performed over 6 weeks (220 repetitions) and found that enhancement of knee flexor strength was only significant if testing was performed on the training apparatus [254]. NHE training significantly enhanced NHE eccentric strength (28-32%) but did not improve isokinetic eccentric strength (3-8%), while isokinetic training did not enhance NHE eccentric strength (3-8%) but did enhance isokinetic eccentric strength (22-28%) [254]. A similar trend was noted in the present chapter for *moderate* to *large* improvements in the flywheel leg curl (78 W) and hip extension (101 W) eccentric specific outcomes (Figure 5.6 & 5.7) while isokinetic isometric (9 Nm; *small*) or eccentric (12 Nm; *moderate*) knee flexor strength changes were not significant and much more modest (Figure 5.4 & 5.5). It is therefore likely that mode (flywheel *vs* isokinetic) and position specific differences between training (prone) and testing (seated) in the present chapter may have also contributed to the findings [254]. It is also possible that a delayed transmutation and 'realisation' of desired adaptations may have occurred in subsequent weeks after training during a realisation phase [255,256]. There are a few theoretical reasons provided within the periodisation literature that support how intensive stress during a short block of training (as imposed within this chapter; Figure 5.2 & 5.3) without an appropriate accumulation phase may not lead to desirable strength and power adaptations immediately [255]. Future work should look to incorporate a more thoroughly periodised and longer training period involving an accumulation, transmutation, and realisation phase [256]. Apart from a specific focus, a greater variation in volume within the initial accumulation phase may allow for a greater focus on power and strength development within the transmutation and realisation phase with lower volumes [256].

5.6. Limitations and future directions

This chapter is not without limitations. Importantly, the within-subjects design may have predisposed participants to a cross-education effect and therefore reduced or masked the effect of training on the intervention limb (due to comparison to the control limb) [257]. It is worth noting that evidence suggests that the cross-education effect is increased when eccentric training paradigms are employed and is mostly due to neurological adaptations, which are likely to proliferate in the initial weeks of training (similar to the present investigation) [257]. Future studies should use a randomised controlled trial design with independent groups to avoid such potential for a cross-education effect. Although this chapter found that flywheel training is effective for improving hamstring eccentric power, the relevance of this parameter to injury or sport specific performance related parameters is unknown. Future studies should aim to understand whether improvements in flywheel eccentric peak power are related to performance, injury, or other strength parameters prior to recommending its application. Although flywheel devices can practically allow for training and assessment of strength and power, the outcomes of a flywheel exercise are based upon appropriate familiarisation, strength levels, moments of inertia, and device type [80,209]. Although a progressive increase in moment of inertia was used, limited information is available for less investigated exercises such as unilateral hamstring exercises for prescribing and periodising training appropriately. Evidence based guidelines are needed to further optimise training prescription [140]. For instance, a greater intensity (> 0.069 kg·m^2), lower volume per session (< 24 repetitions), and a prolonged training duration (>10 weeks) may be necessary to enhance isokinetic eccentric knee flexor strength with unilateral hamstring flywheel training. In comparison, the present study utilised a higher volume of training (640 repetitions) that may have negatively influenced maximal strength adaptations. Further research is necessary to understand whether a lower volume of training at a similar intensity would've stimulated maximal strength adaptations.

5.7. Conclusion

This chapter supports the use of 6-weeks of unilateral hamstring flywheel training for enhancing flywheel eccentric peak power although no improvements in isokinetic eccentric or isometric (long-lever) hamstring strength were seen. A large variation in eccentric overload seen between exercises (larger eccentric overload during leg curl in comparison to hip extension) and sessions supports the need for monitoring of mechanical outputs (and eccentric overload) during flywheel training. Finally, this chapter is the first to report eccentric isokinetic strength utilising a statistical parametric mapping (SPM) approach after flywheel training, which provides additional information regarding the entirety of the range of motion and potential changes in strength.

5.8. Practical applications

Practitioners should consider that strength may be task specific and not translate unanimously between tests, carefully considering what validated tests are selected. Ultimately, tests should also be specific to the qualities that practitioners wish to analyse. Practitioners should aim to monitor and utilise mechanical outputs to guide flywheel training and periodisation as significant differences between exercises are evident.

Chapter 6 - Comparing the effects of flywheel training and barbell training on isokinetic and isometric strength amongst female team sport athletes

6.1. Abstract

The aim of the present chapter was to compare the effects of 7 weeks of flywheel or traditional resistance training on isometric and concentric quadriceps strength amongst a youth female team sport population during the in-season period. The intervention involved 24 female athletes with 13 and 11 athletes in the traditional and flywheel resistance training groups, respectively. Unilateral concentric ($60^\circ \cdot s^{-1}$) and isometric torque (90°) was measured during knee extension before and after the training intervention. Training involved progressive increase in volume or intensity of squats and split squat exercises. There were no significant differences between traditional and flywheel training groups for concentric ($p = 0.57$; $d = 0.25$, small) or isometric ($p = 0.91$; $d = 0.44$, *small*) knee extensor strength. Both groups significantly improved concentric strength ($p < 0.01$; Mean Difference = 13 [4 to 22]; $d = 0.44$, *small*) and isometric strength ($p < 0.01$; Mean Difference = 37 [19 to 56]; = 0.75, *moderate*). Seven weeks of progressively overloaded squat and split squat flywheel or traditional resistance training improved concentric and isometric strength similarly amongst team sport female athletes during an in-season period.

6.2. Introduction

Although the thesis has touched on several key themes: addressing the current state of the literature, the perceptions of flywheel training amongst practitioners working in sport, the influence of moment of inertia on unilateral hamstring exercises and how unilateral hamstring training programme influences hamstring strength and power, the question surrounding the efficacy of flywheel training in comparison to traditional resistance training for enhancing strength hasn't been assessed yet. Strength is often considered an underpinning factor for many of the aforementioned athletic endeavours [2,258]. Indeed, the importance of muscular strength for sport performance is evidenced by the strong relationship between strength and athletic performance parameters (*i.e.,* jump, sprint, and change of direction [COD]) [259,260]. The development of strength has therefore become widely acknowledged as an essential part of the training puzzle when aiming to enhance athletic performance [1,2]. Importantly, this has been identified as a key area of interest in the literature and amongst practitioners in both Chapter 1 and 2.

The effects of flywheel training on female athlete populations have also been previously addressed as a priority but are yet to be investigated (Chapters 1-4) within the literature and amongst practitioners. Specifically, Chapter 3 identified that although 75% of therapists perceive flywheel training to be effective for enhancing strength (Figure 3.7), majority of the limited sample (n= 3/38) of physiotherapists working with competitive and national level female athletes reported not knowing or not believing that flywheel training can effectively improve strength outcomes. Interest in female team sports is growing, seeing greater participation and support all the way from amateur to professional athletes [121]. In line with this, the ability to perform more frequent and more intense jumping, running, and changes of direction are becoming more important at all levels of women's sport to achieve success [261–263]. This has been noted to be the case in women's football, whereby the amount of high-speed running and the maximal speed obtained by players are related to individual and team performance [262]. Similarly, the high speed running demands of international women's hockey players differ significantly to those of national level players (42% greater amongst international in comparison to national level players) [261]. Netball match play also requires a variety of high intensity jumping, cutting, and pivoting actions that can be key performance determinants [263]. Importantly, athletes must perform thousands of complex and taxing actions involving changes in velocity and direction during training and matches [261,263,264]. The exponential growth in participation and athletic demands in women's sport has also been paired with a persistent issue of increased injury risk and severity [121]. It is well evidenced in the literature that female athletes partaking in intermittent sport are at the greatest risk of one of the most severe ligament injuries in team sport (anterior cruciate ligament [ACL] injuries), with athletes potentially at the greatest risk earlier in their careers [93]. More recently, a rising level of competition has also shown to increase risk of severe injuries (where time loss is > 28 days) amongst female athletes [194]. Specifically, injury to the lower limbs (*e.g.,* knee) occur more frequently and often predispose female team sport athletes to recurring injuries [121]. In a similar vein to enhancing performance, a key aspect to reducing likelihood of injury is to identify and address modifiable intrinsic risk factors such as muscular strength [262]. Indeed, it is widely recognised that a key aspect to injury prevention programmes are their strength training components [7,121].

The commonly applied machine based or free-weight (*i.e.,* traditional resistance) exercises constitute a majority of the resistance training literature [1,7]. The application of free weight resistance training can consist of a variety of training implements ranging from kettlebells to barbells [1]. Similarly, exercise selection can vary largely, although practitioners frequently prescribe the bilateral back squat or similar variations (*i.e.,* split squat) [56,140,220]. Moreover, practitioners must also consider the volume and intensity of training to prescribe an efficient and effective training programme. Training is also typically manipulated dependent upon other factors (*i.e.,* competition, travel) [57]. Changes in training prescription and objectives must therefore naturally reflect a multitude of factors in team sport environments, leading practitioners to utilise different methodologies – such as flywheel training [32,220]. A large majority of studied practitioners working in soccer believed that flywheel training is a valid method for enhancing strength [140], supported by a plethora of systematic reviews on the topic [77,138,142]. Indeed with greater integration of flywheel training in practice, the comparison between traditional resistance and flywheel training methodologies for development of strength has become of interest [77,142]. More recently, certain studies with male athletes have continued to compare flywheel and traditional resistance training methodologies. An 8-week traditional or flywheel resistance training intervention performed twice per week with youth (U18-U21) male ice hockey players enhanced squat jump performance to a comparable degree (6-9%) [172]. Similarly, a weekly flywheel or traditional squat training session performed over a 10 week period with semi-professional male soccer players enhanced strength similarly between training methodologies [141]. Both flywheel and barbell squat interventions applied over a 6 week period (3 sessions per week) also elicited favourable hypertrophy adaptations with youth professional soccer players [265].

Most research has been performed with male athletes and healthy males comparing the efficacy of flywheel and traditional resistance training, with little known about how flywheel and traditional resistance training compare when aiming to enhance strength of female team sport athletes.

Specifically, focusing on the more commonly applied exercises (*i.e.,* the flywheel squat) identified in Chapters 2 and 3 seems most appropriate for the development of how flywheel training is applied in practice. Indeed, since less is known with female populations, more studies are needed to understand how such resistance training interventions influence strength during in-season periods [147]. Of the few investigations that have studied the effects of these two training modalities on strength outcomes with female populations, even fewer have compared the effects of flywheel and traditional resistance training with athletic female populations [147]. Therefore, the aims of the present chapter were to compare the effects of a flywheel and traditional resistance training intervention on isometric and concentric quadriceps strength amongst a youth female team sport population during the in-season period. It was hypothesised that flywheel resistance training would increase isometric and concentric strength more so than traditional resistance training amongst female team-sport athletes.

6.3. Methods

Experimental design

A randomised parallel trial design was used to study the effects of a 7-week flywheel or traditional resistance training intervention on isokinetic and isometric quadriceps strength of female team-sport athletes (Figure 6.1). The protocol involved one familiarisation session, three testing sessions, and fourteen training sessions (training performed twice per week for seven weeks). During the first visit, participants' body mass and height were recorded using a stadiometer and weighing scale (Seca 286dp; Seca, Hamburg, Germany) and participants were familiarised with the lower limb tests (isokinetic and isometric strength assessments). All sessions were aimed to be separated from intense activities (training or competition) by 24 hours. All isokinetic and isometric testing were performed at baseline (week 1 / session 2), post-training (week 9 / session 17), and reliability (week 9 /session 18) in a controlled laboratory (19-21 °C) at a similar time of day to reduce the impact of circadian rhythms on performance. Depressants (*e.g.,* alcohol) and stimulants (*e.g.,* caffeine) were not permitted within 12 hours prior to the testing sessions. All training and testing were monitored by a qualified strength and conditioning coach (NSCA) to assure optimised safety and performance.

Participants

An *a priori* power analysis was conducted to determine the appropriate sample size using a statistical software (G*Power version 3.1.9.6, Düsseldorf, Germany). Considering design, a two-way analysis of variance (ANOVA) analysing between-participants, a large effect size (ES) $f = 0.6$, an α-error = 0.05, and a required power $1-\beta = 0.80$, an estimated minimal total sample size of 25 was required (actual power = 0.81). Considering potential drop out, a minimum of 30 participants were recruited and randomly allocated (http://www.randomizer.org/) to the flywheel group (n = 15 participants) or traditional training group (n = 15 participants). Of the 61 athletes contacted, 37 wished to take part and were included in initial testing. Only 24 participants completed at least 90% of training and testing procedures, due to a high dropout of participants either due to injury during sport or personal reasons (35%). Twenty-four healthy female athletes (age 20.3 ± 1.2 years, height 1.67 ± 0.06 m, body mass 65.3 ± 8.7 kg, 1RM = 63 ± 19 Kg; 1RM/BM = 0.97 ± 0.18 $kg \bullet kg^{-1}$) voluntarily participated and completed the protocol (Figure 6.1).

