MICRO-DOSING OF RESISTANCE TRAINING IN SOCCER PLAYERS

Matthew Cuthbert

School of Health and Society, University of Salford, Salford, UK

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Table of Contents:

List of Figures:

List of tables:

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Abstract

Micro-dosing of resistance training is “the division of total volume within a micro-cycle, across frequent, short duration, repeated bouts” as defined within this thesis, and is a concept built on a foundation of well-established training approaches, methods, and theories. Despite drawing influence from many other aspects of resistance training, micro-dosing is still a relatively new term and has only recently begun to be explicitly investigated as a programming strategy. There may be considerable acute benefits of utilising micro-dosing, however, considering the lack of previously published data on the topic, our aim was to lay the foundations and determine whether performing micro-dosing had a similar chronic effect to training adaptations as a traditional approach. This thesis, therefore, includes an investigation comparing the effects of micro-dosing the Nordic hamstring exercises (NHE) as a ‘proof of concept’, prior to a comparison of micro-dosing and traditional approaches to lower body strength training. Following both a systematic review and meta-analysis of the appropriate NHE prescription, and reliability of field-based hamstring strength measurements, a comparison of micro-dosing and traditional prescriptions of the NHE was investigated across a single micro-cycle and a 9-week intervention. The findings of both of these studies indicate that there were no meaningful differences between the micro-dosing and traditional groups. A further systematic review and meta-analyses was carried to determine the effect of resistance training frequency, in well-trained athletes, and potential implications for in-season resistance training, with training frequency appearing to have a trivial effect on lower-body strength increases. Finally, a randomised cross-over feasibility study was conducted, with accompanying between-session reliability of performance measures, in which both micro-dosing and traditional groups followed a 5-week, in-season, strength training intervention. Greater improvements were observed in the micro-dosing group for force production characteristics (g = 0.62-0.64), sprint (g = 0.31-0.58), and change of direction (g = 0.57-1.25) performance. In contrast, there were no meaningful differences in countermovement jump performance between groups. It would therefore appear that micro-dosing can achieve similar, if not superior, training adaptations in comparison to a traditional approach to in-season resistance training. One reason for the micro-dosing group potentially providing superior training adaptations could be due to greater compliance/adherence to training, as the micro-dosing group demonstrated small to moderately greater compliance (g = 0.47- 0.72).

1 Chapter 1: Introduction

Soccer is a sport characterised by intermittent bouts of high-intensity linear and multidirectional activities that are interspersed with variable periods of recovery [1]. Contribution from anaerobic energy systems are responsible for the bouts of high intensity actions, whereas the aerobic energy system is required for recovery between those bouts [2]. Based on reported $\dot{V}O_2$ max values in elite soccer players (55–67 mL/kg.min [2]), aerobic fitness is unlikely to be the limiting factor for performance. As with most team sports, performance depends upon a myriad of factors such as technical, tactical, physical, and psychological [3, 4]. Throughout the competitive soccer season and even during the pre-season period, the technical and tactical outcomes set out by technical coaches are prioritised and often take precedent over all other training activities [5]. A number of methods have been used to investigate the physical demands of soccer match-play including time-motion analysis, computerised tracking systems, or most commonly in practice, global positioning system (GPS) device. GPS is also commonly used to quantify pitch-based training load [6, 7]. Di Salvo et al. [7] have reported that the technical and tactical effectiveness of teams is most important in determining success, which is supported by Bradley et al. [8] who found when comparing three competitive standards in English football that greater physical outputs were observed at lower standards, potentially due to the requirement to compensate for the greater discrepancy in technical ability. The indication is that numerous factors will dictate the physical outputs of match-play, including technical ability, tactical demands, and opposition. Regardless of what dictates the physical output, players are still required to have the underpinning physical capacities to not only ‘cope’ with the demands placed on them during match-play but also to have the ability to compete at the highest-level, fixture after fixture.

Bangsbø [3] has highlighted the importance of aerobic capacity within a soccer game, as across 90 minutes the average intensity oscillates around anaerobic lactate threshold. As well as influencing recovery between bouts during match-play, higher aerobic fitness has also been demonstrated to improve the ability to recover between competition, or more appropriately has an influence on the response to fatigue [9]. In addition to aerobic capacity, strength and power have also been reported as equally important, particularly when considering the most decisive actions of a game occur when performing sprints, jumps, changes in direction and tackles/duels and are crucial to the game’s outcome [2, 4]. These actions are anaerobic in nature, but are underpinned by the players neuromuscular ability to produce force maximally and express that force rapidly through acceleration and deceleration [4]. Akenhead et al. [10] have reported that 18% of total duration completed during competitive fixtures accounts for accelerations and decelerations > -/+ 1 m.s and have a large metabolic and mechanical demand [11, 12] which requires both concentric and eccentric conditioning. Transient reductions in accelerations and decelerations following peak periods of play also demonstrates a players capacity to sustain those activities are temporarily compromised due to the high intensity demand of those actions [10]. These reductions have the potential to not only affect performance but increase the risk of injury [13].

In order to negate some of the negative effects associated with high intensity actions, Byrne et al. [14] suggests that greater strength and enhancement of neuromuscular function may reduce the magnitude of muscle damage following match-play, which may limit the fatigue response. This reduction in fatigue has been demonstrated in soccer players, whereby a moderate and significant relationship between high force production capabilities and reduced post-match markers of fatigue (assessed through measurement of serum creatine kinase) [15]. Whilst the evidence for serum creatine kinase as a marker of fatigue is equivocal, and there being no ‘one size fits all’ assessment for fatigue due to the number of complex mechanisms potentially causing reductions in performance, there is an indication that fitter, faster and stronger athletes are not only better equipped to perform repeatedly but are also able to tolerate greater changes in workload whilst being at lower risk of inducing a non-contact injury [16]. Soccer players appear to have a high prevalence of non-contact injuries such as hamstring strain injuries [17-19] and more serious injuries such as anterior crucial ligament injuries [20]. Strength training has been demonstrated as an effect strategy in reducing the incidence rates of these two injuries as well as a range of other acute and overuse injuries [21].

Since the early 2000’s there has been an observed increase in intensity of match-play as Barnes et al. [1] highlight, total distance covered has remained relatively constant but high-intensity running distance (5.5-6.9 m.s) and sprinting distance (≥ 7 m.s) increasing by ~30%. The suggestion is that due to the increase in intense actions, greater rest periods are present in order for total distance not to have increased, with longer periods where the ball is ‘out of play’. Although the absolute intensity of actions has increased, if players have become fitter and faster, the relative intensity may not have altered. Regardless of whether intensity has increased over time, the length of competition season, and density of fixtures have increased [6]. An example of this increase can be observed in one of the English domestic leagues which now lasts ~40 weeks, with an average of ~1.6 games per week, and ~16 two-game weeks in which the recovery period between fixtures is ~72 hours (with some instances of ~48 hours) [22, 23]. Similar congested periods are also observed during major international tournaments, as the requirement to win the FIFA World Cup is to perform in seven games across ~28 days [24]. Springham et al. [22] have observed small to large decreases in all physical performance indices during matches throughout the aforementioned English domestic league season, particularly in number of sprints, across all positions. It was reported that no changes occurred in team tactics or tactical and physical preparation methods across the sample period with their analyses controlling for situational and contextual variables. Springham et al. [22] concluded that neuromuscular fatigue was the likely cause of the reductions in performance across a season (based on total distance, high speed running, and sprint distance in match-play). It could, however, be argued that a detraining effect may have occurred in the athlete’s force production capabilities as during the competitive season, it is common practice for players to be given 1-2 days off for recovery (involving complete inactivity or light ‘recovery’ type activities) [25]. During periods of fixture congestion, ‘recovery’ can therefore take up a large portion of preparation prior to the next fixture and as Morgans et al. [5] highlighted with technical/tactical sessions taking precedent over other sessions, physical development/maintenance practices can often be neglected.

With a large focus on facilitating recovery during the competitive season, particularly during periods of congested fixtures (which is some cases runs throughout large portions of the competitive season), training stimuli that will provide sufficient stress to allow for the development of aerobic, strength or power capabilities becomes restricted. Evidence of the ability to maintain aerobic performance throughout the course of a season has been outlined previously [26, 27] as a result of match-play and potentially as part of on-pitch technical/tactical sessions. Although high intensity actions such as sprinting, jumping and change of direction are common occurrences in match-play [4], evidence of the reductions in physical outputs across a competitive season suggests that the volume of stimuli produced during matches alone is not enough to maintain or develop strength or power across a season. Rønnestad et al. [28] has provided further evidence of this, whereby a resistance training session based on strength maintenance performed once every two weeks was also not enough to maintain strength/power. As a consequence, continued resistance training aimed at either maintaining or developing force production capabilities across a competitive season is important to prevent declines in performance and increases in injury risk.

Whilst the issue of fixture congestion/dense fixture schedules and performance development/maintenance is not limited to soccer, the aim of this thesis is to outline and investigate possible programming solutions e.g., micro-dosing for soccer players in order for appropriate resistance training prescription to be applied during the competitive soccer season. Below is an outline of the completed process and study titles and aims.

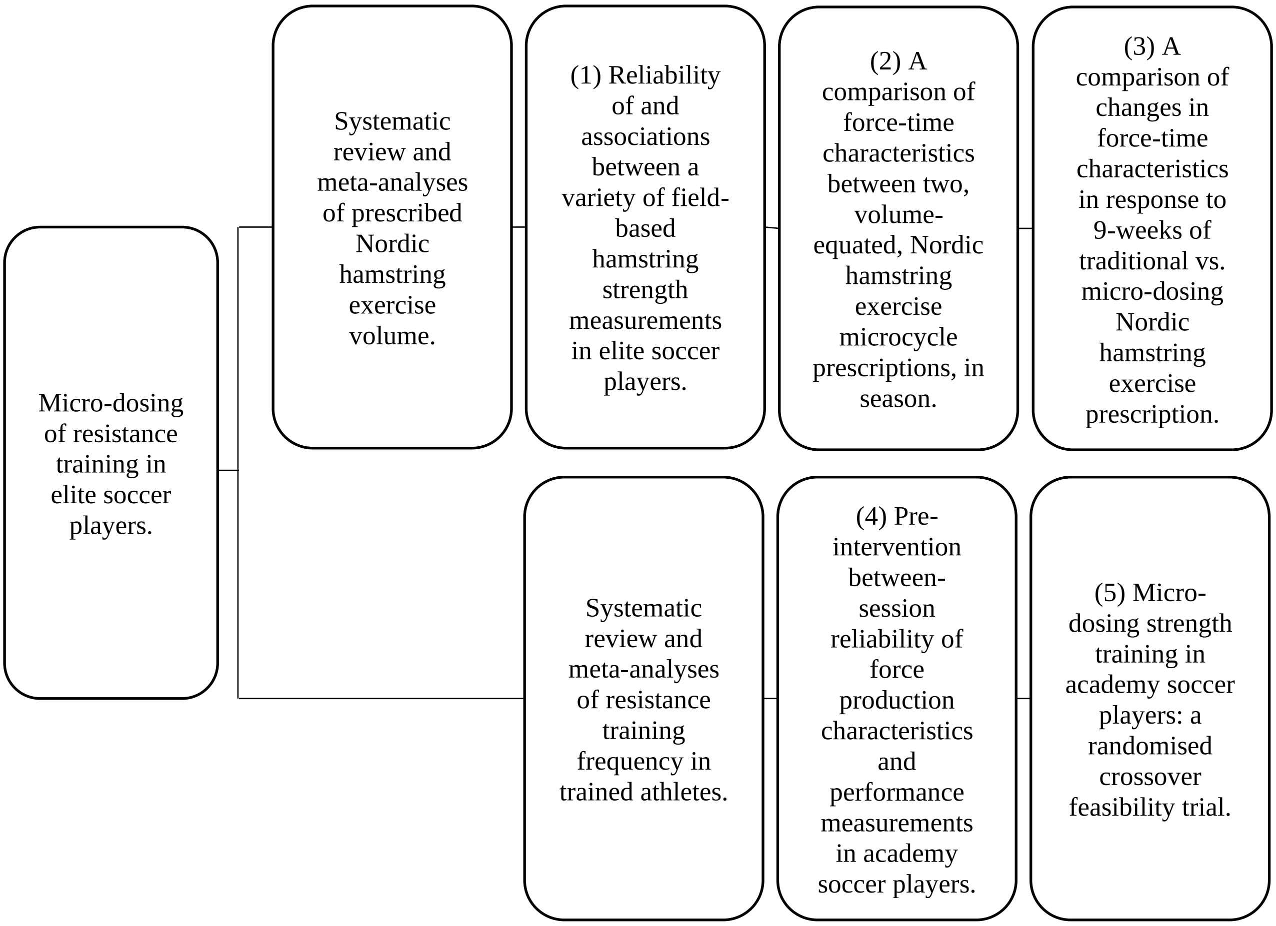


Figure 1.1. A flow diagram depicting the study process included in this thesis.

(1) Reliability of and associations between a variety of field-based hamstring strength measurements in professional female soccer players.

Aims: To quantify within- and between-session reliability of field-based hamstring strength tests and assess the relationship between those tests.

(2) A comparison of force-time characteristics between two, volume-equated, Nordic hamstring exercise microcycle prescriptions, in season.

> Aims: To quantify any differences in performance of a supramaximal eccentric hamstring exercise between two frequency groups across a single microcycle and between consecutive days.

(3) A comparison of changes in force-time characteristics in response to 9-weeks of traditional vs. micro-dosing Nordic hamstring exercise prescription.

> Aims: To quantify differences in hamstring strength between two frequency groups following a strength intervention.

(4) Pre-intervention between-session reliability of force production characteristics and performance measurements in academy soccer players.

> Aims: To quantify the reliability of a battery of strength and performance assessments in a specific cohort.

(5) Micro-dosing strength training in academy soccer players: a randomised crossover feasibility trial.

> Aims: To quantify differences in performance between traditional and micro-dosing interventions.

2 Chapter 2: The effect of Nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses.

2.1 Abstract

Background: Although performance of the Nordic hamstring exercise (NHE) has been shown to elicit adaptations that may reduce hamstring strain injury (HSI) risk and occurrence, compliance in NHE interventions in professional soccer teams is low despite a high occurrence of HSI in soccer. A possible reason for low compliance is the high dosages prescribed within the recommended interventions. The aim of this review was to investigate the effect of NHE training volume on eccentric hamstring strength and biceps femoris fascicle length adaptations. **_Methods:_** A literature search was conducted using the SPORTDiscus, Ovid and PubMed databases. A total of 293 studies were identified prior to application of the following inclusion criteria: (1) a minimum of four weeks of NHE training was completed, (2) mean ± standard deviation (SD) pre- and post-intervention were provided for the measured variables to allow for secondary analysis, and (3) biceps femoris muscle architecture was measured, which resulted in 13 studies identified for further analysis. The TESTEX criteria was used to assess the quality of studies with risk of bias assessment assessed using a fail-safe *N* (Rosenthal method). Consistency of studies was analysed using I^2 as a test of heterogeneity and secondary analysis of studies included Hedges' *g* effect sizes for strength and muscle architecture variables to provide comparison within studies, between-study differences were estimated using a random-effects model. **_Results:_** A range of scores (3 – 11 out of 15) from the TESTEX criteria were reported, showing variation in study quality. A 'low risk of bias' was observed in the randomised control trials included, with no study bias shown for both strength and architecture ($N = 250$ and 663. $p < 0.001$). Study consistency was moderate to high for strength ($I^2 = 62.49\%$) and muscle architecture ($I^2 = 88.03\%$). Within study differences showed that following interventions of ≥ 6 weeks, very large positive effect sizes were seen in eccentric strength following both high volume ($g = 2.12$) and low volume ($g = 2.28$) NHE interventions. Similar results were reported for changes in fascicle length ($g \geq 2.58$) and a large to very large positive reduction in pennation angle ($g \geq 1.31$). Between study differences were estimated to be at a magnitude of 0.374 ($p = 0.009$) for strength and 0.793 ($p < 0.001$) for architecture. **_Conclusions:_** Reducing NHE volume prescription does not negatively affect adaptations in eccentric strength and muscle architecture when compared with high dose interventions. These findings suggest that lower volumes of NHE may be more appropriate for athletes, with an aim to increase intervention compliance, potentially reducing the risk of HSI.