Inclusion criteria were absence of injury or illness, completion of the physical activity readiness-questionnaire (PAR-Q), and at least 6 months of resistance training experience. All athletes invited were required to take part in competitive team-based invasion sports (*i.e.,* soccer, field-hockey) at either the highest university level (British Universities and Colleges Sport) or within a Women's Super League academy (highest soccer academy level). All participants completed at least two training sessions per week of their individual sport, at least two resistance training sessions, and at least one competitive fixture per week. All included participants were also required to have at least 6 months of resistance training experience. The mean estimated back squat 1-RM of the traditional training group was roughly 1 x bodyweight (in Kg) (procedures described below) which suggests that the participants included range from novice to moderately trained. The present population would be representative of a lot of field-based female athletes at this age with regards to their strength, as evidenced by recent literature suggesting youth female team-sport athletes receive less strength and conditioning support and opportunities than males [266]. The intervention was completed between September to December with a variety of factors including lifestyle and university commitments mostly affecting university student athletes and their participation in the intervention (discussed further in the discussion).

All participants completed a written informed consent form after a verbal and written rationale of the experimental procedure was given. The Ethics committee of Liverpool John Moores University (UK) approved this project (22/SPS/051). All procedures were conducted in line with the Declaration of Helsinki for studies involving human participants.

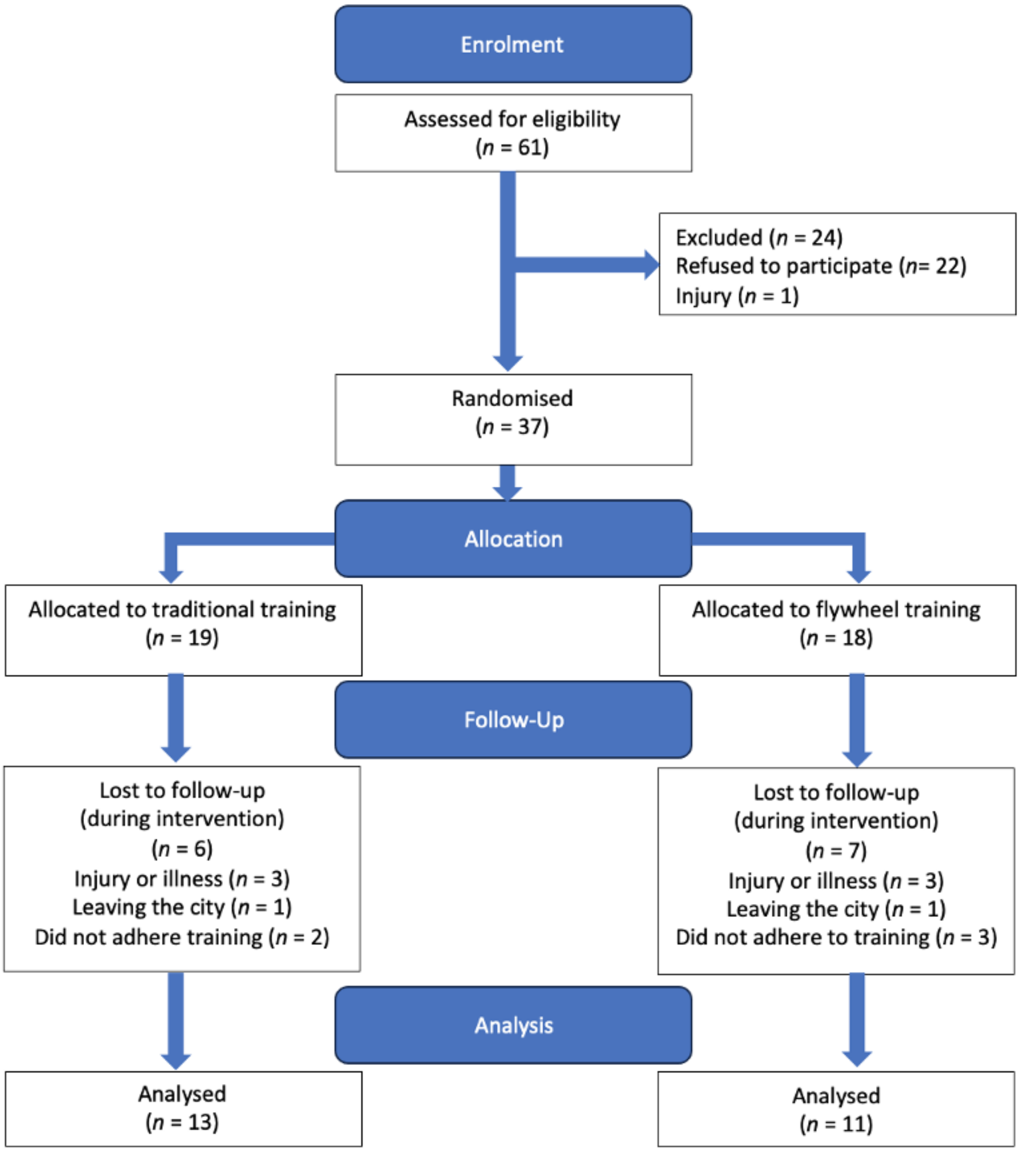


Figure 6.1. CONSORT diagram

Testing

An isokinetic dynamometer (HumacNorm, Massachusetts, USA) was used to measure concentric and isometric knee extension torque. Participants were seated on the dynamometer chair, with an internal hip angle of 95° and the crank axis aligned with the tested knee joint centre of rotation. The trunk, hip, and thigh were firmly strapped to the seating during all isokinetic and isometric testing. To warm up prior to testing, participants were required to perform 5 submaximal concentric repetitions and two repetitions at 50% of maximal isometric strength. Four maximal isometric muscle actions interspersed by 30 s rest were performed with the knee joint set at 90° knee flexion. Participants then performed three maximal concentric knee extension repetitions at $60^{\circ}\cdot s^{-1}$. Isokinetic measures were sampled at 100 Hz, with the device calibrated (with peak torque gravity corrected) according to manufacturer's guidelines. Specifically, prior to each assessment the gravity correction firstly involved a passive measurement to determine a range of motion. Following this, using the software, the torque caused by gravity acting on the limb and dynamometer is accounted for. This value is taken into consideration by the software and thereby for each test, the isokinetic dynamometer more accurately assesses the torque produced by the participant. The data were then processed via open-source (http://www.ikd1d.org/) MATLAB (v 2022b, MathWorks, Natick, MA) script. Torque and crank angular velocity data were filtered using a recursive second-order digital low-pass Butterworth filter with a cut-off frequency of 5 Hz and a torque threshold of 0.1 $Nm{\cdot}kg^{-1}$ applied, again in line with the manufacturer's guidelines. Data points were only considered for further analysis if crank angular velocity was within 5% of the target angular velocity. Crank angle was consistently considered as joint angle (although this likely changes somewhat at smaller knee flexion values). Peak torque of the singular best trial was used for subsequent analysis. The inter-day reliability of the isokinetic concentric (ICC = 0.95 [0.90-0.97]) and isometric (ICC = 0.98 [0.97-0.99]) tests were both rated as *excellent* [229] with reliability procedures detailed in the experimental design.

Traditional resistance training

Three-repetition maximum (3-RM) testing - A three repetition maximal squat test was used to prescribe training intensity for the barbell training group. After a standardised warm-up, 3-RM testing begun at 80-90% of body weight unless the athlete felt they wanted to start at a lower self-selected weight. Load was incrementally increased appropriately until failure or inappropriate technique. Each attempt was followed by 3 min of passive rest. The mean estimated back squat 1-RM of the traditional training group was 63 ± 19 kg. Then, 80% 1-RM (group average was 50 ± 15 kg) of the participants 3-RM back squat was used for the barbell squat training protocol. The use of ± 80% 1-RM is based on previous evidence supporting its use for enhancing strength during an 8-week competitive in-season period amongst youth field-based team sport athletes [267–269]. During the split squat, athletes were encouraged to use dumbbells they felt they were able to lift with a specific perceived exertion (7/10). Throughout the protocol, participants were encouraged to increase the weight lifted of both the back squat and split squat based upon what they felt was feasible while maintaining appropriate form and technique throughout each set. Increments in training intensity occurred by 0.25 kg for the back squat at 2.5 kg for the split squat and were self-selected by the participants. Training was also progressively overloaded by manipulating volume (reported in Table 6.1). Such increases in training intensity are in line with guidelines to enhance strength adaptations in similarly aged team sport athletes [267,269].

Flywheel training

Flywheel training was performed on a commercially available flywheel ergometer (V11 Full, Desmotec, Biella, Italy). Flywheel training initially involved a maximal familiarisation session of 4 sets of 8 repetitions, as commonly performed and recommended [220]. Training was progressively increased by manipulating volume and moments of inertia prescribed (reported in Table 6.1). Range of motion was standardised for the flywheel squat to a ‘half squat’, whereby the participants hips needed to be level with their thighs (Figure 6.2) [159]. Strong standardised verbal encouragements were provided to maximise performance throughout all training.

Table 6.1. Training intervention for both flywheel and traditional resistance training groups.

Group	Week 1	Week 2-3	Week 4-5	Week 6-7
Flywheel Resistance Training	Volume: 3 x (6+2) Intensity: Squat = 0.41 kg•m^2 Split Squat = 0.29 kg•m^2	Volume: 3 x (6+2) Intensity: Squat = 0.61 kg•m^2 Split Squat = 0.29 kg•m^2	Volume: 4 x (6+2) Intensity: Squat = 0.61 kg•m^2 Split Squat = 0.41 kg•m^2	Volume: 3 x (6+2) Intensity: Squat = 0.81 kg•m^2 Split Squat = 0.41 kg•m^2
Traditional Resistance Training	Volume: 3 x 8 Intensity: Squat = 80% 1RM Split Squat = perceived exertion of 7/10	Volume: 3 x 8 Intensity: Squat = >80% 1RM Split Squat = perceived exertion of 7/10	Volume: 4 x 8 Intensity: Squat = >80% 1RM Split Squat = perceived exertion of 7/10	Volume: 3 x 8 Intensity: Squat = >80% 1RM Split Squat = perceived exertion of 7/10

Flywheel Squat

Flywheel Split Squat

Figure 6.2 The exercises utilised in the flywheel resistance training group.

Statistical analyses

The Shapiro-Wilk test was used to determine normality of distributions for all values. Data were presented as mean ± standard deviation (SD). Inter-session reliability of concentric and isometric measures were assessed via intraclass coefficient correlation (ICC; two-way mixed model) as: *excellent*

≥ 0.9; 0.9 > *good* ≥ 0.8; 0.8 > *acceptable* ≥ 0.7; 0.7 > *questionable* ≥ 0.6; 0.6 > *poor* ≥ 0.5; *unacceptable* < 0.5 [229]. The ICC interpretation is based on point estimates and confidence intervals. The between-effect of the training intervention was assessed by analysis of covariance (ANCOVA) with baseline values used as covariate. Delta difference with 95% confidence intervals (CI) were reported, with significance set at $p < 0.05$ throughout. If a significant main effect was reported, post hoc tests (using the Bonferroni correction) were performed. The effect size based on Cohen's d principle was calculated and interpreted as: *trivial* < 0.2; 0.2 ≤ *small* < 0.6; 0.6 ≤ *moderate* < 1.2; 1.2 ≤ *large* < 2.0; *very large* ≥ 2.0 [228]. All statistical analyses were performed using JASP (version 0.9.4; JASP, Amsterdam, the Netherlands).

6.4. Results

After 7 weeks of training, the ANCOVA (with baseline as covariates) reported no significant differences between traditional and flywheel training groups for isokinetic concentric ($F = 0.341$; $p = 0.57$; $d = 0.25$, *small*) or isometric ($F = 0.011$; $p = 0.91$; $d = 0.44$, *small*) knee extensor strength at the end of the intervention.

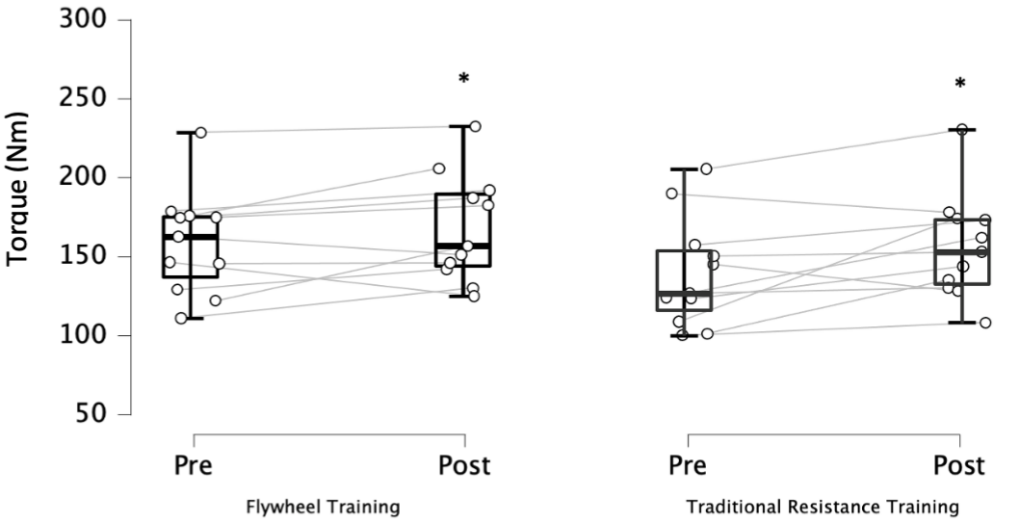


Figure 6.3. Concentric strength increases after 7 weeks of flywheel or traditional resistance training. * = P < 0.05. Nm = newton metre. White circles represent individual participants, with their respective changes between pre- and post-training labelled with a line connecting them. The horizontal lines within the box plot contains the median, 25%, 75%, and 95% ranges of values between pre- and post-training.

A two-way ANOVA reported significant improvement in main effect for time for isokinetic concentric (F = 9.78, *p* = 0.01, *d* = 0.39 [0.06 to 0.71]; *small*) and isometric (F = 19.89, *p* = 0.001, *d* = 0.75 [0.24 to 1.26]; *moderate*) strength for both groups after 7 weeks of resistance training. Specifically, a mean difference of 13 (4 to 22) newtons for concentric and 37 (19 to 56) newtons for isometric strength was reported (Figures 6.3 and 6.4).

No significant differences were seen when considering training (*F* = 1.05; *p* = 0.33) or time by training interaction (*F* = 0.69; *p* = 0.43) effects for concentric strength. Similarly, no significant differences were seen when considering training (*F* = 1.19; *p* = 0.30) or time by training interaction (*F* = 0.368; *p* = 0.56) effects for isometric strength.

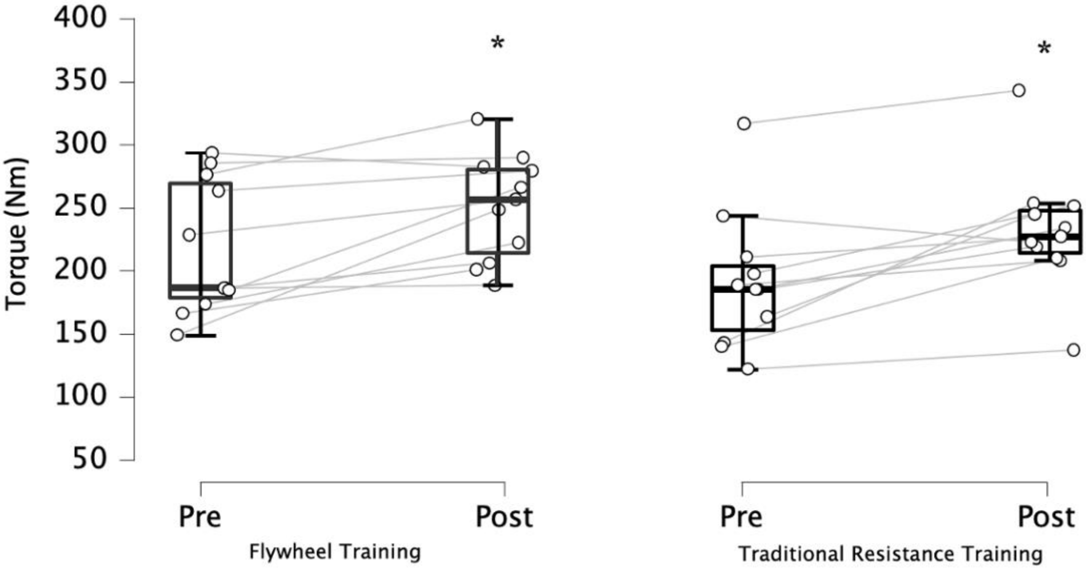


Figure 6.4. Isometric strength increases after 7 weeks of flywheel or traditional resistance training. * = P < 0.05. Nm = newton metre. White circles represent individual participants, with their respective changes between pre- and post-training labelled with a line connecting them. The horizontal lines within the box plot contains the median, 25%, 75%, and 95% ranges of values between pre- and post-training.

6.5. Discussion

The current chapter was the first to compare the use of a multi-component (squat and split squat) traditional or flywheel training protocol on isokinetic and isometric strength amongst female team sport athletes during a competitive in-season period. Seven weeks of high intensity resistance training, performed twice per week, elicited significant concentric and isometric isokinetic knee extensor strength increases, regardless of strength training methodology (Figure 6.3). There are no significant differences between flywheel and traditional resistance training when aiming to improve maximal strength. The present findings do not support the hypothesis that flywheel training is superior to traditional resistance training for enhancing strength parameters with female team sport athletes during the in-season period. An assessment of eccentric strength would've provided greater understanding of how the two resistance training interventions influenced dynamic and isometric strength, as performed before [141]. It is possible that the adaptations in eccentric strength may have differed to those in quadriceps concentric and isometric strength [250,270]. Nonetheless, the objectives of the present investigation were to better understand how traditional and flywheel resistance training protocols may influence dynamic and isometric strength amongst team sport athletes and provides novel and useful data for practitioners and researchers alike (Figure 6.3 & 6.4). Previous investigations have provided interesting and novel findings on strength adaptations using a similar methodology to the present investigation [62,134,181]. As addressed subsequently, the present study could not include an eccentric knee extensor test due to time restrictions (athlete availability in the laboratory) and the prolonged familiarisation necessary with eccentric testing to ensure adequate reliability (>2 maximal testing sessions) that could not be accommodated due to the short period the study could be completed in (September-December).

The present findings highlight that flywheel resistance training is effective for enhancing concentric strength. The noted improvement in concentric strength is in agreement with previous studies in female populations but disagrees with the previous chapter investigating the effects of unilateral hamstring flywheel training on isokinetic strength [271]. Weekly flywheel squat training (4 sets x 8 repetitions; 0.11 kg·m^2) greatly enhanced concentric (61%) and eccentric (57%) flywheel squat power of basketball and volleyball players when performed over a 24 week in-season period [166]. Similarly, a 6-week flywheel squat training intervention induced a *very large* 1-RM squat improvement (20%) with physically active females [20]. The moment of inertia (0.14 kg·m^2) and training volume (4 sets x 7 repetitions performed 2-3 times per week) utilised by Fernandez-Gonzalo and colleagues [20] differs slightly to the intensity (0.041 – 0.089 kg·m^2) and volume (6-8 sets x 6 repetitions performed 2 times per week) implemented in the present chapter. It is likely that the higher moment of inertia previously utilised in comparison to the present chapter elicited a greater increase in maximal strength [20,166]. It is also likely that the similarity between training and testing previously utilised (multi-joint exercise for both training and testing) and discrepancy in the present chapter (multi-joint for training but single-joint for testing) may have influenced the transfer of strength [20,166]. This was also reported in the previous chapter (flywheel, isokinetic, and isometric testing differ) and is an important consideration for comparing outcomes between flywheel exercises too (as they have been shown to differ in chapter 3 too) [224]. The only study to have investigated the effects of flywheel squats on isokinetic strength amongst females reported that a 6 week protocol elicited significant increases in knee extensor strength of professional female soccer players [170]. Interestingly, although the aforementioned studies utilized a greater moment of inertia (0.11 – 0.14 kg·m^2) with female populations [20,166], Pecci and colleagues only utilised 0.025 – 0.050 kg·m^2 - suggesting that significant improvements in strength (10-24%) could be made with lower moments of inertia after only 6 weeks of training during the in-season period. Further study into the use of different protocols (ranging in moment of inertia and training frequency) is warranted based on the present and previous findings.

The novel findings suggest that multi-component traditional and flywheel resistance training similarly enhance concentric strength amongst female athletes, in agreement with previous literature on how flywheel and traditional resistance training influences strength amongst females [65,147]. Changes in neural activation have not been clearly evidenced between flywheel and barbell training but are stipulated to occur in the early weeks of training [63,77]. In a healthy population of females, 8 weeks (2-3 sessions per week) of either flywheel (4 x 7 repetitions) or weight-stack leg extension (4 x 8-12 repetitions) training similarly enhanced 1-RM strength [65]. Although training was significantly improved after both interventions, a greater increase in flywheel peak power was noted after flywheel training (25 W; ES = 1.06) in comparison to after traditional resistance training (14 W; ES = 0.59) even though both training methodologies similarly enhanced 1-RM strength (± 2 kg; ES = 0.77 – 0.84) [65]. Although the present study employed an identical amount of total repetitions (8 per set) between training interventions, the intensity with which those repetitions were performed are likely to have significantly differed due to differences in instructions and methodology. There are some examples within the literature that have utilised a similar methodology when comparing traditional and flywheel resistance training [65]. Specifically, the methodology utilised in the present chapter to initiate flywheel exercise involved two submaximal efforts prior to the completion of the maximal intensity working set of six repetitions [60,67,230]. This therefore led to a large difference in repetitions performed at maximal intensity over the 7-week intervention with the flywheel group performing 828 repetitions and the traditional resistance training group performing 1104 repetitions (Table 6.1). Considering the flywheel group performed 25% less repetitions at maximal intensity than the traditional resistance group but obtained a similar improvement in strength (Figure 6. 3 and 6.4), flywheel training may be considered a more effective training strategy for enhancing isokinetic concentric and isometric strength with female athletes. In agreement with the present findings, a previous protocol comparing the effects of conventional weight-stack (687 ± 73 repetitions) and flywheel (529 ± 17 repetitions) leg extension found that flywheel training elicited similar hypertrophic and strength benefits with significantly fewer repetitions [65].

It is possible that enhancement specific to the testing methodology and equipment may occur as highlighted in the previous chapter. Amongst youth male amateur soccer players, a multi-component flywheel training programme (lateral squats or split squats [0.05 kg·m^2] and squats [0.10 kg·m^2]) was compared to a traditional resistance training programme (barbell squat and split squat; 60% 1RM) [272]. Similar to the present findings, 4 weeks of traditional resistance and flywheel training similarly enhanced 1-RM squat strength [272]. Importantly, neither the present protocol nor the aforementioned traditional resistance training protocol were focused solely on developing maximal strength. The present findings support previous research which has found protocols involving >80% 1RM with novice and moderately strength trained participants have enhanced strength [1,65,269]. Further study and longer interventions (>12 weeks) should confirm how a protocol with greater manipulation of volume and intensity of traditional resistance training (accumulation, transmutation, and realisation phase) may influence adaptations in strength in comparison to a flywheel resistance training protocol.

Some evidence suggests that differences between flywheel and traditional resistance training may enhance concentric and eccentric strength differently. Amongst males, more literature is available and suggests that changes in eccentric and concentric strength may differ dependent upon training modality [3,141]. Although the present chapter highlights that both flywheel training and traditional resistance training elicit significant improvements in concentric strength, it has been suggested that flywheel training may elicit greater eccentric strength adaptations. Amongst male soccer players, a significant increase in quadriceps eccentric peak torque (17%) was seen with flywheel training while no significant improvements were seen with barbell squats (9%) [141]. Interestingly, previous findings amongst female soccer athletes suggest that isokinetic eccentric strength may be improved more so than concentric strength after flywheel training [170]. It was practically not feasible to measure eccentric strength in the present chapter (due to limited athlete availability and time available to perform a longer familiarisation procedure). It is important to note that the participants involved in the present Chapter were not familiar with intense maximal eccentric muscle actions of the quadriceps and were already in a in-season period. This lack of exposure and limited resistance training experience would've likely caused them to take a prolonged period to recover from an initial bout of intense quadriceps eccentric exercise [273]. Although the participants would've likely responded better to a second bout (please see reference for the repeated bout effect) [18,31], it is likely that a lot of the athletes involved would have technical training and competitive matches negatively affected by the protocol. Considering this, the present Chapter did not include any maximal eccentric isokinetic assessments to reduce the likelihood of drop out during the study (which was very high – Figure 6.1) and to reduce the negative effects on performance associated with the protocol. Nonetheless, future studies should aim to confirm whether flywheel training is superior for enhancing eccentric strength or capacity as suggested previously.

A previous study reported *excellent* reliability in isometric testing (ICC = 0.95; CV% = 5.2%) [181], similar to the *excellent* reliability of the present chapter. Similar to the reported improvements in concentric strength in the present chapter, flywheel training also effectively enhanced isometric strength (Figure 6.4). Previously, 5 weeks of knee extensor flywheel training (4 x 7; 2-3 sessions per week) significantly enhanced (10-12%) isometric strength of a healthy mixed male and female cohort [60]. An identical protocol (performed 3 times per week) elicited a marked (39%) improvement with a mixed cohort of younger healthy males and females [72]. Although both studies highlight that flywheel training can be particularly effective for enhancing isometric strength with females, in agreement with the findings the present findings - the previous studies have a few limitations. Neither study reported the moment of inertia utilised and only had a limited number of female participants that were not separated from the male cohort for analysis. In comparison, the present chapter utilised an athletic population and reported for the first time that a flywheel resistance training programme performed over a 7 week in-season period can enhance isometric strength with female athletes.