2.2 Background

The investigation of 'hamstring strain injury' (HSI) within the scientific literature has been substantial over the last two decades, due to evidence highlighting high HSI occurrence, especially in field-based team sports [17, 19, 29-31]. HSIs accounted for 12% of all injuries reported by 17 top flight European soccer teams [17], 13% of American Football injuries over a 10-year period [29], and 16% of rugby union injuries [31]. Two Australian Football clubs have also reported 30% of players during one season reported some level of posterior thigh pain [30, 32]. The financial cost of a HSI has been reported to be approximately €250,000 in top level European soccer clubs for a player that spends two weeks out of competition. The cost does not just come from the rehabilitation and salaries of these injured players, but also with lack of availability potentially costing teams with key players not eligible for selection due to injury. Ekstrand et al. [17] indicated that a squad of 25 players would incur approximately seven HSIs in a season. Consequently, further costs could occur with reduced depth of squad becoming an issue or increased injury risk due to players with a low chronic workload suddenly being called upon to play considerable match minutes. As Gabbett [33] outlines, injury risk increases 2-4 times when acute training load is ≥ 1.5 times the chronic workload. Relatively stronger athletes show a reduced risk of injury overall but possess the ability to tolerate larger changes in load week to week [16]. This increased risk of injury, however, can affect teams around times of fixture congestion with Woods et al. [34] demonstrating that the highest rate of in-season HSI occurs between November and January, traditionally a busy period in English soccer. Teams are also affected towards the end of the season, when training status may have reduced as the importance of results increases. Petersen et al. [35] reports injury occurrence to be highest at this period of the season (April to May) in the Danish leagues where in contrast to English soccer, a winter break is taken. A break in the competitive season therefore appears to delay high occurrences of HSI rather than aid in their prevention. The benefits of reducing the fixtures midway through a season are clear; as it reduces the exposure to repeated high intensities during a period of fixture congestion, seen in English soccer leagues over this time, whilst also providing a period in which strength losses that may have occurred due to a greater focus on competition can be reduced.

High speed running (HSR) activities are reported to be a common cause of HSIs, it has been revealed that a rate of 60% of HSIs reported in professional English soccer across two seasons were caused by HSR [34]. This trend is also observed in English and Australian rugby union where 68% and 80% of HSI occurrence, respectively, were also caused by HSR [36, 37]. This pattern has also been observed in a single Australian football team across four seasons, when a total of twenty-six players sustained a HSI due to HSR [32] which is over half of the average forty-four player squad. These values may differ dependent upon the threshold at which HSR is determined as anthropometric differences based upon position, particularly in rugby union, may determine a lower or higher maximum speed which means some HSR running may not have been registered due to relative differences. The mechanism behind HSI occurrence during HSR tasks is a failure of the tissues to tolerate the forces applied or required during the task. The primary cause of this intolerance is yet to be determined, with some researchers suggesting a “weak link” approach whereby an active lengthening (eccentric muscle action) of the sarcomeres creates a chronic accumulative cytoskeletal damage effect until the HSI occurs. Other researchers, however, have suggested a more ‘catastrophic’ type event in which the strain occurs due to excessive force applied to the hamstring. There is also a disagreement in the literature as to whether the muscle action involved in the hamstrings during HSR is the active lengthening (or eccentric action) [38-44], as described above, or whether it is a quasi-isometric action [39, 43, 45]. Despite this lack of clarity, a number of non-modifiable and modifiable risk factors for HSI have been outlined [46-48] including, age, ethnicity, previous HSI, fatigue, flexibility, muscle architecture and strength.

Hamstring strength has been shown to play a major role in increasing or decreasing the risk of HSI [37, 47, 49]. One method of both training and assessing hamstring strength is through the Nordic hamstring exercise (NHE). The NHE is understood to be an eccentric exercise that is performed on the knees with ankles held/strapped with subjects lowering their upper body towards on a prone position, as slowly as possible. Opar et al. [47] reported that Australian football players who produce relative eccentric strength of < 3.45 $N.kg^{-1}$ or absolute eccentric strength are < 279 N during the NHE of 4.3-5% more likely to experience a HSI, although this risk decreases by 6.3% however for every 10 N increase in force during early pre-season, and 8.9% by late pre-season. A similar trend was also seen in soccer, with a relative eccentric strength of < 4.35 $N{\cdot}kg^{-1}$ and absolute eccentric strength of < 337 N increasing injury risk by up to 4.4%. Differences between an injured group and uninjured group were also shown in eccentric hamstring force, relative to body mass, at the beginning (21% higher in non-injured) and end of their preseason (17% higher in non-injured).

The force production capabilities of the muscle and the velocity at which this occurs are both influenced by muscle architecture [50]. When described in the literature, muscle architecture involves fascicle length (FL), pennation angle (PA), and either muscle thickness (MT), physiological cross-sectional area (PCSA) or anatomical cross-sectional area (ACSA). The size of the muscle (MT, PCSA or ASCA) can be influenced by both FL and PA and vice versa depending upon the mode of training. Muscle size typically increases following hypertrophy-based resistance training, increasing PA and reducing FL. A decrease in fascicle length, alongside a lack of strength, can increase the risk of injury, as previously mentioned [49]. A review by Opar et al. [48] highlights pertinent architectural aspects of the biceps femoris (BF), explaining that longer fascicles reduce the risk of an injury occurring through overlengthening during eccentric actions [51]. The hamstring muscle that lengthens the most during sprinting [52], however, is the BF long head (BF^{LH}), which also has shorter fascicles than that of the BF short head (BF^{SH}), potentially increasing the susceptibility of the BF^{LH} to injury. It appears that increasing FL has the potential to decrease HSI risk, and in conjunction with eccentric hamstring strength may reduce this risk further.

Eccentric training elicits greater adaptive responses when compared to concentric training regarding both muscle strength and architecture. The differences in adaptations between contraction types are a result of the different mechanisms used to generate force, with eccentric actions occurring due to active lengthening of the fascicles, and concentric actions due to active shortening. The slow eccentric nature of the NHE provides a stimulus whereby the myosin heads are already attached to actin and forced to detach by the lengthening of the cross-bridges, incurring muscle damage [53]. The NHE first appeared in academic literature when Brockett et al. [54] investigated the acute effect of the NHE on angle of peak torque of the hamstrings during eccentric isokinetic assessments. The NHE has since been shown to be an effective injury prevention strategy due to the increase in eccentric strength and subsequent reduction in HSI incidence [48, 55-58]. Many of the published training interventions which have incorporated a NHE protocol have replicated, or used a derivation of a 10-week protocol outlined by Mjølsnes et al. [57]. The protocol resulted in an increase in isometric (7%) and eccentric (11%) isokinetic peak torque and was more beneficial than a concentric comparison (hamstring curl) as there were no changes in hamstring strength within that group. The compliance rate of this study was 96%; however, a subsequent study using the same protocol showed around 60% [59] with other studies not reporting compliance rates. The NHE is maximal in nature and appears to result in a true eccentric mechanism, whereby the hamstring muscles are overloaded past their capacity for maximal eccentric or isometric force production. As a consequence of this maximal eccentric effort, a high level of muscle damage is incurred and subsequent delayed onset muscle soreness (DOMS) is likely to be reported as eccentric exercise has long been understood to induce muscle soreness [60]. This soreness may influence compliance rates as Bahr et al. [61] describes a significant minority of teams surveyed for compliance reporting a certain level of resistance from players as they perceive the exercise to be painful and/or causes of fatigue. The intervention outlined by Mjølsnes et al. [57] includes high volumes, with participants performing 700 NHE across 10 weeks, and the combination of high volume and high occurrence of DOMS could be one of the reasons why the same 10-week NHE intervention given to 50 UEFA Champions League clubs has presented a compliance rate as low as 16.7% [61]. Although a minimum dosage has yet to be identified it is important to compare how various volumes that have been used during interventions affect the hamstrings, with the aim of increasing compliance and ensuring the reduction of HSI. The FIFA 11+ has adopted the NHE in its injury prevention styled warm-up used in soccer, likely due to its practicality as a field-based exercise that requires no equipment; however, this was described as ineffective in some cases due to infrequency of use and lack of motivation from coaches.

The aim of this systematic review and meta-analyses was to identify NHE training interventions across all populations, comparing their effectiveness of increasing hamstring strength and altering biceps femoris long head muscle architecture in terms of the volume prescribed throughout the intervention.

2.3 Methods

2.3.1 Study design

The design of this systematic review was developed through adhering to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The PRISMA guideline statement includes a 27-item checklist, designed to be used as a basis for reporting systematic reviews of randomised trials [62]. A review protocol was not pre-registered for this review.

2.3.2 Literature search

A Boolean/phrase search mode was utilised using the following keywords: training intervention AND strength AND training AND volume AND eccentric AND hamstrings AND Nordics OR Nordic hamstring exercise OR Nordic curls OR Nordic drops OR Nordic lowers OR Nordic hamstring lowers OR Russian curls. These keywords were applied in the databases PubMed, SPORTDiscus and Ovid and were filtered to include studies that (1) were presented in peer-reviewed academic journal articles and (2) that were written in the English language. No restrictions were placed upon the age or sex of the subjects, with only an end-date restriction placed upon publication date, due to the NHE being a relatively recent area of research, with the oldest research in this area not yet being surpassed due to any advancements in testing technology.

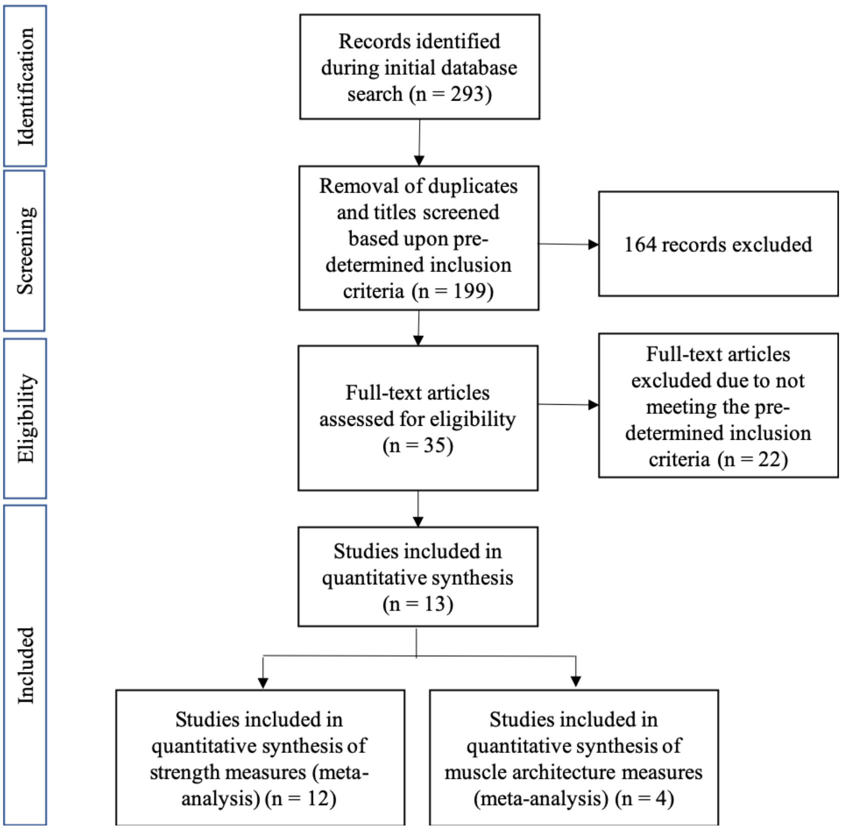


Figure 2.1. PRISMA flow chart.

2.3.3 Inclusion and exclusion criteria

The primary focus of the literature search was the identification of research studies that implemented an intervention involving the NHE; studies utilising other strength-based protocols in series with the NHE were also accepted. The search timeframe was restricted to 1 December 2018, whereby studies published following this date were not included. A total of 293 studies were identified initially for further inspection. Following the removal of duplicate studies, the remaining studies were screened utilising the subsequent criteria. Research was eligible and included within this review providing that (1) a minimum of four weeks of NHE training was completed, (2) mean ± standard deviation (SD) pre- and post-intervention were provided for the measured variables to allow for secondary analysis, and (3) muscle architecture was measured on the BF. Research was excluded due to data being collected through injury incidence questionnaires and not quantifying physiological or performance adaptations. Isokinetic data were also excluded at angular velocities > $120°.s^{-1}$ because reliability and the percentage range of motion at ‘constant velocity’ reduces as angular velocities increase [63, 64]. A summary of the selection process has been outlined in Figure 2.1.

2.3.4 Quality and risk of bias assessment

A subsequent assessment of study quality using the TESTEX scale [65] was then performed by the lead author. The TESTEX scale is an exercise specific scale that has been designed specifically for exercise specialists to assess the quality of reporting of exercise training studies. Two risk of bias assessments were performed through both a fail-safe *N* using the Rosenthal Method and for the randomised control trials included within this review a

Cochrane risk of bias assessment tool was used. A Cochrane risk of bias assessment assesses randomised control trials based on several categories that include sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective outcome reporting and ‘other issues’, these categories will be graded as ‘high risk of bias’, ‘low risk of bias’ and ‘unclear risk of bias’. A fail-safe number of effects was utilised to calculate the number of un-retrieved null effects that would be needed in order to diminish the significance of the observed effect at an alpha level of $p > 0.05$. These analyses were conducted using Jamovi [66].

Table 2.1. Study scores allocated based on TESTEX criteria [65]

	TESTEX criterion												
Study	1 (1 point)	2 (1 point)	3 (1 point)	4 (1 point)	5 (1 point)	6 (3 points)	7 (1 point)	8 (2 points)	9 (1 point)	10 (1 point)	11 (1 point)	12 (1 point)	Total
Alonso-Fernandez et al. [67]	1	0	0	0	0	0	0	0	1	0	1	1	4
Alt et al. [68]	1	0	0	0	0	0	0	2	1	0	1	1	6
Anastasi and Hamzeh [69]	1	0	0	1	0	0	0	2	1	0	1	1	7
Clark et al. [70]	1	0	0	0	0	0	0	0	1	0	1	1	4
Delahunt et al. [71]	1	1	0	1	0	0	0	0	0	0	1	1	5
Freeman et al. [72]	0	0	0	1	0	1	0	1	1	0	1	1	6
Iga et al. [73]	0	0	0	1	0	0	0	2	1	0	1	1	6
Ishøi et al. [59]	1	1	1	1	1	1	0	2	1	0	1	1	11
Mjolsnes et al. [57]	0	0	0	0	0	2	0	2	1	0	1	1	7
Presland et al. [74]	1	0	0	1	0	2	0	2	1	0	1	1	9
Ribeiro-Alvares et al. [75]	1	1	0	1	0	0	0	2	1	0	1	1	8
Seymore et al. [76]	1	0	0	1	0	0	0	2	1	0	1	1	7
Tansel et al. [77]	0	0	0	0	0	0	0	0	1	0	1	1	3

2.3.5 Analysis and interpretation of results

Means ± SDs of strength and architecture measures as well as the duration of the interventions, and total prescribed volumes were independently extracted from the included studies. Strength assessment measures included variables such as relative eccentric peak torque (at 15°s^{-1}, 30°s^{-1}, 60°s^{-1}, 120°s^{-1}), eccentric peak torque (at 60°s^{-1}) and as eccentric force (in newtons). Architectural measures included fascicle length, pennation angle, muscle thickness and muscle cross sectional area. Effect sizes (ES) were calculated as they represent standardised values whereby the magnitude of differences in means between groups or experimental condition can be determined and comparisons made [78]. Hedges’ g and the associated 95% confidence intervals (CI) were used to assess the magnitude of mean differences between pre- and post-intervention as this accounts for the differences in sample size. Calculation of Hedges’ g as an ES was completed using the following formula [79]:

$$g = \frac{\left(Mean_{\text{post}} - Mean_{\text{pre}}\right)}{\text{SD}_{\text{pooled}}}$$

The scale proposed by Hopkins [80] was used for interpretation of the subsequent results whereby the magnitude of ES was considered as trivial (≤ 0.20), small (0.20 – 0.59), moderate (0.60 – 1.19), large (1.20 – 1.99) or very large (≥ 2.00). Consistency of effects were quantified using a test for heterogeneity (I^2) outlined by Higgins et al. [81], whereby a scale of low (< 25%), moderate (25 - 75%) and high (≥ 75%) I^2 values was used for interpretation of consistency. Estimations for between-study variance were calculated for both strength and architecture using random-effects models for all strength and architecture variables with 95% CI.

2.4 Results

2.4.1 Search results

Two hundred and ninety-three titles were identified through databases and reference searches highlighted in the methods section above. The process that was used to identify the articles reviewed within this systematic review can be seen in Figure 2.1, with ninety-four articles excluded due to duplication and then a further one hundred and sixty-four titles that did not fit within the predetermined inclusion criteria (see section 2.3) were excluded. Following this the abstracts and full texts were examined against the inclusion criteria whereby a further twenty-two articles were excluded leaving the thirteen studies included within this review. Data were extracted from the interventions within the included studies from comparisons pre- and post-interventions. Data from testing groups and control groups were extracted, however, it was not a requirement within the inclusion/exclusion criteria to have both, meaning two of the included studies (i.e., Mjølsnes et al. [57] and Freeman et al. [72]) are without controls.

2.4.2 Study quality and bias of results

Consistency between the studies assessed for both hamstring strength measures and muscle architecture was moderate to high, with I^2 values of 58.58% and 88.03%, respectively. Quality of assessment was assessed using the TESTEX criterion (see Table 2.1); the mean score for the studies in this review was six out of a total fifteen, with the highest scoring study being a randomised controlled trial [59] with a score of eleven. Two risk of bias assessments were also performed, the first (Cochrane risk of bias assessment tool) showing a low risk of bias overall within the randomised control studies included in this review (Figure 2.2), the second identifying the results of this meta-analysis are not subject to publication bias ($p < 0.001$) with 178 and 663 “filed-away” studies needed to prove null effects of NHE interventions on strength and architecture, respectively.

	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Other bias
Anastasi and Hamzeh [69]	?	✗	?	?	✓	✓	✓
Iga et al. [73]	?	✗	✓	✓	✓	✓	✓
Ishøi et al. [59]	✓	✗	✓	✓	✓	✓	✓
Mjølsnes et al. [57]	✓	✗	✓	✓	✓	✓	✓
Ribeiro-Alvares et al. [75]	✓	✗	✓	✓	✓	✓	✓
Seymore et al. [76]	✓	✗	?	?	✓	✓	✓

Key
✓ Low risk of bias
✗ High risk of bias
? Unclear risk of bias

Figure 2.2. A depiction of the Cochrane risk of bias assessment.

2.4.3 Systematic review and meta-analyses findings

Within-study differences pre-post intervention are shown in the figures below. Figure 2.2 illustrates the magnitude of the change in strength (ES and 95% CI) of all eight eccentric hamstring strength variables collected across thirteen studies. Only one study which assessed eccentric peak torque showed very large increases ($g = 2.12$) post-intervention, with two studies that assessed isometric peak torque resulting in large increase post-intervention ($g = 1.80$ and 1.29). In contrast, large to very large ($g \geq 1.32$) increases in eccentric force during the NHE were evident post-intervention in the two studies that used this metric. Control groups in all studies showed trivial or negative changes in torque or force ($g \leq 0.14$). The pooled summary of variance from the random effects model was 0.439 ($p = 0.001$, 95% CI = 0.160 to 0.709) for strength and 0.793 ($p < 0.001$, 95% CI = 0.338 to 1.248) for muscle architecture.

Figures 2.3 and 2.4 illustrate the same results as seen in Figure 2.2; however, these are ordered in terms of volume (highest to lowest) prescribed during the interventions (Figure 2.3) and duration (shortest to longest) of the interventions (Figure 2.4). No trend with respect to volume was revealed, with both high and low volumes resulting in very large ES; however, a threshold of six weeks as a minimum intervention duration was detected. Out of the eight studies [68, 70-75, 77] in the short duration group (4-6 weeks), those that only prescribed a 4-week intervention found trivial to small differences pre to post intervention. Large to very large ES were seen only in the single 6-week study [74] and moderate to very large increases in the medium duration studies (8-10 weeks) [57, 59, 69, 76].

Muscle architecture ES is demonstrated in Figure 2.5, with 3 measures of FL showing very large ES ($g \geq 2.58$). Positive improvements (a reduction) in PA can be seen with large to very large ES ($g \geq 1.31$), with no meaningful change ($g \leq 0.47$) in muscle size (MT or PCSA/ACSA). Similar to the strength variables, the control groups also showed either trivial or small negative ES.

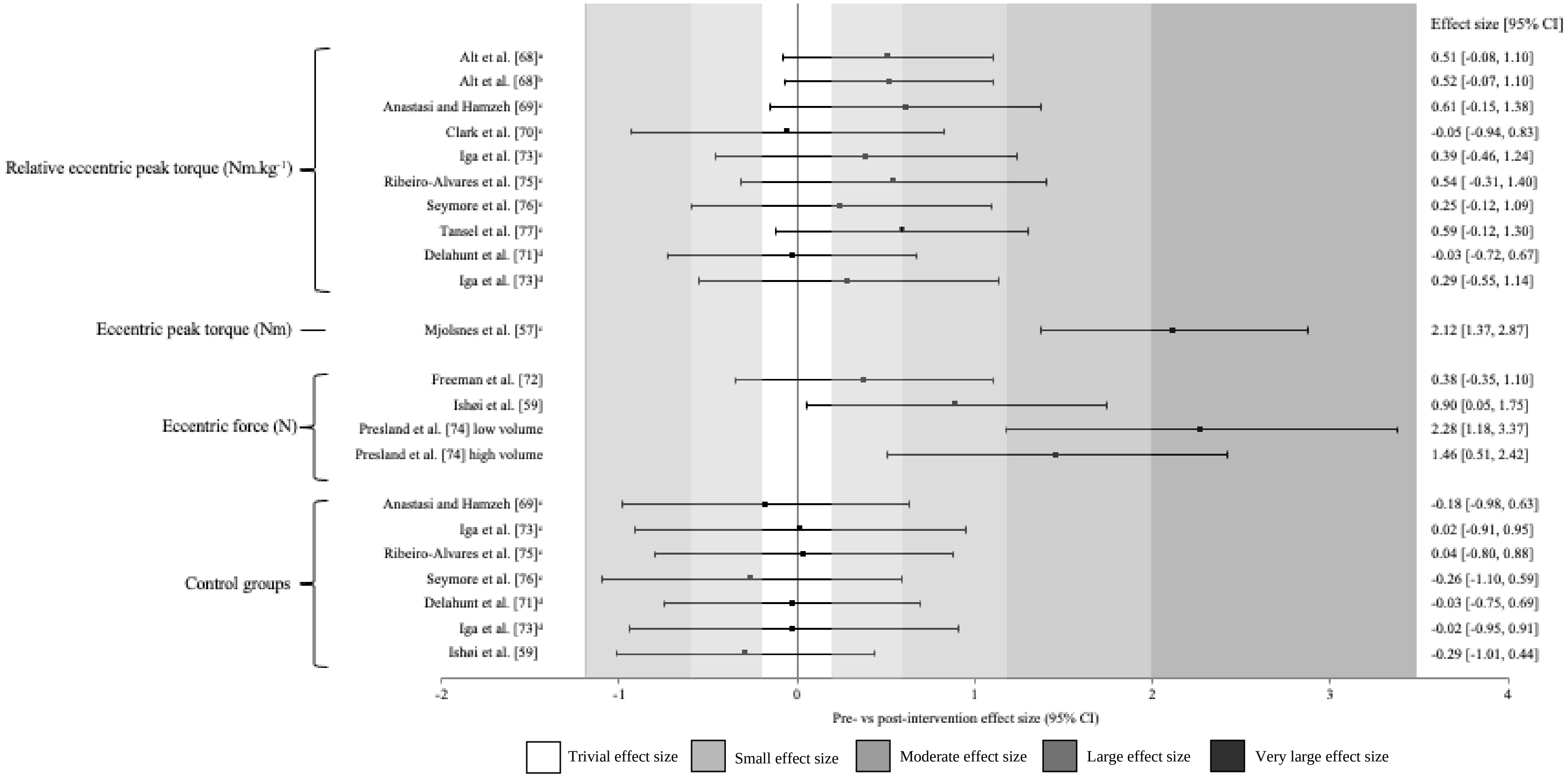


Figure 2.3. Changes in strength pre- and post-Nordic hamstring Exercise intervention.

Nm.kg^{-1} = Newton meters per kilogram; Nm = Newton meters; N = Newtons; CI = confidence interval; ^{a} = 15°s^{-1}; ^{b} = 30°s^{-1}; ^{c} = 60°s^{-1}; ^{d} = 120°s^{-1}.

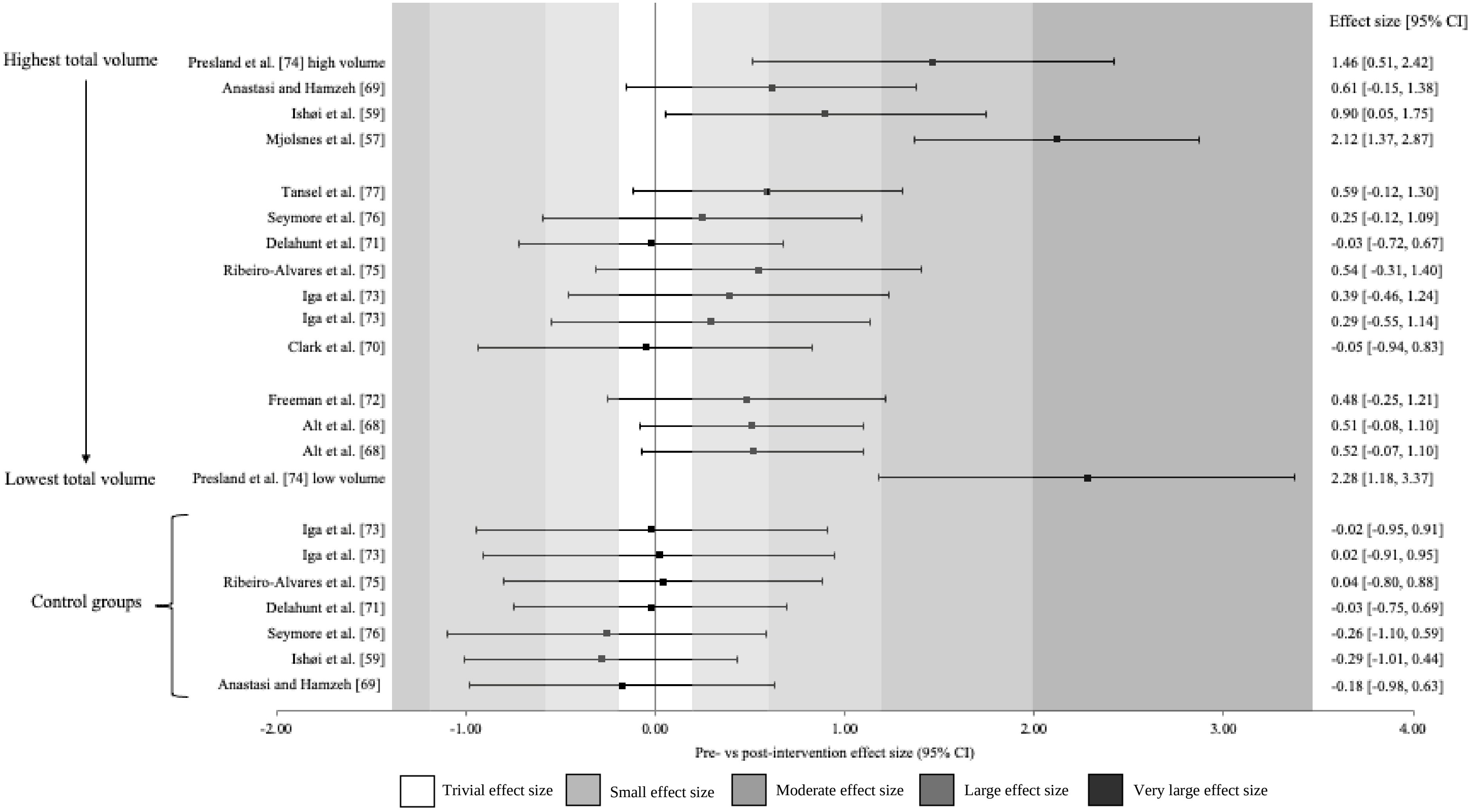


Figure 2.4. Changes in strength pre- and post-Nordic hamstring exercise intervention ranked from highest to lowest total volume.