Although some studies have been performed comparing the effects of flywheel and traditional resistance training on concentric strength amongst females, no studies have compared isometric strength outcomes. Nonetheless, some studies have been performed in male populations. Similar to the present findings, 6 weeks of resistance training significantly enhanced strength of 23 healthy and physically active males [181]. Specifically, a smith-machine half-squat (p = 0.03; d = 0.45) and a flywheel forward lunge (p = 0.01; d = 1.02) enhanced isometric strength [181]. Unlike the previous study, the present chapter utilised loads at an estimated 80% 1RM for back squats (as well as dumbbell split squats) instead of a Smith machine back squat (with loads eliciting maximal concentric power). The aforementioned study supports the present findings that flywheel training and traditional resistance training do not differ largely for enhancing isometric strength. It was not feasible to use an isometric mid-thigh pull as it was not available. Nonetheless, future studies should consider assessing isometric strength using a multi-joint test (*i.e.,* isometric mid-thigh pull) to further understand how flywheel and traditional resistance training interventions influence strength capacities [102].

6.6. Limitations and future directions

Although the present chapter presents some interesting findings, there are some key limitations to consider too. Firstly, the duration of the intervention and training age of the present population are two key limitations with regards to transferability to elite populations. There was little to no control or standardisation of diet, exercise, and lifestyle amongst the participants. It is therefore likely that these factors may have played a role in the strength adaptations investigated in the present chapter. Furthermore, it is unlikely that large differences would be evidenced in a 7-week period since both training methods are likely to similarly enhance strength. Such a short intervention on a population who are still relatively novice and with limited experience in strength training may have influenced adaptations. Another limitation of the present study is the lack of assessment of eccentric strength. An eccentric strength assessment may have highlighted some interesting differences between the two training modalities that may not have been seen with concentric and isometric strength assessment [141]. Considering the protocol and population, it was deemed that an additional familiarisation session would've been necessary. The assessment of eccentric strength was therefore not completed due to the limited time available to complete a familiarisation session and how the use of an eccentric test would've impacted the population doing their competitive season. Additionally, a minimum of 25 participants were required to sufficiently power the present chapter. Due to a large amount of participant drop out (Figure 6.1), the present chapter is slightly underpowered. Considering this and that the present chapter's sample size was calculated to be sufficiently powered to detect *large* differences between interventions – it is possible that if sufficiently powered to determine *small* differences, the present chapter may have concluded slightly different conclusions regarding the effects of flywheel or traditional resistance training on strength. Future study should aim to assess the differences between flywheel and traditional resistance training over a longer period (*i.e.,* > 12 weeks) amongst female athletes. Furthermore, neuromuscular and tendon analysis may also elucidate important differences between flywheel and traditional resistance training and should be performed in the future. Future studies should aim to utilise a multi-exercise protocol to provide practical recommendations and guidance for applied practice.

6.7. Conclusion

The present chapter shows that 7 weeks of flywheel or traditional resistance training (consisting of split squat and squat) performed twice per week during the in-season period can significantly enhance quadriceps concentric and isometric strength of female team sport athletes. In agreement with the hypothesis of this chapter, the present findings suggest that flywheel and traditional resistance training do not differ largely in enhancing concentric or isometric quadriceps strength with female athletes. Future studies should aim to study the specific enhancement of eccentric strength after flywheel and traditional resistance training with female athletic populations. Additionally, future studies should aim to elucidate if either flywheel or traditional resistance training elicits a greater hypertrophy of the tendons or muscles with female team sport athletes.

6.8. Practical recommendations

The present chapter suggests that practitioners can utilise either high intensity (> 80% 1-RM) traditional resistance training or flywheel resistance training to enhance concentric and isometric strength of female amateur athletes. The present chapter shows for the first time that flywheel split squats can be utilised effectively in combination with flywheel squats to enhance strength. Progressive increases in moment of inertia and volume for different exercises must be considered carefully in practice. Overall, when prescribing resistance training, it is important that practitioners consider a variety of factors (*i.e.,* training age, training demands, and compliance to the intervention) as well as the exercises and methodology selected.

Chapter 7 - Synthesis of Findings

7.1. Introduction

The main objectives of this final chapter are to highlight the discoveries of the thesis, their impact on the flywheel training literature and practice, and to explore future directions that should be investigated. The major findings of the present thesis will be presented alongside the latest scientific literature on flywheel training. Importantly, the final chapter of this thesis will discuss limitations and practical applications related to flywheel training as well as recommendations for future research into flywheel training. The main aim of the present thesis is to enhance the use of flywheel training in field-based team sports. The thesis's main aim is achieved by, firstly, appraising the literature on flywheel training, secondly, understanding how flywheel training is perceived and applied; and lastly, understanding how it can practically be utilised to enhance strength and power performance in field-based team sports. The chapters of this PhD thesis are therefore structured as follows:

Chapter 1 provides an overarching rationale for the thesis, explains important background information and highlights key themes that are subsequently discussed in the thesis.

Chapter 2 provides a detailed summary of how flywheel training enhances strength and physical capacities in healthy and athletic populations. The quality and limitations of current evidence (expert-based reviews and meta-analytical evidence) are also summarized to generate important research avenues to further explore.

Chapter 3 describes current application and perception of flywheel-based resistance training in field-based team sports, aiming to contextualise how flywheel scientific literature is being applied and to identify whether gaps in current knowledge and application of flywheel training exist.

Chapter 4 explains how altering flywheel moment of inertia would influence concentric and eccentric peak power and eccentric:concentric peak power ratio during unilateral flywheel leg curl and hip extension exercises. Additionally, another objective of the present chapter was to analyse the inter-session reliability of concentric, eccentric, and the eccentric:concentric ratio of peak power during both exercises.

Chapter 5 investigated whether unilateral flywheel hamstring training (a combination of hip extension and knee flexion exercises) enhances eccentric, isometric knee flexor strength and flywheel derived power more than a control condition.

Chapter 6 compares the effects of a flywheel and traditional resistance training intervention on isometric and concentric quadriceps strength amongst a youth female team sport population during the in-season period.

Chapter 7 discusses the impact of the thesis on flywheel training literature, practice, and explores future directions that should be investigated.

7.2. Discussion

The present thesis highlights that flywheel training can be considered a valuable and practical tool to train, monitor, and test field-based team sport athletes. Chapter 2 offers a comprehensive summary of how flywheel training enhances strength and physical capacity in healthy and athletic populations, emphasizing the need for evidence-based approaches. Chapter 2 encapsulated all the available literature on flywheel training (11 included reviews, which comprised 38 primary studies), demonstrating that flywheel training is effective for enhancing muscular strength, power, COD/manoeuvrability, and jump performance, with most studies biased towards healthy and athletic male populations. Reviews in support of this finding existed and already provided relevant conclusions on flywheel training and its application amongst male and female populations [77,142,144,147]. Nonetheless, the present thesis is the first to systematically appraise and consider the limitations of reviews that ranged in quality, aims, and conclusions [144]. Importantly, Chapter 2 provides an updated systematic review of all evidence available to practitioners and researchers alike. Building on from the findings and limitations addressed in the literature and practice (Chapter 2 and 3), a consensus statement involving 19 world-leading authors on the topic of flywheel training converged together to create an internationally recognized consensus on terminology and the application of flywheel resistance training in sport [66]. The findings of chapter 2 formed the backbone of the consensus statement that addressed the most important and relevant statements and recommendations on how flywheel training should be applied [66]. One topic highlighted in the consensus statement was the definition of eccentric overload during flywheel training [66]. Previously, within the scientific literature, flywheel training had been referred to solely as eccentric overload training without consideration for whether an actual eccentric overload occurred [62,63,274]. In line with this, Chapter 3 identified that practitioners value flywheel training because it is able to provide an eccentric overload that is difficult to attain with traditional resistance training methods. More recently, evidence suggests that some flywheel training exercises are unlikely to elicit an eccentric overload without a specific technique and if certain equipment is utilised [78,80]. In agreement with the findings of chapter 2 and as identified being important to practitioners in chapter 3, the consensus statement and more recent evidence on flywheel training recommend measuring and confirming eccentric overload when applying flywheel training rather than just assuming it occurs [66,78,80].

In agreement with the consensus statement and more recent evidence [66,170], Chapter 2 supports the use of flywheel training for improving various strength and power parameters amongst females. Nonetheless, significant gaps in the literature remain. Indeed, Chapter 2 notes that while male athletes have benefited from the application of flywheel training, there is little evidence to support its efficacy for female athletes, especially young or elite female athletes. Similarly, few practitioners working with female athletes responded in Chapter 3, highlighting a limited response amongst female practitioners. For example, no studies had directly compared flywheel training to traditional resistance training for enhancing strength in youth athletic female populations, marking a significant gap in the literature.

Importantly, the integration of flywheel training into a framework and methodology that holistically develops an athlete is important to ensure training is applied in an ecologically valid manner [136]. For example, recent evidence-based guidelines have been developed to help structure and plan training aimed at improving horizontal deceleration ability in athletes who require multi-directional speed [258]. Similar to the views of practitioners of Chapters 3, the framework recognises the importance of high intensity eccentric muscle actions for the development of neuromuscular qualities that are unlikely to be developed using traditional resistance training methodologies. Also in agreement with the findings of the thesis (Chapters 2 and 3), the framework promotes the use of flywheel training to enhance strength, hypertrophy, braking capabilities and thereby performance of fast deceleration and COD tasks amongst team-sport athletes [258]. Although prescription of flywheel training is predominantly based on squat protocols (Chapter 3), a variety of exercises are applied within the literature and amongst practitioners more generally [84,274]. It is likely that as practical recommendations evolve and access to equipment increases, training prescription and the evidence base for such exercises will continue to increase [95,258]. Similarly, the use of flywheel devices will not be limited to solely training but also towards monitoring and testing processes going forwards [102]. Such findings are in line with the perceived practicality of flywheel training amongst practitioners (Chapter 3). Specifically, it has been proposed that flywheel training may be utilised for strength training and assessment of asymmetry amongst athletic populations [95,102,192]. Currently, limited evidence supports the use of flywheel asymmetry assessments [102] although some studies have investigated the use of flywheel training for the reduction of inter-limb asymmetries [275,276].

The use of unilateral hamstring exercises (as presented in chapter 4) may provide interesting data on unilateral hamstring capacity, with a recent review suggesting they may be useful for rehabilitation of elite soccer players [95]. Overall, the current flywheel asymmetry assessment and training literature does not support the use of flywheel devices for the reduction of asymmetry (and it's relationship with injury risk) in sporting populations, similar to the limited evidence supporting other methodologies [102,277].

As detailed in Chapter 1, flywheel resistance training differs from traditional resistance training in progression of load. Indeed, the thesis highlights the importance of utilising appropriate mechanical variables to monitor flywheel training and potentially individualise training accordingly. In support of the present findings, the literature recommends the integration of encoders to monitor mechanical outputs to practically quantify and progress flywheel training [66]. Chapter 3 brings to light that the appropriate changes in moment of inertia are likely dependent upon participants, exercises, machines, and moments of inertia – in line with what is currently reported in the literature [80,83,225]. Furthermore, the thesis highlights the importance of a sufficient (and maximal) familiarisation phase to ensure that the reliability of data for testing and profiling is appropriate. Similar to the recommendations made in the most recent consensus statement [66], the present thesis recommends the analysis of absolute mechanical outputs rather the use of ratios (*i.e.,* concentric:eccentric) to determine exercise intensity and outcomes. As suggested in the present thesis (Chapter 4), significant differences may occur at the group and individual level when altering moment of inertia [82,83]. Although it is currently unclear whether an individualised approach is more beneficial than a "one-size fits all" approach, current recommendations are to individualise moment of inertia prescription with team-sport athletes [136]. Nonetheless, the typical prescription of flywheel training is more often than not based on a "one-size fits all" rather than an individualised approach in team-sport environments [84,141]. Time constraints during the competitive period often leads practitioners to rely on group-level inertia profiles or none at all and therefore to the arbitrary use of moments of inertia. While team-based profiles offer a compromise, they may not be as effective as individualised approaches. The application of flywheel training may be limited by the potential inappropriate progression of intensity typically applied using current methodologies. Apart from individualised approaches, monitoring peak power outputs during unilateral hamstring exercises could help improve training outcomes, but more research is needed to confirm the best methods for prescribing flywheel training intensity. Building on from the findings and difficulties discussed in the present thesis, the use of rate of perceived exertion (RPE) to manipulate and monitor training intensity has become of interest with flywheel training [209]. When comparing assisted and unassisted squats, significant (*moderate* to *very* large) changes were seen in concentric and eccentric peak power outputs whereas no differences were noted in RPE reported [209]. Further investigation (data unpublished) has continued to explore the potential use of RPE as a method to monitor and prescribe flywheel training as an adjunct or alternative to the methods that have currently been less effectively integrated within team sport environments [66]. The thesis has formed foundational work for the current ongoing projects that will enhance the prescription and monitoring of flywheel training in practice.