CI = Confidence interval

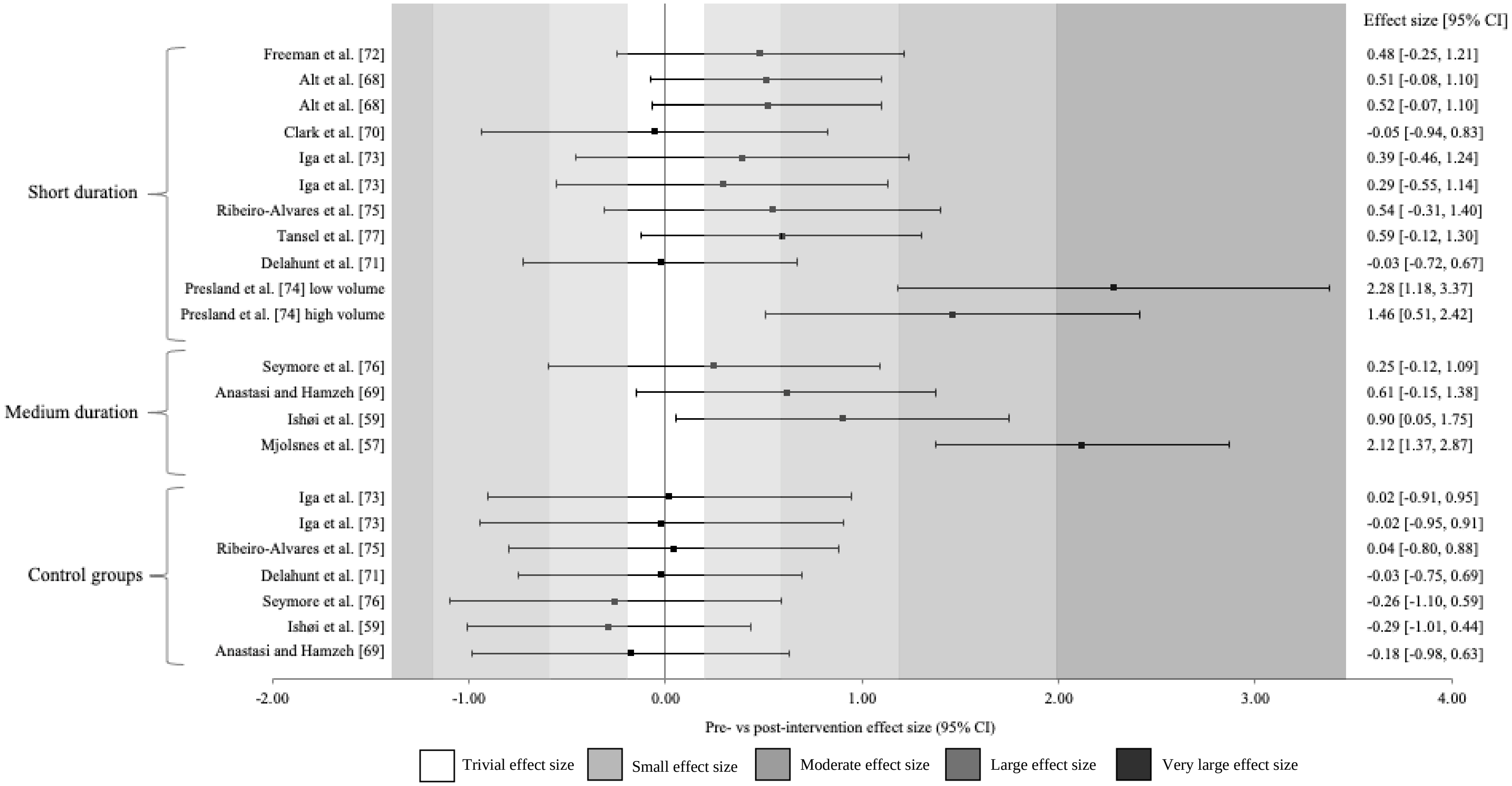


Figure 2.5. Changes in strength pre- and post-Nordic hamstring exercise intervention ranked from short duration (4-6 weeks) to medium duration (8-10 weeks).

CI = Confidence interval

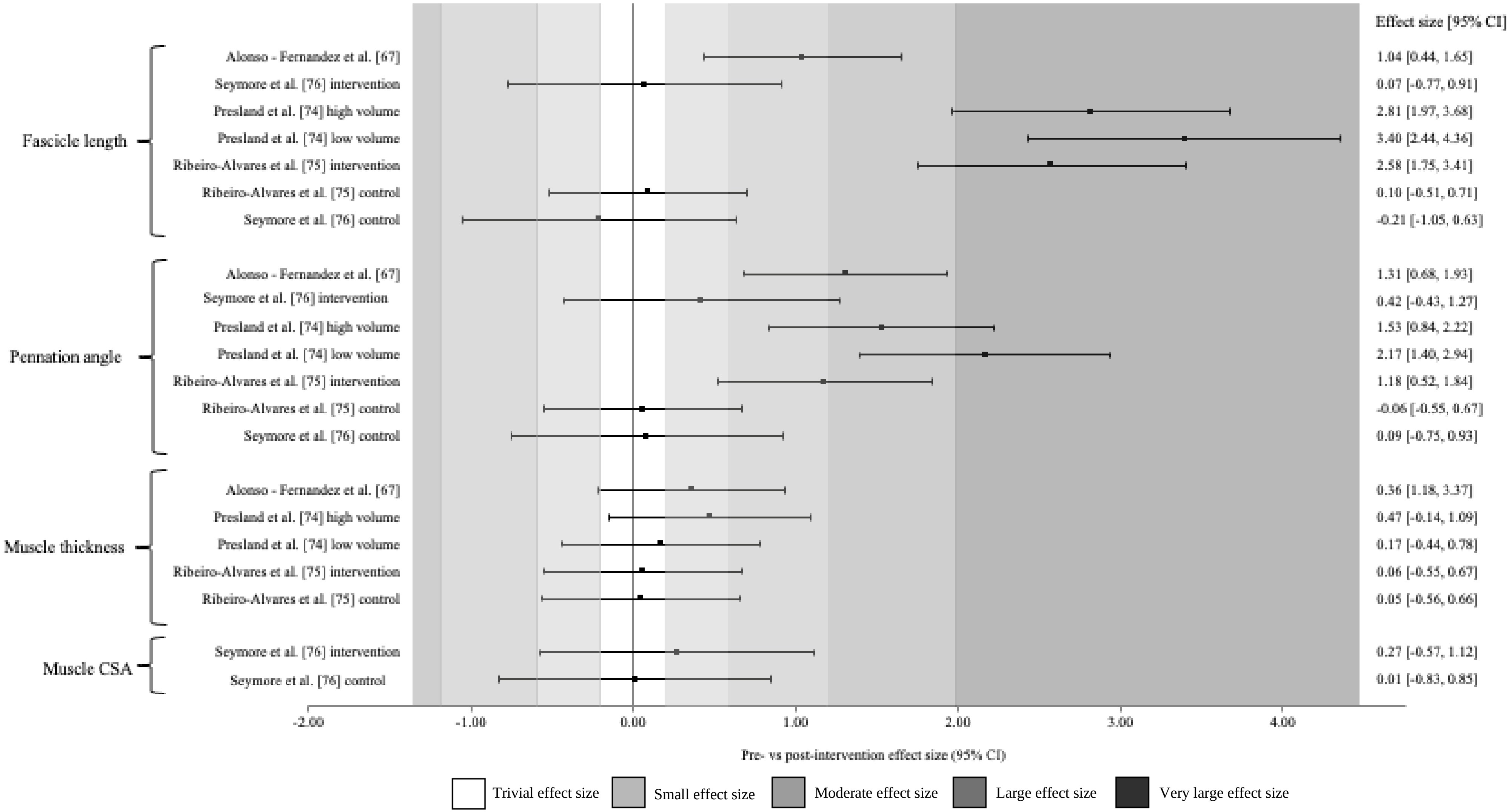


Figure 2.6. Changes in muscle architecture pre- and post-Nordic hamstring exercise intervention.

CSA = Cross-sectional area; CI = Confidence interval

2.5 Discussion

The purpose of this review and meta-analysis was to identify the effect of training volume, prescribed through a NHE intervention, on changes in eccentric hamstring strength and BF^{LH} muscle architecture. The evidence collected suggests that both high and low volume prescription can produce large to very large improvements in both strength (eccentric torque and eccentric force) and muscle architecture (FL and PA) over a minimum duration of six weeks. The quality and bias of the studies reviewed, assessed using the TESTEX scale, showed a large variation with many of the studies scoring less than half of the total available. The majority of studies failed to report levels of compliance, activity levels of control groups and did not use a blind assessor or report concealment of group allocation.

2.5.1 The effect of volume on eccentric strength

A wide range of volumes and durations were identified following the literature search (Table 2.2). An average weekly volume across interventions ranged from 21 repetitions a week to as high as 73 repetitions a week. The majority of studies within this review built up the volume throughout, with highest weekly volumes reaching 90-100 repetitions. Further investigation showed that repetitions within sets reached between 8 and 12 towards the end of many of the interventions. The risk of incurring a HSI is increased due to a lack of hamstring strength; however, traditional strength training would recommend ≤ 6 repetitions at ≥ 85% of one repetition maximum (RM) according to National Strength and Conditioning Association (NSCA) guidelines [82] with an increase in intensity producing the most effective increases in force production capabilities. The NHE being supramaximal or conceptually ‘above 1RM’, the assumption would be that fewer repetitions would be required to create the same stimulus.

Table 2.2. Characteristics of the Nordic hamstring interventions used in studies included in this review.

Study	Subjects	Population	Duration (weeks)	Intervention (repetitions x sets x frequency)	Total volume (repetitions)	Average weekly volume (repetitions)	Outcomes
Alonso-Fernandez et al. [67]	n = 23	Recreationally active males	8	Week 1 - 2 = 2 x 6 x 2 Week 3 - 4 = 3 x 4 - 6 x 3 Week 5 - 6 = 3 x 8 x 3 Week 7 - 8 = 3 x 10 x 3	480	60	Significant increases in FL and MT of the BF^{lh} and significant decreases in PA.
Alt et al. [68]	n = 16	Regional to national level male sprinters	4	Week 1 - 4 = 3 x 3 x 3	108	27	No significant increases in peak torque as a result of the intervention.
Anastasi and Hamzeh [69]	n = 24	Amateur female rugby union players	10	Week 1 - 2 = 3 x 6 x 3 Week 3 - 4 = 3 x 7 x 3 Week 5 - 7 = 3 x 8 x 3 Week 8 - 10 = 3 x 10 x 3	720	72	Increases in peak torque of both limbs pre to post.
Clark et al. [70]	n = 9	Amateur Australian Rules Football players	4	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 x 3 Week 4 = 3 x 8 x 3	160	40	Significant reductions in peak torque pre to post.
Delahunt et al. [71]	n = 29	Recreationally active males	6	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 x 3 Week 4 = 3 x 8 x 3 Week 5 - 6 = 3 x 12, 10, 8 x 3	340	57	Significant increases in peak torque pre to post, with large effect sizes.
Freeman et al. [72]	n = 28	Team sport adolescent athletes	4	Week 1 = 2 x 5 x 2 Week 2 = 3 x 4 x 2 Week 3 = 3 x 5 x 2 Week 4 = 3 x 6 x 2	110	28	Significant increases in peak eccentric force pre to post, with small effect sizes.
Iga et al. [73]	n = 18	English professional male soccer players	4	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 x 3 Week 4 = 3 x 8 x 3	160	40	Significant increases in peak torque at 3 different angular velocities pre to post.

Ishøi et al. [59]	n = 35	Amateur male soccer players	10	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 - 8 x 3 Week 4 = 3 x 8 - 10 x 3 Week 5 - 10 = 3 x 12, 10, 8 x 3	700	70	Significant increases in peak eccentric hamstring force pre to post.
Mjølsnes et al. [57]	n = 21	Competitive male soccer players	10	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 - 8 x 3 Week 4 = 3 x 8 - 10 x 3 Week 5 - 10 = 3 x 12, 10, 8 x 3	700	70	Significant increases in peak torque pre to post. Significantly greater increases compared to concentric exercise.
Presland et al. [74] (high volume)	n = 20	Recreationally active males	6	Baseline week 1 - 2 = 4 x 6 x 2 Week 3 = 4 x 8 x 2 Week 4 = 4 x 10 x 2 Week 5 - 6 = 5 x 10 x 2	392	73	Significant increases in BF FL for both groups and decreases in PA in the pre to post for the low volume group. No significant differences were observed for MT. Eccentric hamstring force also increased significantly in both groups.
Presland et al. [74] (low volume)				Baseline week 1 - 2 = 4 x 6 x 2 Week 3 - 6 = 2 x 4 x 1	80	21	
Ribeiro-Alvares et al. [75]	n = 20	Healthy young adults (aged 18-35)	4	Week 1 = 3 x 6 x 2 Week 2 = 3 x 7 x 2 Week 3 = 3 x 8 x 2 Week 4 = 3 x 10 x 2	186	47	Significant increases in peak torque pre to post, with moderate effect sizes. BF MT did not change pre to post, FL did increase and PA decrease to a very large and large effect size, respectively
Seymore et al. [76]	n = 20	Recreationally active adults	6	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 x 3 Week 4 = 3 x 8 x 3 Week 5 - 6 = 3 x 12, 10, 8 x 3	340	57	No significant increases in peak torque as a result of the intervention. BF FL and PA both increased without significance, CSA increased significantly.
Tansel et al. [77]	n = 26	Healthy boys (aged 10-12)	5	Week 1 = 2 x 5 x 1 Week 2 = 2 x 6 x 2 Week 3 = 3 x 6 - 8 x 3 Week 4 = 3 x 8 - 10 x 3 Week 5 = 3 x 12, 10, 8 x 3	286	57	Significant increases in hamstring peak torque pre to post.

The two studies resulting in the greatest increase in eccentric hamstring strength [57, 74] differed in the prescribed volume with high volumes applied during the intervention by Mjølsnes et al. [57] and the low volumes by Presland et al. [74]; however, both included periods of ≥ 4 weeks whereby volume was not increased, unlike the other interventions identified in this systematic review. With no increase in volume (sets and/or repetitions), the intensity of the exercise may have increased as a result of an increasing breakpoint angle (the angle at which the hamstrings inhibit, and the upper body falls to the floor), i.e., the individual gets closer to the ground before falling, which in turn increases the torque due to force being applied over a greater moment. This increase in intensity, much with traditional strength training, is likely to be the reason for the effectiveness of these two programmes. Understanding intensity may be an issue when prescribing NHE volume because of the inverse relationship it has with rate of perceived exertion (RPE). Although RPE may be relatively high initially when performing the NHE, it is likely to increase with an increase in repetitions. Conversely, although intensity should always be supramaximal, force production is likely to decrease due to fatigue and a reduction in the breakpoint angle, meaning the amount of "work done" may reduce. Even with high levels of fatigue, athletes can still perform the movement to an extent, resulting in the perception of high levels of exertion. Ishøi et al. [59] replicated the intervention designed by Mjølsnes et al. [57] but observed only moderate improvements in eccentric strength across the 10 weeks, this, however, was likely due to the compliance of the subjects within the studies with Ishøi et al. [59] reporting only 60% compliance compared to the 96% reported by Mjølsnes et al. [57].

Potential conflict in the findings may be related to methodological differences when testing eccentric strength, combinations of eccentric force, and relative peak torque at various angles and angular velocities are reported. Poor agreement ($r = 0.35$) between eccentric force collected during the NHE and isokinetic eccentric peak torque at $60°.s^{-1}$ has been reported previously [83], suggesting a difference between the two methods of assessing eccentric force production. Although there were very large improvements both in terms of isokinetic torque, and eccentric force, the greatest improvements across studies were seen in eccentric force, which was due to the testing procedure being a NHE, whereby a learning effect in addition to any improvements in strength may have been present. When considering the discrepancy between angular velocities tested across the studies, given that this analysis only evaluated effect sizes pre- and post-intervention and the testing procedures being consistent within all studies, this is unlikely to have had any influence on the findings of this review.

2.5.2 The effect of volume on eccentric muscle architecture

Despite high training volumes being associated with hypertrophic responses, no interventions identified had any meaningful effect on either MT or muscle CSA, which could have been a result of relatively short intervention durations with the longest being 8 weeks (see Table 2.2). In contrast, there were very large increases in FL attributed to three different volumes, including both the highest based on the average weekly volume and the lowest [74] between pre and post intervention. This was also true of PA, which was associated with large to very large decreases appearing as a positive ES in Figure 2.4, due to a decrease in PA being the desired outcome. Presland et al. [74] showed no statistical differences ($p = 0.982$) in the increases in FL between the high and low volume groups; however, the lower volume group showed significantly greater ($p < 0.001$) decreases in PA pre-post intervention compared to the changes reported in the higher volume group.

Trivial to small changes in ES of FL and PA were only observed by Seymore et al. [76], who consequently claimed that an increase in FL is unlikely to be responsible for the injury protection that a NHE provides. This statement, however, does not consider other factors that may have influenced the lack of change in muscle architecture and eccentric hamstring strength in this study. Firstly, both FL and PA were assessed as an average of the proximal, middle, and distal portions of the hamstring, which would not have taken into consideration any regional improvements that other studies may have found by typically assessing just the muscle belly or 'middle' portion. Seymore et al. [56] also reduced the data down into a group of 'responders' and 'non-responders' to outline the individualistic changes in the experimental groups. The group termed 'responders' showed considerably lower relative eccentric hamstring torque compared to the non-responders pre-intervention. Subsequently the responders showed significantly large increases in both CSA and PA ($p \leq 0.008$ and $d \geq 1.34$) and a slight reduction in FL, suggesting a hypertrophic response much like a non-trained athlete would demonstrate, whereas the group termed 'non-responders' did show large increases in FL ($d = 1.65$), despite a reduction in strength. This appears to contradict their argument somewhat as there was an increase in FL, just not in the weaker group, but a subsequent lower volume strength focused program may provide those changes. Unfortunately, these groups were only a fraction of the sample size, and it is therefore recommended that further investigations determine if differential changes occur in strong versus weak subjects.

2.5.3 Compliance and delayed onset muscle soreness

As previously highlighted in section 4.1, compliance in terms of real-world application of NHE interventions or hamstring injury prevention programmes is low [61]. In this systematic review, low compliance was reported by Ishøi et al. [59] who achieved only 60% compliance during their intervention. Not all studies have reported compliance, however, which could be a potential cause for those studies that have demonstrated low effectiveness of intervention, given the high levels of effectiveness of other interventions included within this review. A common reason for athletes not complying with NHE interventions or coaches not prescribing the NHE at all is the high levels of DOMS experienced as a consequence of the large eccentric stimulus the exercise provides. Three studies [57, 68, 72] identified DOMS or muscle soreness through a visual analogue scale which is used as a scale for pain, with the data being obtained following each warm-up prior to the intervention sessions. The scores recorded were no higher than six out of ten, attributing the soreness to moderate to low levels of pain. Both pain level and the difference between soreness and pain are subjective measures. In the study by Ishøi et al. [59], subjects who reported hamstring pain were removed from the study, which would have been the reason for low compliance. Further clarification needs to be conducted within studies as to whether this is just due to a high level of muscle soreness, rather than pain due to injury, as it may then be necessary to provide a longer period prior to any intervention to allow for a gradual increase in exposure to the exercise.

2.5.4 Study quality and bias

The variability of the quality of studies included in this review, as highlighted by the TESTEX scores provided (Table 2.1), allows for the identification of potential discrepancies when comparing studies. The common shortfalls throughout the range of studies are based around the methodological control of concealing group allocation and blinding assessors, as well as monitoring activity within the control groups and outside the training intervention. The blinding of assessors may not be viable in terms of the strength measures, however, when considering the muscle architecture measurements there may be some element of assessor bias as the measurements or analysis are somewhat subjective. Due to the nature of most interventions being applied within a ‘real-world’ type setting, it is important to include any concurrent training stimuli in order to fully assess if there were any outside interactions with any adaptations seen following an intervention. In the TESTEX criteria the reporting of compliance and adherence is given a greater portion of the scores, however, only four studies scored at least one point out of a possible three within the section. The low compliance of studies could explain low effectiveness and reporting on compliance may prevent inaccurate conclusions being drawn about the possible impact of such interventions. Publication bias was not present in the studies included within this review, as highlighted in the results, with Figure 2.2 also depicting a ‘low risk of bias’ for the majority of the seven categories, the only ‘high risk of bias’ identified being through the allocation concealment. Allocation concealment refers to both participants and investigators enrolling participants not foreseeing group allocation; however, this is not always ecologically valid, especially within a sporting club setting which is consistent across all the included studies. The studies categorised as ‘unclear’ were due to a lack of detail and description within those studies.

2.6 Conclusion

Many NHE interventions are derived from the original model provided by Mjølsnes et al. [57], which is understandable due to the effectiveness shown for increasing both hamstring strength and FL whilst reducing PA. This, however, has not been effectively replicated since, and whether that is attributable to lower compliance throughout the intervention or reducing the length of the intervention so that it does not allow for a plateau in training volume, it seems a new approach is needed in order for the general compliance rate in real-world application to increase. This review has shown that a reduction in overall training volume need not have a negative effect; however, the focus needs to be on allowing the intensity of the exercise to increase, as would occur in traditional strength training. Allowing players to ‘get better’ at the exercise by keeping the training volume consistent, to allow them to slowly produce force over a greater range of motion, seems to be the most effective way of producing the desired adaptations. Although a minimal dosage is yet to be determined, the recommendations based on the evidence found in this review would be to reduce the training volume and keep it at a consistent level if the lack of compliance in players is due to severe DOMS. Although outside the scope of this review, it is important to consider that the NHE should be part of a wider holistic hamstring programme in order to account for both strength, architectural adaptations and ability to withstand high velocity actions that are observed within sporting actions. Future studies should investigate how the frequency of NHE prescription effects adaptations, whilst also looking to increase study quality.

2.7 Commentary 1

As the title of chapter 2 suggests, the systematic review of NHE intervention research only allowed us to present the data with a focus on the volume of prescription and intervention duration, rather than any interaction with frequency which is one of the main aims of this thesis. The results from the meta-analyses, however, have demonstrated that volume prescription has typically been inappropriate for in-season training which is one suggestion as to why compliance is low particularly in soccer players. Only once volume is appropriate and compliance high enough to enable any adaptations can we begin to understand whether frequency has an effect on adaptation or not, certainly for the NHE alone. Following the conclusions of Chapter 2, there is an understanding that appropriate NHE volume prescription is important, and more is not always better. There is also a clear area for future research in understanding whether frequency influences NHE prescription. With this in mind, the aims stated for investigation into the frequency of hamstring training across consecutive days, a microcycle, and a 9-week intervention will be inclusive of appropriate volume prescription. We then also needed to further review previous literature to understand whether a lack of research into the training frequency in athletic populations is limited to the NHE or if further gaps are present in which we can explore.

As part of the PhD process, chapter 2 has been published in Sports Medicine (open access), and has already accrued over 30 citations [84]. That is not to say it has gone without any learning experiences, as corrections were required to be submitted (which have been made to the thesis chapter) [85], followed by a letter to the editor which was submitted regarding the article [86], and subsequently followed by our response [87]. The experience of going through that process proved valuable for then moving onto chapter 3, whereby a second systematic review and meta-analyses were conducted.

3 Chapter 3: Effects of Variations in Resistance Training Frequency on Strength Development in Well-Trained Populations and Implications for In-Season Athlete Training: A Systematic Review and Meta-analysis.

3.1 Abstract

Background: In-season competition and tournaments for team sports can be both long and congested, with some sports competing up to three times per week. During these periods athletes need to prepare technically, tactically and physically for the next fixture and the short duration between fixtures means that, in some cases, physical preparation ceases, or training focus moves to 'recovery' as opposed to progressing adaptations. ***Objective:*** The aim of this review was to investigate the effect of training frequency on muscular strength to determine if a potential method to accommodate in-season resistance training, during busy training schedules, could be achieved by utilising shorter more frequent training sessions across a training week. ***Methods:*** A literature search was conducted using the SPORTDiscus, Ovid, PubMed and Scopus databases. 2134 studies were identified prior to application of the following inclusion criteria: (1) maximal strength was assessed, (2) a minimum of two different training frequency groups were included, (3) participants were well trained, and finally (4) compound exercises were included within the training programmes. A Cochrane risk of bias assessment was applied to studies that performed randomised control trials and consistency of studies was analysed using I^2 as a test of heterogeneity. Secondary analysis of studies included Hedges' g effect sizes (g) and between-study differences were estimated using a random-effects model. ***Results:*** Inconsistency of effects between pre- and post-intervention were low within-group ($I^2 = 0\%$), and moderate between-group ($I^2 \leq 73.95\%$). Risk of bias was also low based upon the Cochrane risk of bias assessment. Significant increases were observed overall for both upper ($p \leq 0.022$) and lower ($p \leq 0.008$) body strength, pre- to post-intervention, when all frequencies were assessed. A small effect was observed between training frequencies for upper ($g \leq 0.58$) and lower body ($g \leq 0.45$). ***Conclusion:*** Over a 6 to 12-week period there are no clear differences in maximal strength development between training frequencies, in well-trained populations. Such observations may permit the potential for training to be manipulated around competition schedules and volume to be distributed across shorter, but more frequent training sessions within a micro-cycle rather than being condensed into 1-2 sessions per week, in effect, allowing for a micro-dosing of the strength stimuli.

3.2 Background

The basic demands of many sports require athletes to rapidly exert high forces to accelerate or decelerate external objects [88, 89] and/or manipulate their own body mass, an opponent's mass in addition to their own, or an implement and/or projectile [88]. Resistance training focused primarily on the development of strength, rather than strength endurance or hypertrophy, is arguably the most critical focus for improving athletic performance and underpins both individual and team sports [88, 90]. Evidence of this has been provided through numerous studies demonstrating moderate to large correlations between maximal strength and dynamic performance [88]. In addition, strength training has also been outlined as a potent method to reduce the risk of muscular injuries [91, 92] with well-developed lower body strength, repeated sprint ability, and speed increasing an athlete's tolerance to higher training loads and in turn reducing risk of injury compared to lower performance groups in the aforementioned areas [93].

Resistance training (RT) has long been used to improve skeletal muscle function, architecture and activation. The manipulation of sets, repetitions, and load lifted (usually as a percentage of repetition maximum [RM]) during RT dictates the muscular and neurological adaptations. Typically, RT application consists of a focus on strength (low volume [3-5 sets of ≤6 repetitions] - high load [≥ 85% 1RM]), hypertrophy (high volume [3-5 sets of 6-12 repetitions] - moderate load [67-85% 1RM]), endurance (high volume [~3 sets of ≥ 12 repetitions] - low load [≤ 67% 1RM]) [82], or power. Increased power output can be achieved via numerous means, for example in untrained/weak individuals this can be accomplished via increased focus on basic strength training [94, 95]. Stronger athletes, however, need to include loaded high velocity ballistic tasks such as weightlifting [88, 89] and higher velocity jump and plyometric training, using minimal additional load [94, 96], or dependent upon the periodisation model used, a mixture of each of these modes (strength, ballistic and plyometric training) can be employed [97]. Within periods of an athlete's career, across each season, and based on the athlete's training status and goals, the emphasis on certain training foci is more appropriate than others. Appropriately planned RT can help to increase specific musculoskeletal and neurological adaptations through the manipulation of and interaction between specific training principles, including volume (sets x repetitions), load (often referred to as intensity) and frequency.

The current American College of Sports Medicine (ACSM) guidelines suggest that, for 'general muscular fitness' training, sessions should occur 2-3 days per week with 48 hours recovery in between [98]. The National Strength and Conditioning Association (NSCA) also suggest training frequencies of 2-3 times per week for beginners, 3-4 times per week for intermediates and 4-7 times per week for those with advanced training status [82]. Within an athletic population, however, such training frequencies are generally unrealistic due to the demands of in-season competition, especially within team sports where competitions can be as frequent as 2-3 times per week. In well-trained/athletic populations RT typically follows some form of periodisation. The traditional approach to periodisation, whereby the competition year/macrocycle is divided into a preparation, competition and transition period, as seen in the model outlined by Matveyev [99], was originally developed for individual athletes where 'maintenance' of strength is the primary goal during a relatively short competition period. Maintenance of strength and athletic abilities during the competition period is therefore not always appropriate within all team sport settings, due to their competition period lasting between 3-9 months, depending on the sport. Effectiveness and duration of off-season / pre-season preparatory periods, for the development of physical qualities, need to be considered when planning and implementing in-season training priorities. Density of competition does, however, play a role in the planning and regularity of RT with basketball teams required to play three times per week, and some soccer teams required to compete three times in ten days. International tournaments also include dense fixture schedules, where dependent upon the age group competing, games are typically played 72 hours apart [100] but can be played between 48 and 96 hours apart. The ability to provide sufficient periods of recovery, as well as opportunities to provide stimuli for the maintenance of strength through RT, become limited during these periods of congested fixtures when following the ACSM frequency guidelines [98].

Lundberg et al. [101] concluded that two resting days (~72h between matches) are not sufficient for players to recover from match-induced muscle soreness during congested periods. Although the NSCA guidelines do take fixtures into account by recommending a reduced RT frequency of 1-3 times per week in-season compared to their usual recommendations [82], this is not entirely dissimilar from the ACSM's recommendation of 2-3 times a week and therefore the same argument could apply. Athletes with greater strength, high intensity running capability and aerobic capacity have demonstrated an ability to recover quicker than those less conditioned, despite having worked at higher intensities during competition [102, 103]. Greater ability to recover may allow for the two rest days between fixtures, highlighted by Lundberg et al. [101] to allow sufficient recovery, however this has not been investigated over a period of chronic fixture congestion. In-season strength maintenance in soccer has only been exhibited over a 12 week period, whereby Rønnestad et al. [28] demonstrated that RT once per week, over the first 12 weeks of the season, permitted the maintenance of strength, compared to one session every two weeks which resulted in an average strength loss of 10% in a 1RM half squat. For sports where there are regularly ≥ 2 games per week, and a large technical-tactical focused approach, accompanied by a low-intensity recovery focus [104], there would potentially be a detrimental long term effect as the athletes would not be able to maintain strength throughout a full season. The majority of team sports' competitive seasons last longer than 12 weeks, however, suggesting there needs to be a greater level of insight into whether the lower end of the NSCA's frequency guidelines are appropriate for competition periods >12 weeks. The 'maintenance' of strength throughout a season/tournament is therefore likely to be most appropriate during short, condensed seasons, as seen in many U.S. collegiate sports [28] whereby the teams that decline the least over that short period will likely improve their chances of success. These athletes also benefit from having relatively long periods to enhance their physical capabilities prior to and following competition. Focussing on 'maintenance' is arguably a poor training goal during long seasons, much like those seen in the National Basketball Association, National Hockey League and soccer leagues worldwide, especially in light of the fact that small but progressive increases in performance can be achieved depending on training status of the athletes and periodisation model used [105]. When the importance of competition increases as the competitive season progresses, with teams competing in play-offs or knockout stages of competitions, performance needs to remain high and injuries minimised. With limited off/pre-seasons, it is therefore important to continue strength development during the season to ensure the best athletes are available and appropriately prepared.