The thesis has also significantly contributed to the development of flywheel training by leading to the development of flywheel squat prescription and methodology [209]. Specifically, the present body of work (Chapters 2-5) have highlighted the relevance and perceived importance of eccentric overload (and it's quantification) for practitioners and researchers alike. Previous methodology (*i.e.,* 2 legs up [concentric], one leg down [eccentric]) in the flywheel literature [134] and the use of spotters and weight-releasers in traditional resistance training to elicit greater eccentric overload [10] highlights a variety of methods that can be used to elicit eccentric overload. Currently, the main methods of eliciting a greater eccentric overload are through the manipulation of moments of inertia or the technique (delayed braking to the last third of the eccentric phase) utilised with flywheel training [83,209]. Although concentric phase assistance during flywheel squats are utilised in practice, the effects of such changes remain unclear. Considering flywheel squats are the most frequently researched and prescribed exercise and achieving eccentric overload is perceived important but difficult (Chapter 2 and 3), developing a system that enhances their eccentric outputs is relevant [209]. Indeed, the use of assisted squats may elicit a greater eccentric peak power output and may stimulate more consistent and greater neuromuscular adaptations than unassisted squats [67,134]. Importantly, the assisted squat provides practical alternatives to progressively increase mechanical load in a manner that is not limited by the few combinations of moments of inertia used in practice (0.025 – 0.0100 kg·m^2) with *excellent* reliability [209].

Although the present findings support previous evidence suggesting practitioners predominantly utilise the squat when prescribing eccentric training [56], Chapter 3 also highlighted that practitioners utilise a variety of exercises (such as unilateral hamstring exercises) that are not as thoroughly researched. The use of unilateral hamstring flywheel protocols have been recognised in a recent framework as relevant and important for the development of maximal eccentric strength [258]. This is likely related to the important association between maximal eccentric strength and enhanced maximal horizontal deceleration ability [258]. Although bilateral leg curl and leg extension flywheel protocols have proven to effectively enhance strength [61,72], unilateral leg curl training protocols have not enhanced hamstring strength previously in the literature [134]. Chapter 5 supports previous evidence suggesting that current approaches to unilateral flywheel hamstring training may not be effective for enhancing eccentric hamstring strength with males. Specifically in Chapter 5, several factors relating to the volume and intensity prescribed for such unilateral hamstring exercises are explored with future recommendations provided. The development of flywheel training methodology within rehabilitation settings has integrated some of the practical recommendations developed from Chapter 5 and are founded on the common application of such unilateral hamstring exercises discovered in Chapter 3 [95]. The present findings suggest the combination of a knee- and hip-based flywheel hamstring protocol do not enhance isokinetic and isometric strength. Nonetheless, previous evidence highlights that hamstring exercises involving the stretch shortening cycle and eccentric training are likely to enhance strength[216,231,243].

As addressed in chapter 2, the performance of flywheel training with appropriate technique allows for a safe, effective, and more demanding eccentric phase (and potential eccentric-overload) when compared to traditional resistance training (involving dumbbells or barbells) [67,137]. Such differences in exercise intensity are supposed to lead to significant changes in strength and power adaptations [63,141]. Indeed, the integration of flywheel training is also supported for the enhancement of COD performance amongst male team sport athletes [258]. Such guidelines and frameworks facilitate the introduction of flywheel training within male team sport environments by providing evidence-based recommendations and strong rationale for the inclusion of flywheel training [136]. Indeed, amongst youth athletes (8 out of 10 studies with males), flywheel training interventions were similarly effective to traditional resistance training for enhancing strength and physical performance parameters [278]. The present thesis highlights the large gap in the literature and thereby in guidelines for the integration of flywheel training within female team sports (Chapter 2 and 3). The findings of Chapter 6 are in agreement with the literature that flywheel training can enhance strength of team sport athletes during the competitive in-season period if integrated appropriately [7,136]. Specifically, Chapter 6 shows that the application of only 14 sessions of a multi-exercise flywheel protocol similarly enhances isokinetic concentric and isometric strength when compared to a traditional resistance training protocol amongst female team sport athletes. Importantly, similar outcomes between flywheel and traditional training were achieved even though flywheel training utilised 25% less high intensity repetitions than the traditional resistance training protocol. The findings of the present thesis are in line with previous similar studies and may be associated with the greater demands and activation during flywheel training in comparison to traditional resistance training [62–65,72]. Overall, the limited evidence available amongst female athletes makes comparison difficult to the present results [147,170,191]. Nonetheless, the findings of the thesis support the application of flywheel training for the enhancement of strength and power amongst female team sport athletes. Chapter 6 should encourage coaches to consider which high intensity resistance training methodology is more feasible and practical within their environment. The findings also support the notion that both can potentially be utilised interchangeably and are likely to have more similarities than differences, especially within shorter periods.

7.3. Limitations and future directions

The present thesis has some limitations. Firstly, the thesis was severely affected by the COVID-19 pandemic and the ensuing lockdowns that were imposed. The protocols and planning necessary to implement training protocols limited interaction with sports organisations and may have affected the application of the findings to elite athlete populations (the chapters mostly used university athletes). For example, the lack of control over external factors such as diet and lifestyle further complicate the interpretation of the results of the thesis. It is likely that these variables could significantly influence strength adaptations although it was not feasible to control for them. Furthermore, both Chapters 5 and 6 were short interventions (6 and 7 weeks, respectively), limiting conclusions on long-term adaptations. Due to time restrictions, the inability to assess eccentric strength in Chapter 6 prevents a deeper understanding of how flywheel training impacts eccentric versus concentric strength in comparison to traditional resistance training. Furthermore, the populations investigated were predominantly soccer related – limiting the application of findings to other field based team sports.

The present thesis identifies several avenues for future research to improve the understanding and application of flywheel training. Firstly, Chapter 2 recommends avoiding the term "eccentric overload" unless it can be confirmed with appropriate measurements. Future studies should aim to develop clear criteria for defining eccentric overload and investigate its role in enhancing strength and performance outcomes. Similarly, future studies and reviews must carefully consider the tests selected (and the specific qualities) involved when reporting findings. For example, future research should carefully consider the use of change of direction or manoeuvrability tests and discuss them appropriately. Further investigation into unilateral hamstring exercises is also warranted. Chapter 3 notes that these exercises have garnered considerable attention from practitioners, but there is limited research on how they influence key training variables such as peak power and velocity. Future studies should aim to determine the optimal training parameters for these exercises, including appropriate moments of inertia, to maximize strength and injury prevention benefits. Chapter 4 and

5 highlights that an area of interest is the integration of flywheel devices into performance assessments, particularly for evaluating inter-limb asymmetries. The use of unilateral exercises such as the unilateral leg curl and hip extension could provide practitioners with actionable data during rehabilitation or within a season where traditional testing methods may not be practical. Contrasting evidence regarding the importance of asymmetry to sporting populations exists. Specifically for the assessment of asymmetry using flywheel devices more research is necessary prior to commonplace implementation. Future studies should investigate how daily fluctuations in flywheel training parameters impact training outcomes and the reliability and validity of specific assessments must be completed to determine the signal: noise ratio. This may be particularly relevant for athletic populations, where factors such as travel and fixture congestion may require specific adjustments to training protocols, including changes to moment of inertia and training volume. Like Chapter 4, future studies should explore how loading parameters and familiarization with flywheel devices affect training outcomes, especially for populations with limited exposure to flywheel training. Building on Chapter 5, future randomised control trials should also aim to examine the relationship between flywheel eccentric peak power improvements and sport-specific performance outcomes, such as injury prevention or enhanced athletic performance. Such research would provide stronger evidence for the practical application of flywheel training in various athletic populations. Building on Chapter 6, research into how flywheel training and traditional resistance training alter neuromuscular qualities (*i.e.,* tendon, muscle cross-sectional area) particularly with female athletes would be beneficial for understanding how strength adaptations occur. Specifically, a future study should assess concentric, isometric, and eccentric strength alongside other field-based measures of athletic performance to determine the effects of flywheel training interventions. Furthermore, consideration for multi-joint assessments of dynamic and isometric strength are warranted and may provide a greater understanding of the influence of training on strength performance.

Practical Applications

Several practical applications can be taken away from the thesis and the work that has built on from it. Firstly, the present thesis is the first to summarise the flywheel training literature systematically and appraise the limitations of systematic and narrative reviews (Chapter 2). Additionally, the thesis provides invaluable information on the application and opinions of practitioners working within sport – highlighting key issues and aspects that must be further investigated (Chapter 3). The thesis further confirms the importance of utilising the technology that has advanced significantly over recent years (*i.e.,* encoders) (Chapter 3 and 4). Practically, the use of encoders is recommended to at least prescribe training on a group or individual basis. Encoders are typically now built-in to flywheel devices and can allow for biofeedback and facilitate prescription of training. Importantly, the thesis highlights the need to confirm such outputs to ensure that the familiarisation, device, moment of inertia, and exercise performed are appropriate if practitioners are aiming to achieve a desired eccentric training effect – rather than simply assuming it occurs. Practical recommendations for altering flywheel training building on from the thesis also recommend further investigation into the use of concentric phase assistance (*i.e.,* utilising the upper body or two limbs) to enhance eccentric phase demands. The present thesis (Chapters 4 and 5) presents for the first time some important considerations on unilateral flywheel hamstring training. In particular, the integration of flywheel training into a holistic hamstring training model (hip- and knee-based exercises) should be nuanced and consider the distinct differences between exercises and potential outcomes (Chapter 4 and 5).

Chapter 6 provides invaluable research on flywheel training with female athletes that has been consistently lacking (Chapter 2 and 3). Coaches can confidently integrate flywheel training protocols adapted from the findings of Chapter 6 to enhance strength in female athletes during the in-season period. Indeed, flywheel training can be an effective alternative to traditional resistance training, offering similar strength gains with fewer volume, which may be relevant during the in-season period for balancing training stimuli and recovery.

Overall, the present findings do not suggest that flywheel training is superior to traditional resistance training for enhancing strength, power, or sport performance. Currently the evidence supporting the use of flywheel training over other methodologies remains limited. Rather than promoting one methodology, system, or approach over another, the present thesis aims to promote the integration of flywheel training into a broader model. Indeed, the development of physical performance is likely to benefit from a rounded approach (involving plyometrics, traditional resistance, etc.) rather than an isolated and dogmatic one.

It is hoped that the findings of the present thesis provide some nuance around the literature, perspective on the application of flywheel training currently, some novel information on the use of two unilateral hamstring exercises, and a thorough comparison of flywheel and traditional resistance training on strength amongst female athletes. These individual chapters provide practical considerations for coaches and practitioners to optimize the use of flywheel training in their team sport environments, ensuring it aligns with the needs and goals of their organisation.

Chapter 8 - Bibliography

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Chapter 9 - Appendix

Appendix A

Preamble: Flywheel questionnaire for practitioners working in soccer.

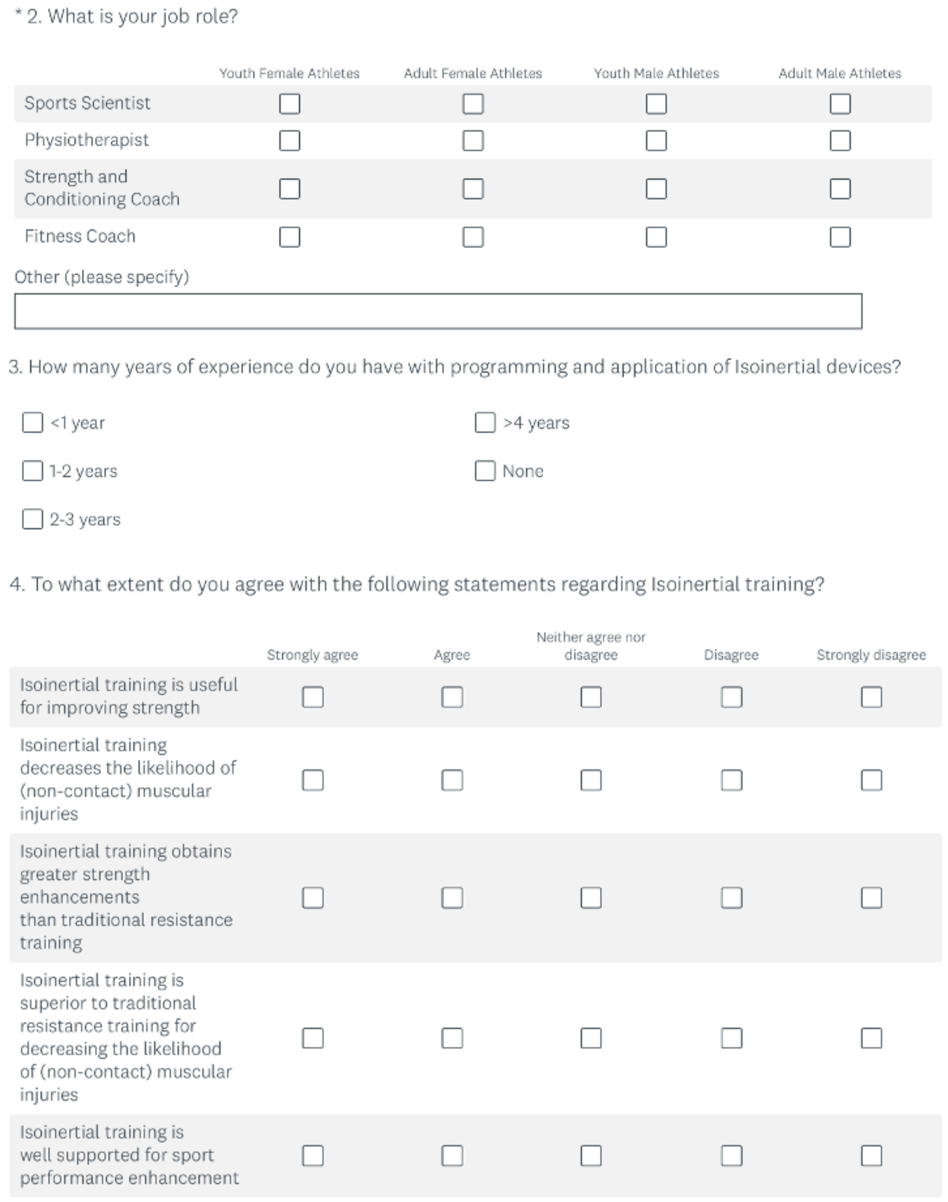
Flywheel training, a method aimed at reducing injury risk and enhancing athletic performance has gained significant attention in recent years. Despite the surge in research on flywheel training and its application in sports, there remains a gap in our understanding of how practitioners perceive and implement flywheel training. This study seeks to address this gap by exploring the current practices, perceived benefits, and limitations of flywheel training among soccer practitioners.

Project Summary: Flywheel training provides resistance that is near maximal and based on the moment of inertia, intent, technique, and machine utilised. However, while the scientific literature has expanded rapidly, practical insights from practitioners working in soccer remain scarce. By investigating perspectives and application, this knowledge gap and future research directions can be addressed.

Informed Consent: The questionnaire that follows is completely anonymised and voluntary. Institutional review board approval (University of Suffolk, UK) was granted before the commencement of this study in accordance with the Declaration of Helsinki.

Project Purpose: The present research serves several purposes. Firstly, it will identify potential areas for further investigation, guiding future studies on flywheel training. Secondly, it will highlight practical considerations that practitioners encounter. Importantly, this will shed light on common challenges and difficulties faced.

Eligibility Criteria: To participate, you must be over 18 years old and have experience working in soccer as a strength and conditioning coach, sports scientist, fitness coach, physiotherapist or similar. The questionnaire that follows is completely anonymised and voluntary. Institutional review board approval (University of Suffolk, UK) was granted before the commencement of this study in accordance with the Declaration of Helsinki.



* 2. What is your job role?

	Youth Female Athletes	Adult Female Athletes	Youth Male Athletes	Adult Male Athletes
Sports Scientist	☐	☐	☐	☐
Physiotherapist	☐	☐	☐	☐
Strength and Conditioning Coach	☐	☐	☐	☐
Fitness Coach	☐	☐	☐	☐

Other (please specify)

3. How many years of experience do you have with programming and application of Isoinertial devices?

☐ <1 year

☐ 1-2 years

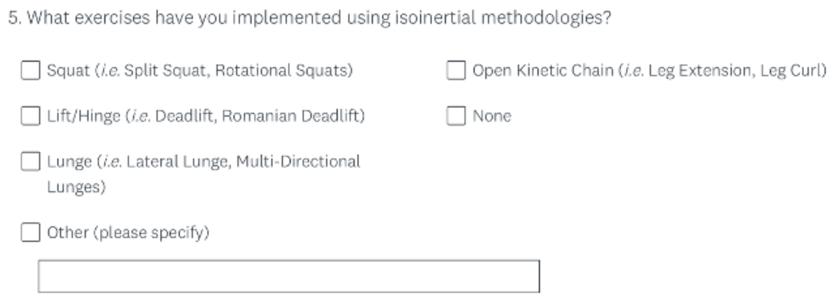
☐ 2-3 years

☐ >4 years

☐ None

4. To what extent do you agree with the following statements regarding Isoinertial training?

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
Isoinertial training is useful for improving strength	☐	☐	☐	☐	☐
Isoinertial training decreases the likelihood of (non-contact) muscular injuries	☐	☐	☐	☐	☐
Isoinertial training obtains greater strength enhancements than traditional resistance training	☐	☐	☐	☐	☐
Isoinertial training is superior to traditional resistance training for decreasing the likelihood of (non-contact) muscular injuries	☐	☐	☐	☐	☐
Isoinertial training is well supported for sport performance enhancement	☐	☐	☐	☐	☐



5. What exercises have you implemented using isoinertial methodologies?

☐ Squat (*i.e.* Split Squat, Rotational Squats)

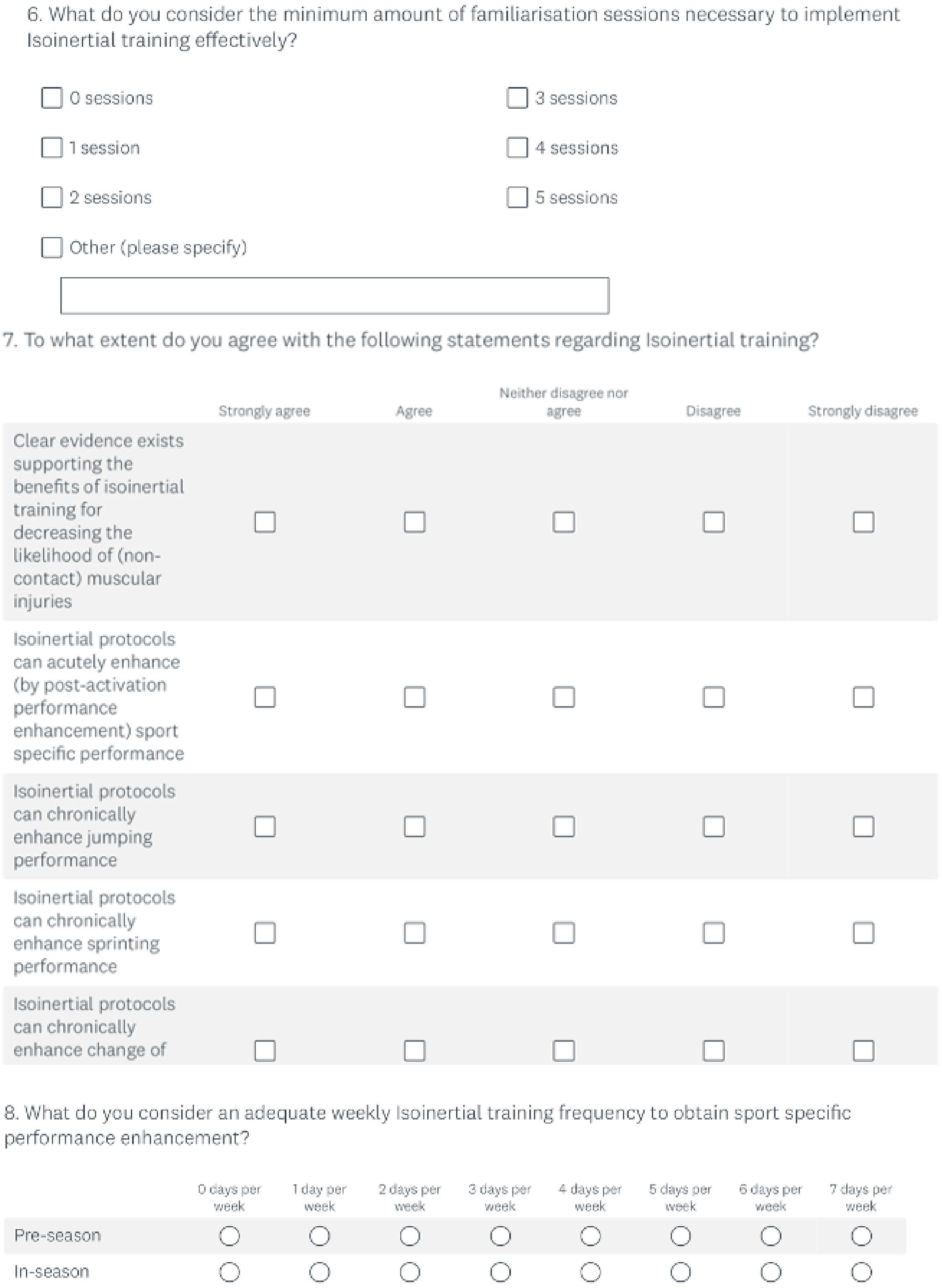
☐ Lift/Hinge (*i.e.* Deadlift, Romanian Deadlift)

☐ Lunge (*i.e.* Lateral Lunge, Multi-Directional Lunges)

☐ Other (please specify)

☐ Open Kinetic Chain (*i.e.* Leg Extension, Leg Curl)

☐ None



6. What do you consider the minimum amount of familiarisation sessions necessary to implement Isoinertial training effectively?

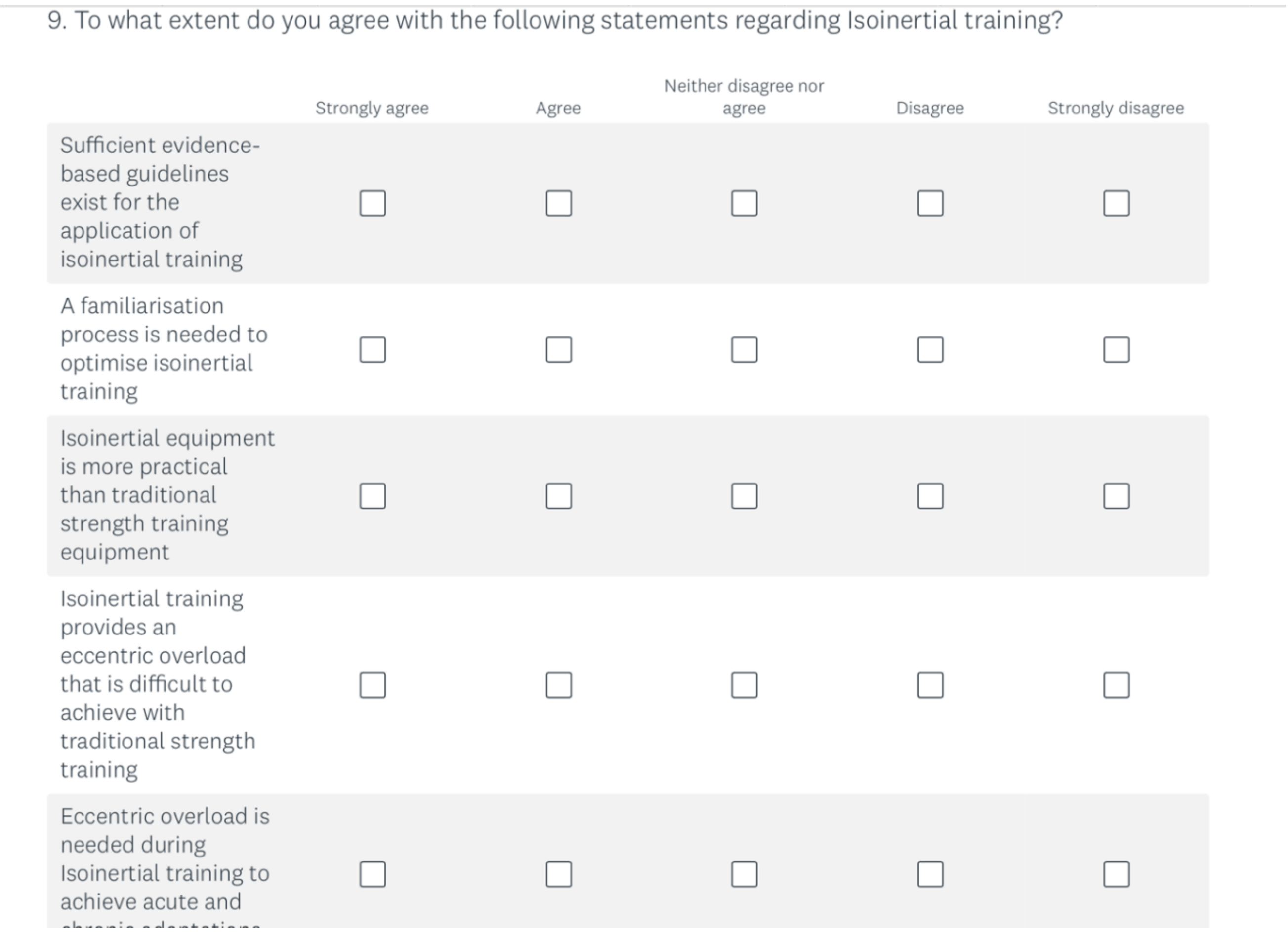
☐ 0 sessions
☐ 1 session
☐ 2 sessions
☐ 3 sessions
☐ 4 sessions
☐ 5 sessions
☐ Other (please specify)

7. To what extent do you agree with the following statements regarding Isoinertial training?

	Strongly agree	Agree	Neither disagree nor agree	Disagree	Strongly disagree
Clear evidence exists supporting the benefits of isoinertial training for decreasing the likelihood of (non-contact) muscular injuries	☐	☐	☐	☐	☐
Isoinertial protocols can acutely enhance (by post-activation performance enhancement) sport specific performance	☐	☐	☐	☐	☐
Isoinertial protocols can chronically enhance jumping performance	☐	☐	☐	☐	☐
Isoinertial protocols can chronically enhance sprinting performance	☐	☐	☐	☐	☐
Isoinertial protocols can chronically enhance change of	☐	☐	☐	☐	☐

8. What do you consider an adequate weekly Isoinertial training frequency to obtain sport specific performance enhancement?