Resistance training frequency has previously been reviewed meta-analytically [106, 107], with what appears to be differing conclusions regarding the improvements in strength through RT. Grgic et al. [106] attributed increased RT frequency to increased 'gains' in muscular strength, whereas Ralston et al. [107] report no significant differences ($p = 0.25$) between low and high frequency training. Grgic et al. [106] are explicit, however, in describing that when their data set is analysed in sub-groups, no significant differences ($p = 0.324$) occurred between groups when volume is equated, suggesting that weekly RT volume was the underlying determinant of improvements in muscular strength, rather than training frequency. The limitations of both reviews are due to the populations included, both having analysed data that included largely untrained populations and young, middle-aged, and older subjects. Evidence provided through the use of untrained populations is not always valid when making comparisons to trained individuals and athletic populations due to untrained populations responding and adapting favourably to a multitude of different stimuli [108]. Inspection of the appropriateness of exercise prescription within the interventions was not included in either of the aforementioned meta-analyses, with the authors only critiquing the lack of equated volumes in some cases, whereas most of the studies included did not prescribe repetitions, sets and load based upon recommended strength training thresholds (3-5 sets, ≤ 6 repetitions, load ≥ 85% 1RM) [82] but those more appropriate or 'optimal' for hypertrophy (2-5 sets, 8-12 repetitions, loads equivalent to ≤ 80% 1RM) [82, 106, 107].

The aim of this systematic review and meta-analysis was to assess the effect of RT frequency on maximum strength in athletic and well-trained populations in order to provide possible implications for how this may affect practitioners in-season RT prescription.

3.3 Methods

3.3.1 Study design

This systematic review design was developed in adherence to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA). The PRISMA guidelines include 27-items within a checklist that is designed to be used as the basis for reporting systematic reviews [62]. The research question being investigated within this review as defined by the PICO model (population, intervention, comparison and outcome) is whether in a well-trained population, during volume matched resistance training interventions, does the frequency of training have an effect on both lower and upper body strength outcomes during experimental randomised and non-randomised studies. A protocol was not pre-registered for this review.

3.3.2 Literature search

A Boolean/phrase search mode was applied using the following keywords: "resistance training" AND "frequency" AND "volume" AND "intensity". The keywords were inputted using this format into four different databases, including PubMed, SPORTDiscus, Ovid and Scopus. Filters were applied to all databases to include studies that were written in the English language and presented in peer-reviewed academic journal articles. No restrictions were placed upon the sex of subjects; age, however, was restricted to no greater than 35 years, with no lower age cut-off.

3.3.3 Inclusion and exclusion criteria

The primary focus of this literature search was to identify studies that have assessed the effect of different RT frequencies in trained/athletic populations. The search timeframe was restricted up to and including 1st April 2020, with no earliest date restriction, following this search there were 2134 articles identified for further inspection. All duplicated studies were removed initially with the remaining studies then being screened utilising the subsequent criteria. Research articles were included and eligible within this review provided that (1) a measure of maximal strength was assessed, (2) a minimum of two different training frequency groups were included, (3) the population of the studies were stated as well trained, and finally (4) multi-joint exercises were included within the training programmes. Studies were excluded for using subjects that were not injury free for the 6 months prior, along with any systematic or narrative reviews. A summary of the above selection process is outlined in Figure 3.1. Means and standard deviation (SD) were required from all papers to be analysed further, if these values were not present but the study met the rest of the criteria, the corresponding authors were contacted in order to obtain these values.

3.3.4 Quality and risk of bias assessment

Following the identification of the studies included within this review, the quality and risk of bias were assessed. This included a Cochrane risk of bias assessment tool to assess the risk of bias within the randomised control trials. The Cochrane risk of bias assessment tool evaluates randomised controlled trials based on several categories that include sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective outcome reporting, and 'other issues.' Grades for these categories were provided as either 'high risk of bias', low risk of bias, or 'unclear risk of bias'.

3.3.5 Analysis and interpretation of results

Means and SDs of upper and lower body maximal strength measures were independently extracted from the included studies for further analysis. Maximal strength tests included one RM back squat, leg press, and bench press, and maximum voluntary isometric contraction of the knee and elbow flexors. Hedge's g effect sizes (g) were calculated from the pre- to post-intervention results of each study in order to provide a standardised value whereby the magnitude of differences can be determined and compared across interventions whilst accounting for differences in sample size. The scale for interpretation of g was proposed by Hopkins [80] as follows; trivial ($\leq$ 0.20), small (0.21–0.59), moderate (0.60–1.19), large (1.20–1.99), or very large ($\geq$ 2.00). An estimation for between-study variance was calculated using a random-effects model, with associated Z-value, p-value and 95% confidence intervals (95% CI), absolute heterogeneity was assessed using Tau^2 and this was estimated using the restricted maximum likelihood method. Finally, a test for relative heterogeneity (I^2), as outlined by Higgins et al. [81], was used to quantify the relative inconsistency of effects, using a scale of low (< 25%), moderate (25-75%) and high ($\geq$ 75%) and the associated significance with an a priori alpha level of $p < 0.05$. All statistical analyses were carried out using Jamovi [66]. Training frequency of the lower and upper body was defined as the number of sessions that included exercises targeting those areas, respectively, per week. Comparisons were made between the lower frequency and higher frequency groups within each study. Training frequencies can be interpreted across the whole spectrum, with some sports considering a 'high' frequency to be the equivalent of a 'low' frequency in other sports, for example within basketball, the majority of the season is spent playing three games per week, whereby one or two dedicated RT sessions would be considered high frequency, compared to a sport such as rugby or American football whereby that same frequency would be considered low. From a research perspective, there is also no clear definition of what constitutes high and low frequencies, with some studies for example labelling three sessions a week as low [109, 110] frequency and some as high [111-114]. The authors therefore have not definitively classified any frequency as either being low or high but made comparisons as lower and higher. Due to body mass not being reported for individual groups in all of the included studies both pre- and post-intervention, changes in relative strength of each group could not be assessed. Instead, baseline strength between groups within each study were compared separately in order to highlight magnitude of strength differences between the study groups. All studies included within the meta-analyses were independently evaluated by two of the authors (NR and PC) for methodological quality.

3.4 Results

3.4.1 Search results

Two thousand, one hundred and thirty-four studies were identified within the four databases highlighted in section 2.2. Figure 3.1 illustrates that of the total studies identified, 142 articles were duplicates and therefore removed first. Following the application of the predetermined inclusion/exclusion criteria to both titles and abstracts of the identified studies, and with further inspection of the full text if required, a total of 10 studies remained for further analysis [109-118].

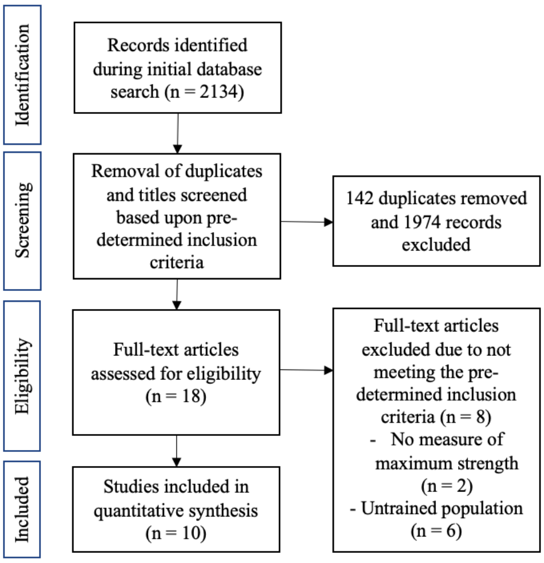


Figure 3.1. PRISMA flow chart

3.4.2 Systematic review and meta-analyses findings

The results of two different meta-analyses were calculated in order to evaluate the effectiveness of the interventions on both lower and upper body strength pre- and post-intervention as well as the differences in effect between the lower and higher frequencies for each study (Table 3.1). Pre- to post-intervention effect sizes can be seen in Appendix 1 and 2, with most of the interventions, regardless of frequency, demonstrating small to moderate (g = -0.40 – 1.11) increases in strength. The estimated overall effect for strength in both the lower body ($g = 0.562$) and upper body ($g = 0.323$) pre- to post-intervention demonstrated the effectiveness of resistance training with significant increases for each of the meta-analyses, respectively ($p < 0.001$) (Table 3.1). When comparing between lower and higher frequencies groups of each study, no overall significant effect was observed for lower body (p = 0.453 and g = 0.088) and upper body (p = 0.505 and g = 0.088).

Table 3.1. A summary of the meta-analytical statistics for intervention effect and frequency differences.

Pre vs post-intervention

	Overall effect	Z	p	95% CI	Tau^2	I^2 (%)	p
Upper body	0.323	3.674	< 0.001	0.151 - 0.495	< 0.001	0.00	0.983
Lower body	0.562	6.309	< 0.001	0.387 - 0.737	< 0.001	0.00	0.881

Lower vs higher frequency

	Overall effect	Z	p	95% CI	Tau^2	I^2 (%)	p
Upper body	0.088	0.667	0.505	-0.171 - 0.348	< 0.001	0.00	0.990
Lower body	0.061	0.453	0.651	-0.202 - 0.323	< 0.001	0.00	0.851

Z = z score, CI = confidence interval

3.4.3 Study quality and bias results

Heterogeneity of the completed meta-analyses were conducted and can be seen in Table 3.1, with inconsistency of effects being extremely low pre- to post-intervention (Tau^2 = < 0.001, I^2 = 0%). A Cochrane risk of bias assessment was completed (Figure 3.2) on all studies that described some level of randomisation within their methods, with the results of this generally showing low risk of bias around the reporting of blinding of participants as this was unlikely to influence the results. Selection bias for the most part was unclear as the majority of the studies, although stating that groups were randomly allocated, did not report methods of allocation.

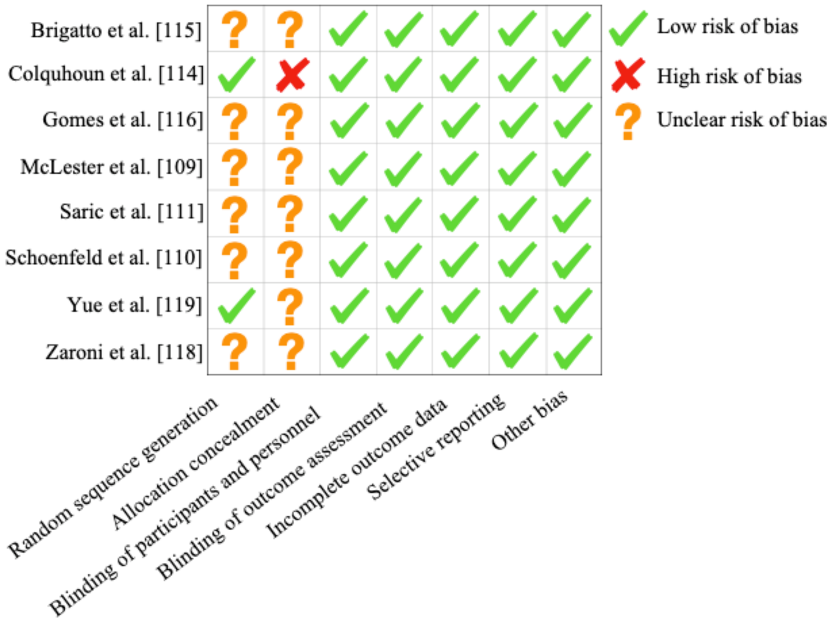


Figure 3.2. Depiction of the Cochrane risk of bias assessment.

3.5 Discussion

The purpose of this review was to identify the effect of different RT training frequencies on maximum strength in well-trained populations, in order to understand the influence different RT frequencies may have on athletes' strength levels in-season. The findings of the systematic review and meta-analyses demonstrate that although the majority of interventions demonstrated significant and small positive effects ($p < 0.001$ and $g \leq 0.562$) of resistance training (pre- to post-intervention) for upper ($p = 0.505$ and $g = 0.088$) and lower body ($p = 0.651$ and $g = 0.061$) strength, there was no significant difference and trivial effect in regard to the frequency of training, when volume was equated (Table 3.1). A Cochrane risk of bias assessment was used to assess the quality and bias of the studies reviewed, the results of which showed low risk of bias for the majority of categories assessed, with unclear bias around allocation concealment and method of random sequence generation. The findings of this review therefore agree with previous meta-analyses conducted by both Grgic et al. [106] and Ralston et al. [107] who investigated training frequency within a number of different, mostly untrained, populations suggesting that RT frequency has no significant effect on strength when volume is equated.

Table 3.2. Characteristics of the training frequency interventions used for the lower body in the studies included within this review.