	0 days per week	1 day per week	2 days per week	3 days per week	4 days per week	5 days per week	6 days per week	7 days per week
Pre-season	○	○	○	○	○	○	○	○
In-season	○	○	○	○	○	○	○	○



9. To what extent do you agree with the following statements regarding Isoinertial training?

	Strongly agree	Agree	Neither disagree nor agree	Disagree	Strongly disagree
Sufficient evidence-based guidelines exist for the application of isoinertial training	☐	☐	☐	☐	☐
A familiarisation process is needed to optimise isoinertial training	☐	☐	☐	☐	☐
Isoinertial equipment is more practical than traditional strength training equipment	☐	☐	☐	☐	☐
Isoinertial training provides an eccentric overload that is difficult to achieve with traditional strength training	☐	☐	☐	☐	☐
Eccentric overload is needed during Isoinertial training to achieve acute and	☐	☐	☐	☐	☐

Appendix B – Survey used for Chapter 2B.

Preamble: Flywheel questionnaire for therapists working in sport.

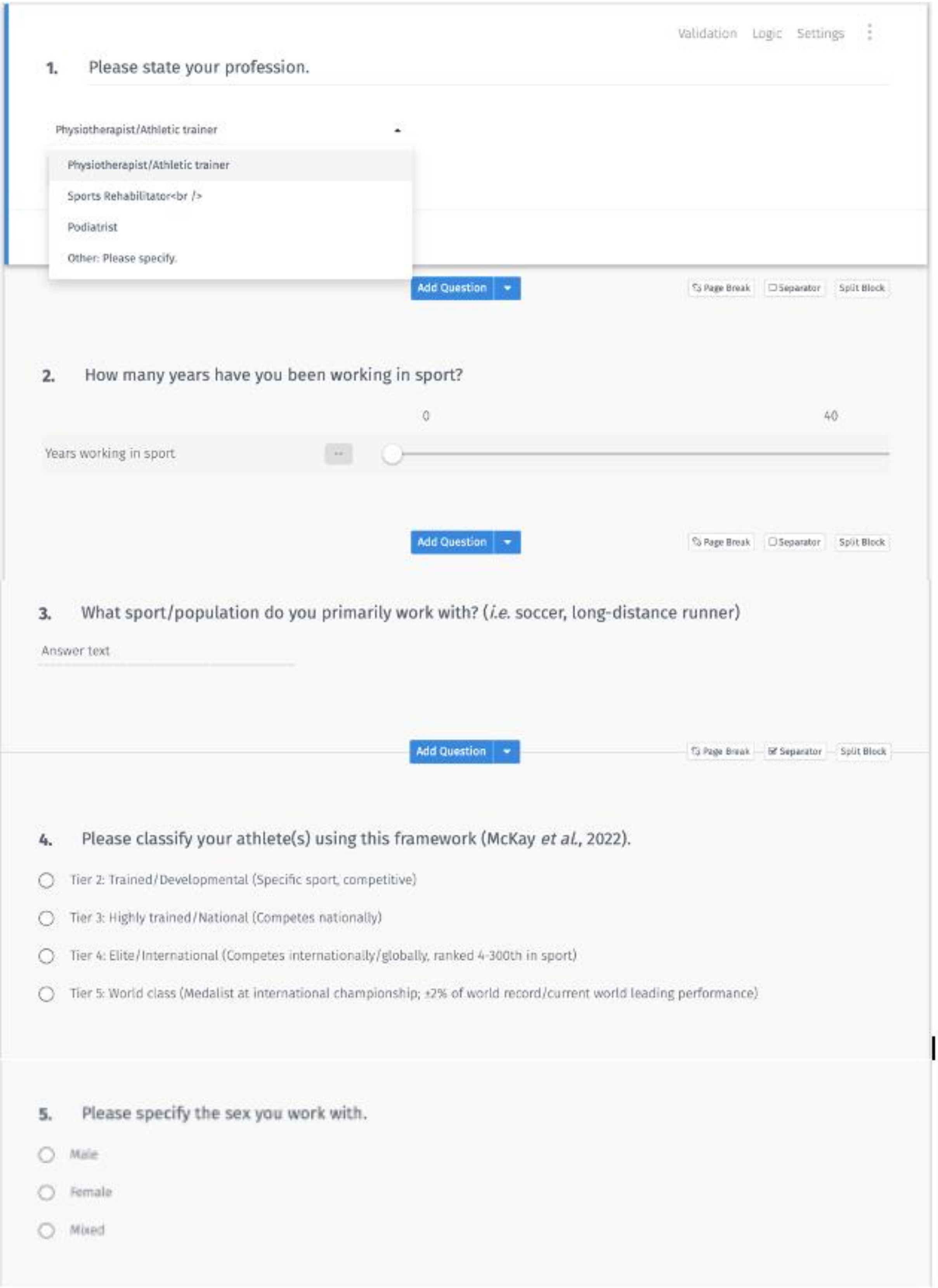
Flywheel training, a method aimed at reducing injury risk, enhancing athletic performance, and facilitating rehabilitation, has gained significant attention in recent years. Despite the surge in research on flywheel training and its application in sports, there remains a gap in our understanding of how therapists perceive and implement flywheel training. This study seeks to address this gap by exploring the current practices, perceived benefits, and limitations of flywheel training among sports therapists.

Project Summary: Flywheel training provides resistance that is near maximal and based on the moment of inertia, intent, technique, and machine utilised. However, while the scientific literature has expanded rapidly, practical insights from therapists— those at the 'coal face' of athlete support and rehabilitation —remain scarce. By investigating perspectives and application, this knowledge gap and future research directions can be addressed.

Informed Consent: The questionnaire that follows is completely anonymised and voluntary. Institutional review board approval (University of Suffolk, UK) was granted before the commencement of this study in accordance with the Declaration of Helsinki.

Project Purpose: The present research serves several purposes. Firstly, it will identify potential areas for further investigation, guiding future studies on flywheel training. Secondly, it will highlight practical considerations that therapists encounter in real-world settings, distinct from controlled laboratory environments. Importantly, this will shed light on common challenges and difficulties faced by practitioners.

Eligibility Criteria: To participate, you must be over 18 years old and have experience working in sports therapy or rehabilitation within sport (e.g., as a physiotherapist, sports therapist, or strength and conditioning coach). Institutional review board approval was granted before the commencement of this study in accordance with the Declaration of Helsinki.



1. Please state your profession.

Physiotherapist/Athletic trainer

- Physiotherapist/Athletic trainer
- Sports Rehabilitator
- Podiatrist
- Other: Please specify.

2. How many years have you been working in sport?

0 40

Years working in sport

3. What sport/population do you primarily work with? (*i.e.* soccer, long-distance runner)

Answer text

4. Please classify your athlete(s) using this framework (McKay *et al.*, 2022).

○ Tier 2: Trained/Developmental (Specific sport, competitive)

○ Tier 3: Highly trained/National (Competes nationally)

○ Tier 4: Elite/International (Competes internationally/globally, ranked 4-300th in sport)

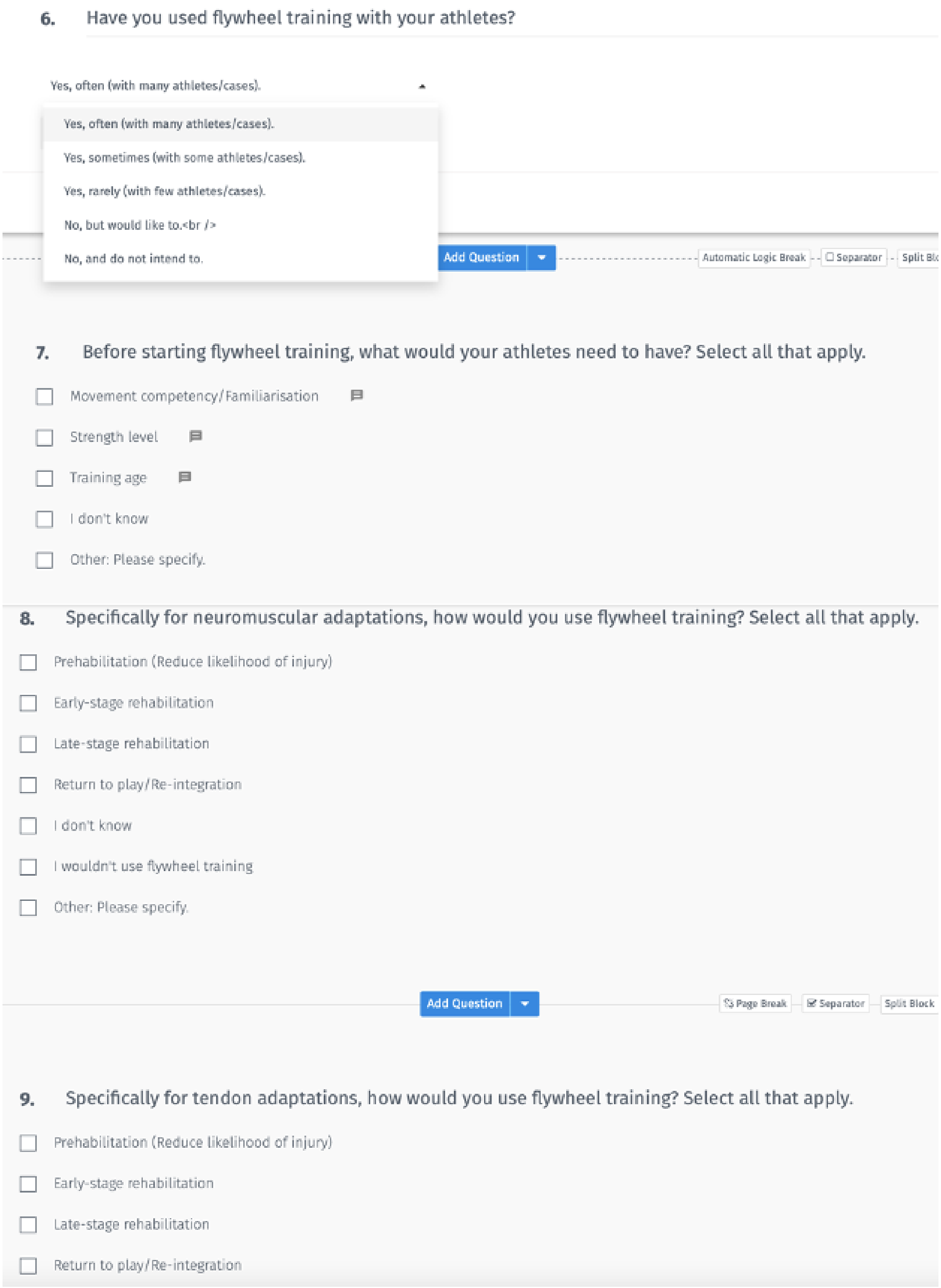
○ Tier 5: World class (Medalist at international championship; ±2% of world record/current world leading performance)

5. Please specify the sex you work with.

○ Male

○ Female

○ Mixed



6. Have you used flywheel training with your athletes?

Yes, often (with many athletes/cases).

- Yes, often (with many athletes/cases).
- Yes, sometimes (with some athletes/cases).
- Yes, rarely (with few athletes/cases).
- No, but would like to.
- No, and do not intend to.

7. Before starting flywheel training, what would your athletes need to have? Select all that apply.

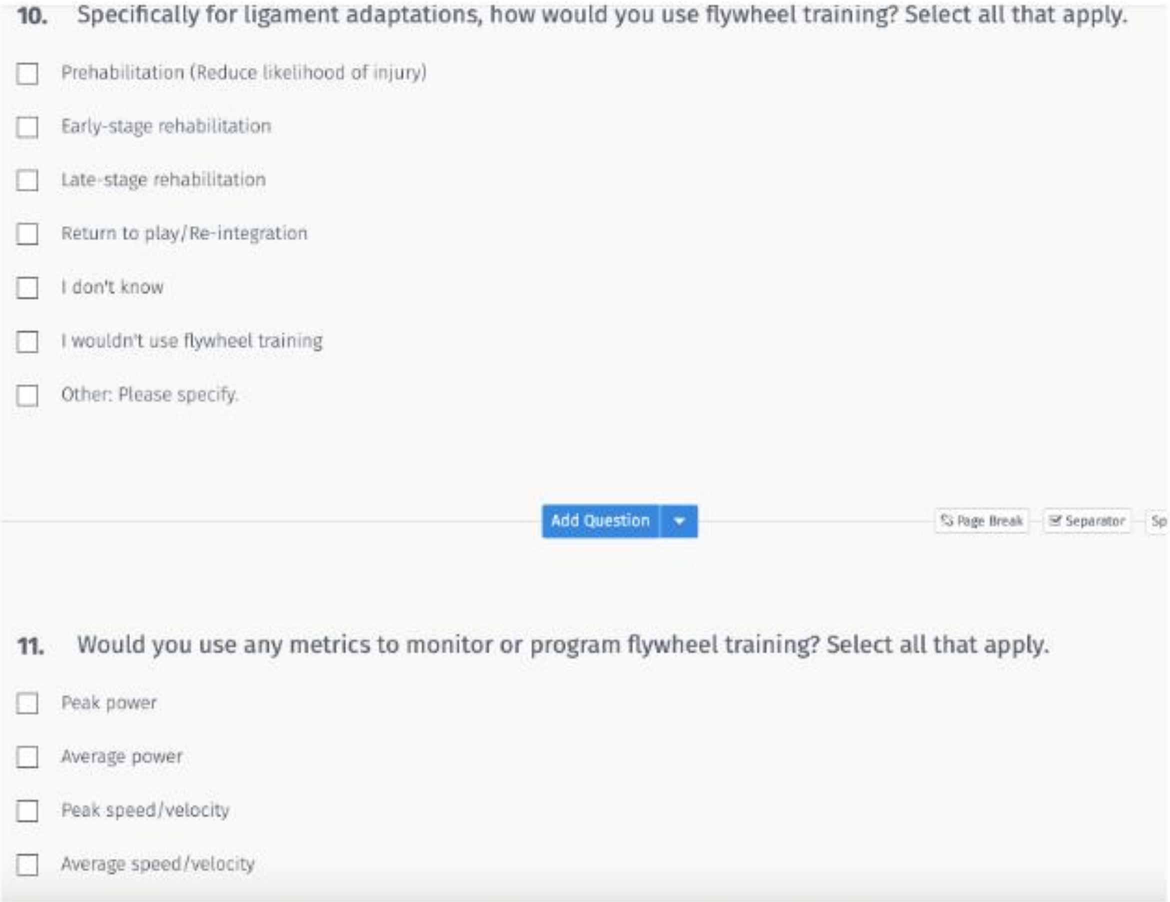
☐ Movement competency/Familiarisation
☐ Strength level
☐ Training age
☐ I don't know
☐ Other: Please specify.

8. Specifically for neuromuscular adaptations, how would you use flywheel training? Select all that apply.

☐ Prehabilitation (Reduce likelihood of injury)
☐ Early-stage rehabilitation
☐ Late-stage rehabilitation
☐ Return to play/Re-integration
☐ I don't know
☐ I wouldn't use flywheel training
☐ Other: Please specify.

9. Specifically for tendon adaptations, how would you use flywheel training? Select all that apply.

☐ Prehabilitation (Reduce likelihood of injury)
☐ Early-stage rehabilitation
☐ Late-stage rehabilitation
☐ Return to play/Re-integration

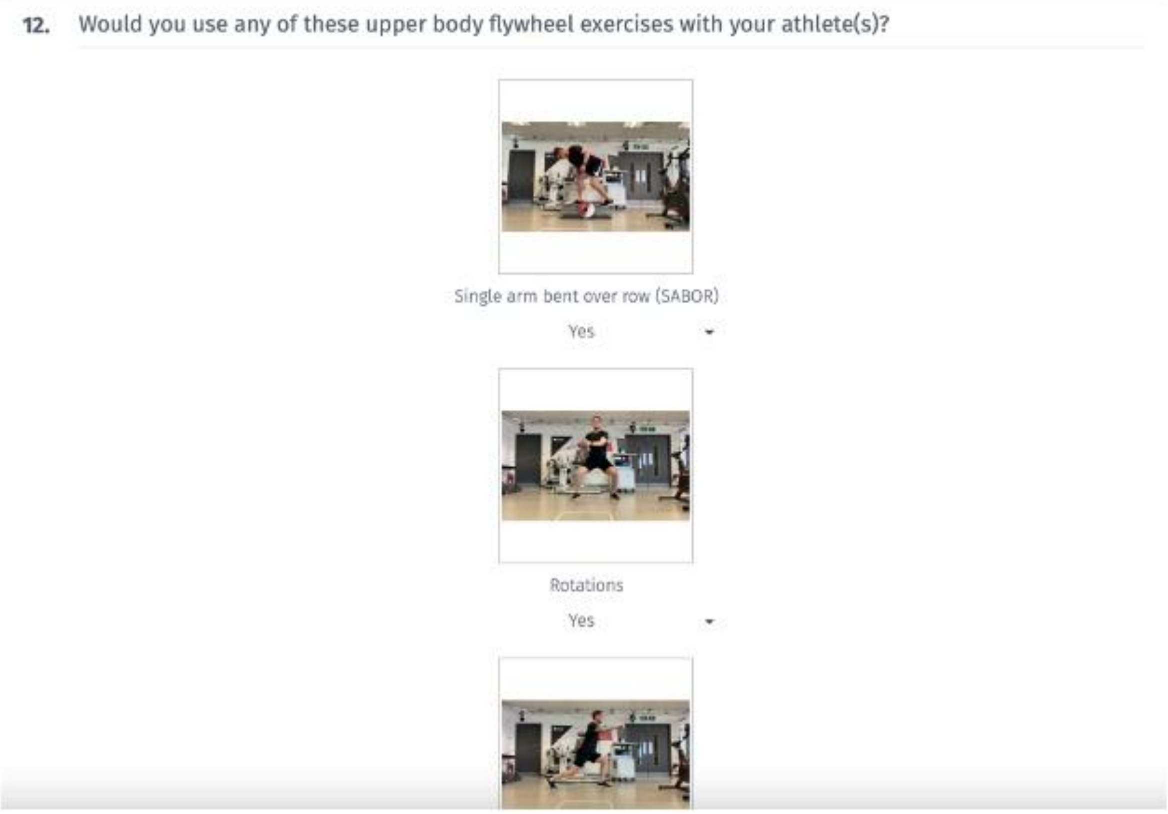


10. Specifically for ligament adaptations, how would you use flywheel training? Select all that apply.

- ☐ Prehabilitation (Reduce likelihood of injury)
- ☐ Early-stage rehabilitation
- ☐ Late-stage rehabilitation
- ☐ Return to play/Re-integration
- ☐ I don't know
- ☐ I wouldn't use flywheel training
- ☐ Other: Please specify.

11. Would you use any metrics to monitor or program flywheel training? Select all that apply.

- ☐ Peak power
- ☐ Average power
- ☐ Peak speed/velocity
- ☐ Average speed/velocity



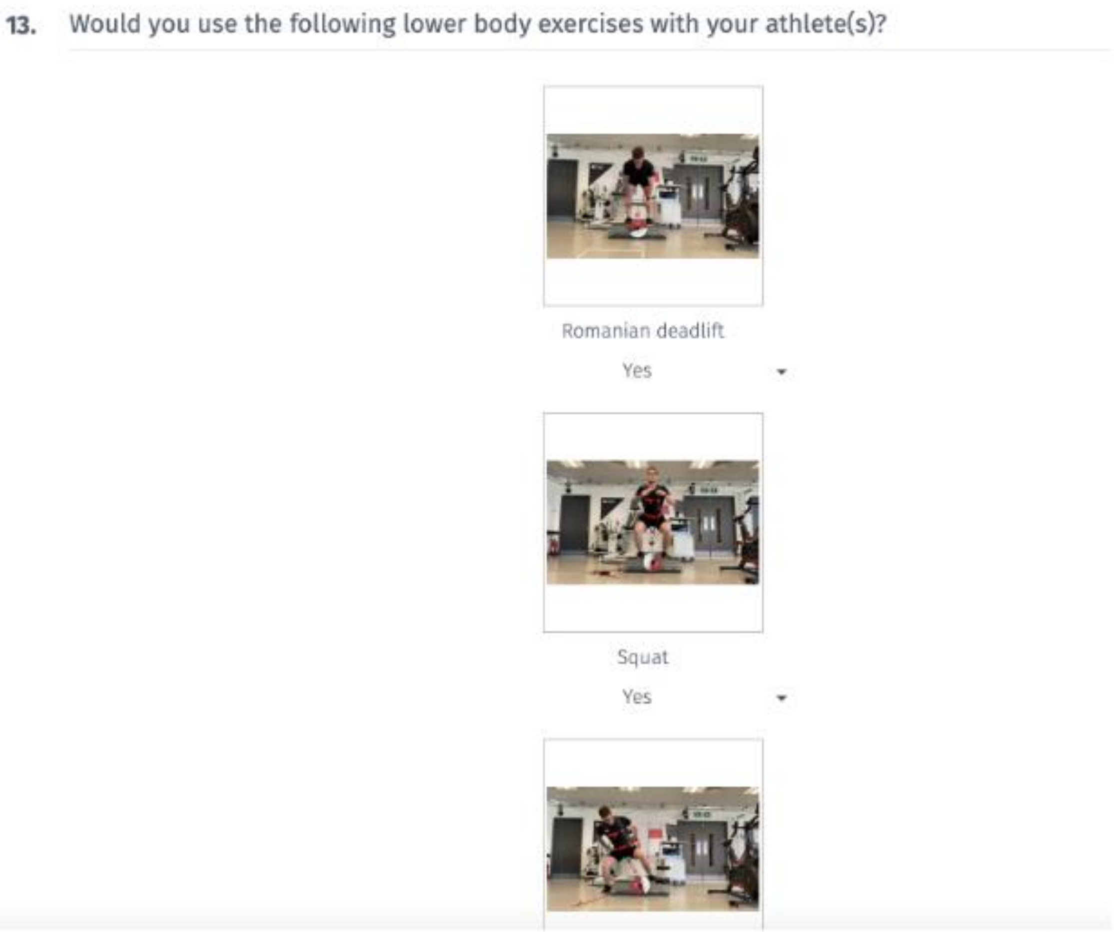
12. Would you use any of these upper body flywheel exercises with your athlete(s)?

Single arm bent over row (SABOR)

Yes

Rotations

Yes



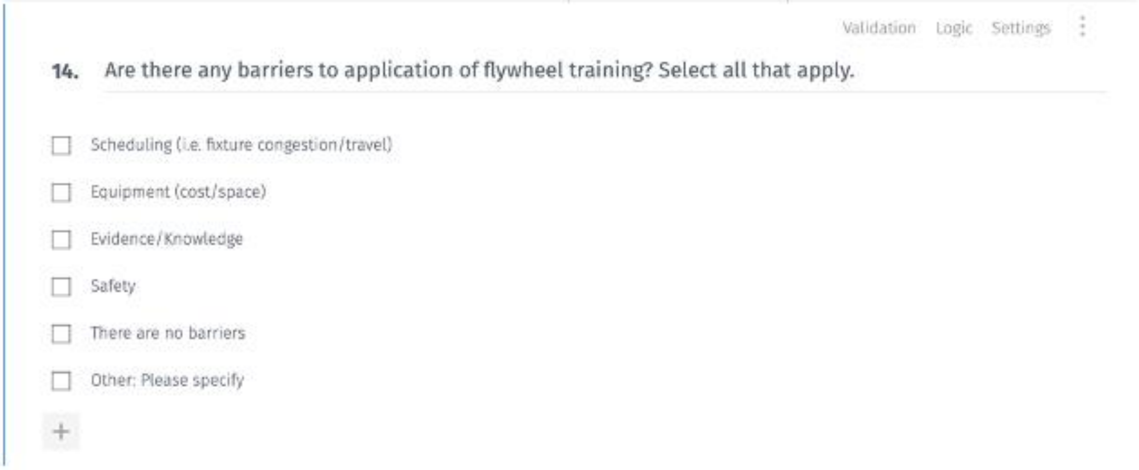
13. Would you use the following lower body exercises with your athlete(s)?

Romanian deadlift

Yes ▾

Squat

Yes ▾



14. Are there any barriers to application of flywheel training? Select all that apply.

- ☐ Scheduling (i.e. fixture congestion/travel)
- ☐ Equipment (cost/space)
- ☐ Evidence/Knowledge
- ☐ Safety
- ☐ There are no barriers
- ☐ Other: Please specify

15. Please **read carefully** and select how strongly you agree/disagree with the following statements.

	Left Anchor					Right Anchor
	I don't know	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Flywheel training does not enhance strength.	○	○	○	○	○	○
Flywheel training can reduce likelihood of non-contact muscular injury.	○	○	○	○	○	○