Study	Title	Subjects	Population training status	Duration	Strength measures	Volume matched	Set x rep ranges	Frequencies (x a week)	Relative strength at baseline	Subject age (years)
Brigatto et al. [115]	Effect of resistance training frequency on neuromuscular performance and muscle morphology after eight weeks in trained men	n = 20	RT experience 4.1 ± 1.8 years	8 Weeks	1RM Back squat	Yes	8 x 8-12RM	1	1.59 (kg.kg^{-1})	27.1 ± 5.5
								2	1.61 (kg.kg^{-1})	
Colquhoun et al. [114]	Training volume, not frequency, indicative of maximal strength adaptations to resistance training	n = 28	RT training minimum of 3x a week for 6 months and 150% of BW for deadlift 1RM	6 Weeks	1RM Back squat	Yes	4 x 3-8 (Daily undulating)	3	1.73 (kg.kg^{-1})	22 ± 2
								6	1.65 (kg.kg^{-1})	22 ± 3
Gomes et al. [116]	High-frequency resistance training is not more effective than low-frequency resistance training in increasing muscle mass and strength in well-trained men	n = 23	RT Experience 6.9 ± 3.1 years	8 Weeks	1RM Back squat	Yes	10 x 8-12RM	1	1.70 (kg.kg^{-1})	25.5 (24.0 – 26.5)
								5	1.56 (kg.kg^{-1})	27.1 (25.0 – 28.7)
Hoffman et al. [113]	The effects of self-selection for frequency of training in a winter conditioning program for football	n = 61	NCAA Division I athletes	10 Weeks	1RM Back squat	No	5 x 2-10	2	1.84 (kg.kg^{-1})	20.1 ± 1.5
								3	1.74 (kg.kg^{-1})	19.7 ± 1.4
								5	1.72 (kg.kg^{-1})	20.1 ± 1.1
								6	1.71 (kg.kg^{-1})	19.7 ± 1.1
Kilen et al. [112]	Adaptations to short, frequent sessions of endurance and strength training are similar to longer, less frequent exercise sessions when the total volume is the same	n = 29	Military personnel with a minimum of 6 months RT experience	8 Weeks	MVIC Knee extensor	No	2-3 x 8RM Lower body 2-3 x 5RM upper body	3	8.99 (N.kg^{-1})	22 ± 3
								9	9.06 (N.kg^{-1})	25 ± 3
McLester et al. [109]	Comparison of 1 day and 3 days per week of equal-volume resistance training in experienced subjects	n = 25	Minimum of 12 weeks RT experience	12 Weeks	1RM Leg press	Yes	3 x 3 - 10 Lower body 3 x 5 - 10 upper body (Muscle failure)	1	2.60 (kg.kg^{-1})	26.0 ± 3.8
								3	2.65 (kg.kg^{-1})	23.8 ± 5.4

Saric et al. [111]	Resistance training frequencies 3- and 6-times per week produce similar muscular adaptations in resistance-trained men	n = 27	RT training minimum of 2x a week for 6 months	6 Weeks	1RM Back squat	Yes	4 x 6-12RM (Muscle failure)	3	1.41 (kg.kg^{-1})	22.6 ± 2.1
								6		
Schoenfeld et al. [110]	Influence of resistance training frequency on muscle adaptations in well-trained men	n = 20	RT training minimum of 3x a week for 1 year	8 Weeks	1RM Back squat	Yes	2-3 x 8-12 (Muscle failure)	1 (Split)	1.47 (kg.kg^{-1})	23.5 ± 2.9
								3 (Total)		
Yue et al. [119]	Comparison of two equated resistance training weekly volume routines using different frequencies on body composition and performance in trained males	n = 18	RT Experience 3.0 ± 0.5 years	6 Weeks	1RM Back squat	Yes	4 x 8-12	1	1.17 (kg.kg^{-1})	28 ± 7.9
								2	1.3 (kg.kg^{-1})	21 ± 3.2
Zaroni et al. [118]	High resistance-training frequency enhances muscle thickness in resistance-trained men	n = 18	RT experience range from 2-10 years	8 Weeks	1RM Back squat	Yes	3 x 10-12	1 (Split)	1.33 (kg.kg^{-1})	26.4 ± 4.6
								5 (Total)		

RT = resistance training, RM = repetition maximum, BW = bodyweight, DOMS = delayed onset muscle soreness, MVIC = maximum voluntary isometric contraction

Table 3.3 Characteristics of the training frequency interventions used for the upper body in the studies included within this review.

Study	Title	Subjects	Population training status	Duration	Strength measures	Volume matched	Set x rep ranges	Frequencies (x a week)	Relative strength at baseline	Subject age (years)
Brigatto et al. [115]	Effect of resistance training frequency on neuromuscular performance and muscle morphology after eight weeks in trained men	n = 20	RT experience 4.1 ± 1.8 years	8 Weeks	1RM Bench press	Yes	8 x 8-12RM	1	1.19 (kg.kg^{-1})	27.1 ± 5.5
								2	1.23 (kg.kg^{-1})	
Colquhoun et al. [114]	Training volume, not frequency, indicative of maximal strength adaptations to resistance training	n = 28	RT training minimum of 3x a week for 6 months and 150% of BW for deadlift 1RM	6 Weeks	1RM Bench press	Yes	4 x 3-8 (Daily undulating)	3	1.28 (kg.kg^{-1})	22 ± 2
								6	1.22 (kg.kg^{-1})	22 ± 3
Gomes et al. [116]	High-frequency resistance training is not more effective than low-frequency resistance training in increasing muscle mass and strength in well-trained men	n = 23	RT Experience 6.9 ± 3.1 years	8 Weeks	1RM Bench press	Yes	10 x 8-12RM	1	1.32 (kg.kg^{-1})	25.5 (24.0 – 26.5)
								5	1.28 (kg.kg^{-1})	27.1 (25.0 – 28.7)
Hoffman et al. [113]	The effects of self-selection for frequency of training in a winter conditioning program for football	n = 61	NCAA Division I athletes	10 Weeks	1RM Bench press	No	5 x 2-10	3	1.33 (kg.kg^{-1})	19.7 ± 1.4
								4	1.36 (kg.kg^{-1})	20.1 ± 1.5
								5	1.32 (kg.kg^{-1})	20.1 ± 1.1
								6	1.28 (kg.kg^{-1})	19.7 ± 1.1
Kilen et al. [112]	Adaptations to short, frequent sessions of endurance and strength training are similar to longer, less frequent exercise sessions when the total volume is the same	n = 29	Military personnel with a minimum of 6 months RT experience	8 Weeks	MVIC Elbow flexor	No	2-3 x 8RM Lower body 2-3 x 5RM upper body	3	4.73 (N.kg^{-1})	22 ± 3
								9	5.51 (N.kg^{-1})	25 ± 3
McLester et al. [109]	Comparison of 1 day and 3 days per week of equal-volume resistance training in experienced subjects	n = 25	Minimum of 12 weeks RT experience	12 Weeks	1RM Bench press	Yes	3 x 3 - 10 Lower body 3 x 5 - 10 upper body (Muscle failure)	1	0.98 (kg.kg^{-1})	26.0 ± 3.8
								3	0.75 (kg.kg^{-1})	23.8 ± 5.4

Saric et al. [111]	Resistance training frequencies 3- and 6-times per week produce similar muscular adaptations in resistance-trained men	n = 27	RT training minimum of 2x a week for 6 months	6 Weeks	1RM Bench press	Yes	4 x 6-12RM (Muscle failure)	3	1.05 (kg.kg^{-1})	22.6 ± 2.1
								6		
Schoenfeld et al. [110]	Influence of resistance training frequency on muscle adaptations in well-trained men	n = 20	RT training minimum of 3x a week for 1 year	8 Weeks	1RM Bench press	Yes	2-3 x 8-12 (Muscle failure)	1 (Split)	1.19 (kg.kg^{-1})	23.5 ± 2.9
								3 (Total)		
Yue et al. [119]	Comparison of two equated resistance training weekly volume routines using different frequencies on body composition and performance in trained males	n = 18	RT Experience 3.0 ± 0.5 years	6 Weeks	1RM Bench press	Yes	4 x 8-12	2	0.91 (kg.kg^{-1})	28 ± 7.9
								4	0.97 (kg.kg^{-1})	21 ± 3.2
Zaroni et al. [118]	High resistance-training frequency enhances muscle thickness in resistance-trained men	n = 18	RT experience range from 2-10 years	8 Weeks	1RM Bench press	Yes	3 x 10-12	1 (Split)	1.10 (kg.kg^{-1})	26.4 ± 4.6
								5 (Total)		

RT = resistance training, RM = repetition maximum, BW = bodyweight, DOMS = delayed onset muscle soreness, MVIC = maximum voluntary isometric contraction

3.5.1 Intervention frequency

Due to a whole range of frequencies being investigated across the studies analysed in this review (Table 3.2 and 3.3), the authors were unable to make enough comparisons to moderate the meta-analyses based on the frequency of each group. The lack of grouping has therefore led to some crossover between studies that have used one frequency as the 'higher' frequency that has also been included in a different study as the 'lower' frequency. An example of the crossover in training frequencies is demonstrated by McLester et al. [109] and Schoenfeld et al. [110] who both utilised 3 times per week as their higher RT frequency, whereas 3 times per week was used as the lower frequency in a number of the other studies included [111-114]. Although the crossover between descriptors of 'lower' and 'higher' frequencies may appear to be a possible issue in the reporting of data it is important to bear in mind that the differences in effect observed range from trivial to small (g = -0.10 – 0.33) for both lower and upper body regardless of the descriptor used. It is possible, however, to make a number of direct comparisons based on studies that utilised the same frequencies within their interventions. As mentioned previously McLester et al. [109] and Schoenfeld et al. [110] both investigated once per week compared to 3 times per week, with neither resulting in once a week being favourable compared to 3 times per week. When comparing 3 times a week as a lower frequency, in studies conducted by Colquhoun et al. [114] and Saric et al. [111] who investigated 3 times per week compared to 6 times per week, the results were mixed. Lower body strength improved to a greater extent for the group training 3 times per week in the study by Saric et al. [111] whereas the greater improvement in the study by Colquhoun et al. [114] was observed in the 6 times per week group. The reverse was true for the upper body. The only frequency analysed within this review that consistently demonstrated superior effect when compared with others for lower body strength was 5 times per week. Gomes et al. [116] and Zaroni et al. [118] both investigated once per week compared to 5 times per week, with both favouring the higher frequency for lower body strength. A similar trend was shown by Gomes et al. [116] in the upper body, however Zaroni et al. [118] found that once a week demonstrated greater increases in upper body strength. Although the study by Hoffman et al. [32] observed in Figure 3.3 very slightly favours 'lower' frequency, this is likely due to the study itself investigating four different frequencies and therefore the results were aggregated, when comparing all the groups individually the trend observed by Gomes et al. [116] and Zaroni et al. [118] is also demonstrated, with 5 times per week consistently demonstrating the greater effect for the lower body (Appendix 3). When inspecting the upper body strength changes individually for the study by Hoffman et al. [113] the pattern followed the same trend as the study by Saric et al. [111] whereby 6 times per week was consistently the superior frequency (Appendix 4). Again, however, the differences in observed effect between the studies was trivial to small, much like the overall effect of the meta-analyses which also demonstrates non-significant differences. Due to the low heterogeneity for both the upper and lower body observed in Table 3.1 (I^2 = 0%), there would continue to be minimal differences even if the sampling error of the interventions were to be removed.

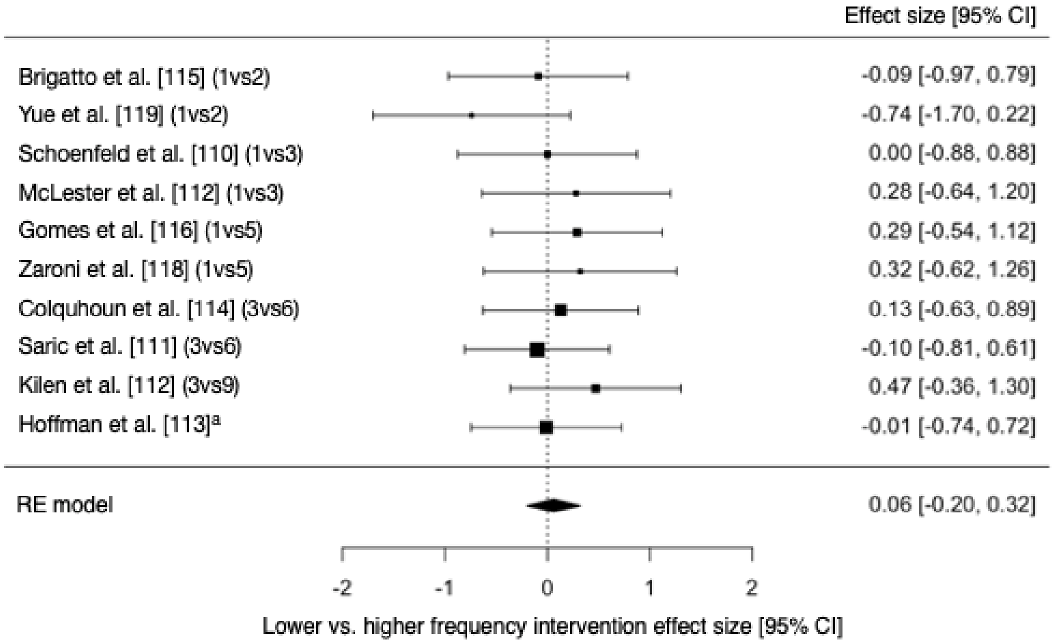


Figure 3.4. Differences in effect size between lower frequency and higher frequency groups on lower body strength (positive values favour the higher frequency groups and negative values favour the lower frequency groups).

(1vs2) = once-weekly vs twice-weekly, (1vs3) = once-weekly vs 3 x/week, (1vs5) = once-weekly vs 5 x/week, (3vs6) = 3 x/week vs 6 x/week, (3vs9) = 3 x/week vs 9 x/week

^{a} Aggregation of effect sizes due to the study comparing more than two groups
RE = random effects, CI = confidence interval.

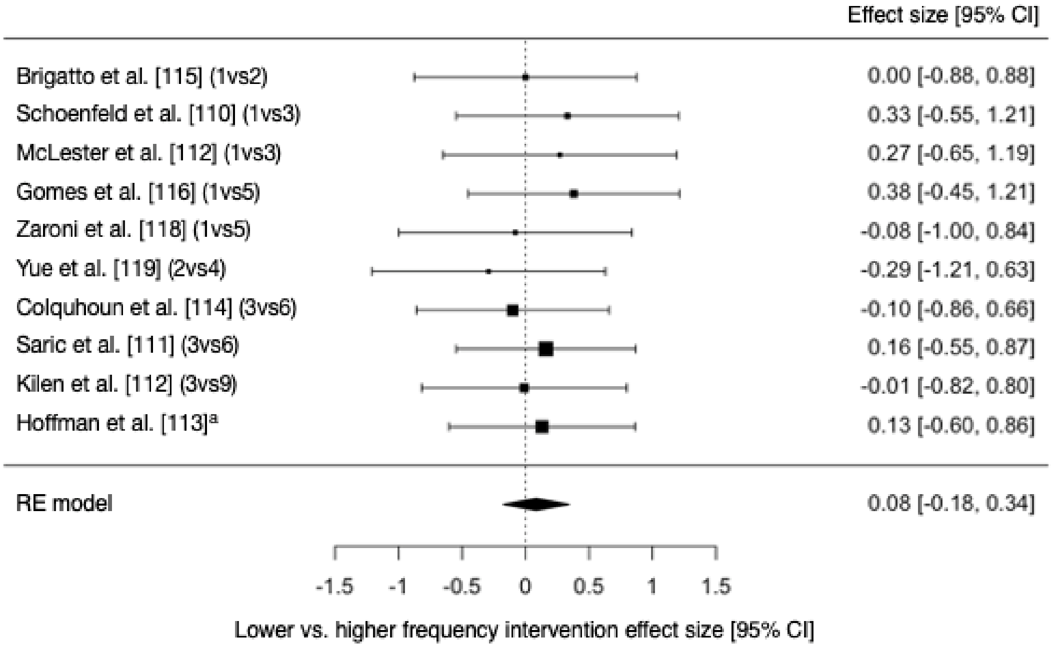


Figure 3.3. Differences in effect size between lower frequency and higher frequency groups on upper body strength (positive values favour the higher frequency groups and negative values favour the lower frequency groups).

(1vs2) = once-weekly vs twice-weekly, (1vs3) = once-weekly vs 3 x/week, (1vs5) = once-weekly vs 5 x/week, (2vs4) = twice-weekly vs 4 x/week, (3vs6) = 3 x/week vs 6 x/week, (3vs9) = 3 x/week vs 9 x/week

^{a} Aggregation of effect sizes due to the study comparing more than two groups
RE = random effects, CI = confidence interval.

3.5.2 Intervention exercise prescriptions

Pre- to post-intervention showed trivial to moderate changes in maximum strength of both the lower and upper body with the majority of the interventions included within this review demonstrating the positive effects of resistance training on strength adaptations. It is, however, important to understand the potential mechanisms responsible when considering adaptations in strength. An increase in strength but no increase in muscle mass may suggest adaptations occurred predominantly due to increased fascicle length, reduction in pennation angle [120] and neural adaptations [121]. Alternatively, an increase in strength and increase in muscle mass will likely lean towards increased muscle thickness and pennation angle as well as possible increases in fascicle length [120]. This intuitively suggests that some strength adaptations will occur during hypertrophy training in response to an increase in muscle mass but may not be elevated to the level that would occur in response to a solely strength-focused training program. A summary of the studies analysed within this review can be seen in Table 3.2, whereby the set and repetition ranges of each of the interventions can be observed. It is clear that based upon our earlier definition of training methods seen in Section 3.2, the majority of these RT interventions are not focussed on strength but heavily biased towards hypertrophy training with almost all interventions outlining sets above the recommended 3-6 repetitions [82], and most commonly employing 8-12 repetitions (see Table 3.2).

Despite all of the interventions including exercises to RM, only three were explicitly reported to include the performance of sets to muscle failure [109, 111, 122]. The RM approach to load prescription is based upon performing the sets and repetitions with the maximum load possible to complete the full prescription, likely resulting in training to muscle failure. It is worth noting that within this review 'load' is referred to when describing the amount of weight lifted, as Steele [123] and Arent et al. [124] have outlined how intensity (often used interchangeably with load) can be a better representative of effort. The reason for clearly defining the difference between load and intensity (effort) is to highlight that although the RM approach is performed with the maximum load possible for the sets and repetitions prescribed, this load may still be low-moderate, even when performed to failure and perceived to be high intensity by the athlete. Constantly training to muscle failure has been reported to have a potentially deleterious effect on performance [125]. Evidence of this effect has been observed when a group performing sets at a load relative to their maximum, compared to RM sets, demonstrated greater increases in jump performance, rapid isometric force production and muscular adaptations [125, 126]. The differences observed between the two groups is likely due to better fatigue management and potentially optimal performance adaptations, which is likely more appropriate for well-trained and professional athletes. The magnitude of load participants experienced throughout the majority of the interventions could explain why only trivial to moderate improvements in strength were observed across the 6-12 weeks. Schoenfeld et al. [122] have demonstrated similar hypertrophic responses are elicited when comparing a moderate load (3 sets of 10RM) vs high load (7 sets of 3RM) when volumes are equated, however, the high load group demonstrated the greatest improvements in both back squat and bench press 1RM. In addition, well-trained populations will likely see less strength adaptations in response to hypertrophy training and specific strength training due to already having a greater base level of strength [105, 127]. Two out of the ten studies included within this review do not appear to be volume equated (Table 3.2 and 3) [112, 113]. In a recent meta-analysis, Grgic et al. [106] used equated volume as a moderator, suggesting that increases in strength associated with higher frequencies of RT are largely attributed to the additional training volume. Due to the groups in studies by Hoffman et al. [113] and Kilen et al. [112] not being volume equated it is not possible to determine whether training volumes observed in the higher frequency groups affected the resultant adaptations. The beneficial effect of increased RT volume on hypertrophic responses has previously been demonstrated [128], however, the effect on strength is not as clear, or at which point increased volume may reduce the adaptive responses.

Only one study reported negative effects in response to a lower frequency RT intervention, where the authors observed small decreases in upper body and lower body strength [112]. A potential cause for these findings could be the testing battery used. Rather than using 1RM testing, a maximum voluntary isometric contraction was used to assess the knee and elbow flexors, which was unlike the actions used within the studies training intervention. Another reason for the reduction in strength could have been due to this being the only study to use a concurrent training approach. Due to the population used (i.e., military personnel), there was a requirement to not only train muscular strength but also aerobic and muscular endurance. The requirement to train concurrently is also present in team sports however, and the findings from Kilen et al. [112] support the complexity of this process. Due to the demands of team sports, ensuring appropriate development of all physical attributes (i.e. muscular strength and power, muscular endurance and aerobic endurance) is essential, not only to enable a greater ability to recover between efforts in training and competition but also to recover between fixtures within congested periods of a season, or during tournaments as highlighted in Section 3.2. Wilson et al. [129] has suggested that significant decrements in maximal strength may not occur as a result of endurance training but only through the incorrect training modality and/or dose. Kilen et al. [112] demonstrated the effect of traditional concurrent training whereby their “classical training” (lower frequency) group who performed training sessions of high intensity cardiovascular, muscular endurance and strength training within their program, experienced a decrease in maximal strength. In contrast, increases in maximal strength were observed in the “micro-training” (higher frequency) group who performed the same exercises, intensity and volume, albeit divided over shorter, higher frequency bouts (Figure 3.3 and 3.4).

3.5.3 Baseline strength level

One of the aims of this review was to identify if RT frequency influences strength in well-trained athletes. Quantifying training experience and categorising an athlete as ‘well-trained’ is not simple. Rhea [130] has proposed possible thresholds for g values to use based upon training experience (categorised as ‘untrained’, ‘recreationally trained’ and ‘highly trained’) when inspecting treatment effects. The criteria for this review, however, was for studies to state their population as well-trained, but as Table 3.2 and 3.3 outlines, the variation in criteria for this population is large, ranging from 6 months to 10 years. The duration an athlete has trained for does not necessarily dictate how well-trained they are, as the training they could have experienced at times throughout their career may be suboptimal. It could therefore be more applicable to categorise athletes based on their relative strength levels as evident within the study by Colquhoun et al. [114] who accepted subjects based upon a criteria that included both length of training history and a minimum strength level (150% of bodyweight for a deadlift), similar to the selection criteria for ‘previously weight trained’ individuals outlined by Willoughby [131], of a parallel back squat 1RM ≥ 1.5 times bodyweight as this is more likely to dictate the response to the

RT interventions. Relative strength levels pre-intervention have been calculated and are outlined in Table 3.2 and 3.3. A possible reason for there being small to moderate changes overall regardless of frequency, could be due to the populations of these studies actually being well-trained as the majority of groups exceed the 1.5 times bodyweight threshold previously described for lower body strength by Willoughby [131]. The greatest difference observed between two frequencies in the lower body was observed by Yue et al. [117] (Figure 3.3), an explanation for this potentially being due to the lower frequency group being the weakest at baseline in comparison to the higher frequency group and in comparison to the other studies investigated within this review. The lower relative strength results in a greater potential for improvement over the same period when exposed to the same volumes. The length of the interventions within this review could have also had an effect on the small to moderate change observed overall in Appendix 1 and 2. Unfortunately, the authors were unable to calculate relative strength changes due to a lack of reporting bodyweight post-intervention, or bodyweight for the different frequency groups rather than the whole sample population. The duration of the RT interventions included within this review were 6-12 weeks in duration. If the athletes were well trained, as described, it is unlikely that large changes to relative strength will be observed pre-post.

3.5.4 Study quality and bias

A Cochrane risk of bias assessment (Figure 3.2) was carried out in order to understand the bias across the studies that used a randomised approach. The overall conclusion would be that the risk of bias is low or even slightly unclear due to lack of detail around the way the randomisation in six out of the eight randomised studies. The concealment of allocation was also unclear in seven out of the eight studies, with the eight explicitly outlining that concealment of allocation did not occur. Depending upon the setting of these studies, however, that is not always ecologically possible, particularly when working in a team sport setting. Ecological validity could also provide a rationale as to the lack of control groups within all but one of the studies. Understanding links between strength training and reduction of injuries it could be viewed as unethical to have a control group that only takes part in the sport if they already have a background in RT as this could put them at a greater risk of injury and possible reduction in competitive advantage over those without such a background.

3.5.5 Limitations and areas for future research

The inclusion/exclusion criteria were initially designed to allow for a range of different potential moderators to be applied within the current meta-analysis. There was, however, a lack of consistent moderators available, which highlights a limitation of this review but also highlights gaps in the current literature and provides a strong rationale for future research areas in exercise prescription. The low consistency of effect (high heterogeneity) between the studies assessed in this review may have been attributed to certain commonalities. This low inconsistency is not necessarily a limitation but does highlight areas for which researchers need to expand on in the future. For example, all of the interventions included in this review were completed on male subjects, with the vast majority being ‘recreationally trained’ and completing the same test for maximal strength. Some areas for future research would therefore be to investigate both sexes, but particularly females, to provide comparison to the current literature. Taking samples from athletes within different team sport settings would also be appropriate, as one set of sporting demands or type of sporting schedule may benefit from one particular approach compared to another. Research conducted within competitive team sports would, however, require the acceptance of ecological validity, whereby a number of factors that are likely outside of any investigators control would need to be considered. It is also important to understand that the description of team sport athletes as being 'well-trained' may only apply to their sport and not when it comes to resistance training. The majority of interventions in this review included the exercises that were used to test their participants' maximum strength (1RM). Utilising the exercises tested within the intervention may have resulted in improvements purely based on improvement of technique or familiarisation, however due to the 'well-trained' nature of the population this is unlikely. Another potential issue with the maximal testing used to assess strength was that only bench press was used as a measure of compound upper body strength, whilst most interventions included a full body approach, meaning there was a lack of evidence to demonstrate upper body strength increase as a whole. A possible limitation of only measuring maximal strength means that the rate at which the participants could produce force was not measured. The force production capabilities of athletes are important for performance and associated with injury risk reduction, therefore not only is it important to apply force maximally, but the rate at which it is applied is also important. Measures of multi-joint rapid force production (e.g., using the isometric mid-thigh pull) should also be assessed when considering the implications for athletic populations.

Finally, as mentioned when considering concurrent training, Kilen et al. [112] described their higher frequency RT group as a "micro-training" group. Considering the overall lack of difference between training frequencies, further investigation should look into a variation of the term used by Kilen et al. [112] which has become more commonly used by practitioners which is "micro-dosing". Micro-dosing was initially coined from a performance perspective by Hansen [132] but has not been widely used within peer-reviewed literature, therefore having no clear definition. We therefore define micro-dosing training as "the division of total volume within a micro-cycle, across frequent, short duration, repeated bouts" and suggest that such an approach should be thoroughly investigated in the future.

3.6 Conclusion

It is evident that within the studies included in this review, there is no clear difference between RT frequencies in populations described as well-trained over a 6- to 12-week period. Not knowing which method is superior may appear negative to some practitioners who are looking for clear guidance on the most efficient way to train their athletes. No clear difference between different RT frequencies is potentially a positive when trying to address the issues stated in this review around in-season training, fixture congestion and tournament schedules. The lack of difference in agreement with previous frequency reviews suggests that volume and load dictate adaptations in strength over frequency. This may provide the opportunity for a micro-dosing approach, meaning more frequent but shorter duration, less fatiguing bouts of RT activity, or micro-dosing. Alternatively, a more traditional approach to training may also be appropriate at times throughout a season based on the time constraints placed on the practitioner, providing both the volume and load are comparable between the two approaches. Researchers should look to initially assess the effect of different RT frequencies on a strength focused training program which uses the strength thresholds recommended by the NSCA before then exploring its interaction with pitch-based training and the possible benefits on concurrent training.

3.7 Commentary 2

Similar to Chapter 2, Chapter 3 has been published in Sports Medicine and is also open access [133]. Whilst there have been at least two meta-analyses previously performed regarding the frequency of resistance training, none have looked specifically at ‘well-trained’ or athletic populations, nor regarding the potential influence on the “in-season” competition period. Despite this, it is becoming clear that training frequency has little effect on adaptations when appropriate volumes are matched. These findings have allowed us to present a formal definition of micro-dosing as a possible programming strategy that could be utilised in-season for team sports in particular, and therefore potentially in soccer. Initially the planned process was to follow Chapters 2 and 3 with empirical research, which was underway following the completion of both literature reviews. Having introduced the formal definition of micro-dosing we felt it was important to follow that up by expanding our thoughts on what the concept included and the possible ways it could influence programming. Paired with the fact that data collection had to stop due to a global pandemic, this then led to the creation and inclusion of Chapter 4. In Chapter 4 we take inferences from a range of different research areas and provide a conceptual framework for possible uses, benefits and in some cases limitations of micro-dosing.

4 Chapter 4: Micro-dosing: a multifaceted programming concept for resistance training in team sports or just another ‘hipster-magnet’.

4.1 Abstract

Background: The term micro-dosing, in the context of resistance training, has recently been popularised and become “fashionable” in applied settings where it is frequently used amongst performance practitioners. A clear definition has been provided within the literature, however, the extent to which the concept has been explicitly investigated in empirical research is limited. There also appears to be a few misinterpretations of the term for example using micro-dosing interchangeably with minimum effective dose. There are, however, many related research areas or themes that indicate the potential benefits of micro-dosing as an overarching concept. ***Objective:*** The aims of this review were to outline and discuss where some of these theories and concepts may or may not be appropriate for practitioners to use in team sports, whilst also highlighting areas in which researchers could investigate the application of micro-dosing in further detail. ***Conclusion:*** Although micro-dosing may be a relatively new term, which has been described as ‘trendy’ amongst practitioners, the underlying principles have been expressed and investigated for a long time, suggesting that micro-dosing may just be a means in which the application of a number of theories and concepts can resonate with coaches and practitioners.

4.2 Introduction

Recently, the concept of ‘micro-dosing’ has become a popular topic of discussion and debate amongst strength and conditioning professionals. This concept originally appeared in clinical research regarding drug development during the 1990’s, as a method of assessing pharmacokinetics (how a substance reacts when given to a living organism) prior to full Phase I clinical trials [134]. In clinical environments micro-dosing involves the application of a dose that is sub-pharmacological and sub-therapeutic [135]. More recently the concept has also been associated with psychedelics whereby typically 10-20% of a recreational dose (most commonly lysergic acid diethylamide [LSD] or psilocybin) is ingested regularly as a micro-dose [136]. Within this context a micro-dose stimulates metabolic reactions, but these effects are not perceived by the individual. Although mostly anecdotal, recommendations of these sub-perceptual doses were first published in 2011 in a book entitled “*The psychedelic explorer’s guide: safe, therapeutic, and sacred journeys*” [137]. From a physical performance perspective (within sports) the term was initially introduced by Hansen [132], since then however, micro-dosing has commonly been misconceived to be synonymous with the ‘minimal effective dose’ [138]. This misconception is understandable as until recently no formal definition of exercise micro-dosing had been present in the literature. Based upon this recent definition micro-dosing has been clearly defined as “the division of total volume within a micro-cycle, across frequent, short duration, repeated bouts” (Section 3.5.5 [133]).

More recently, Hansen [139] has proposed an alteration to the original naming of his approach to contextualise micro-dosing as ‘micro-priming’. Whilst Hansen [139] rightly highlights that many practitioners continue to improperly label and apply the micro-dosing concept, without providing a full picture of the potential applications, benefits and pitfalls of the concept, practitioners are likely to struggle to navigate between effective training practices and the “flavour-of-the-month” programming trends [139]. Though the authors agree with the notion that a greater focus should be placed upon doing the basics consistently and at a greater frequency, where feasible, Hansen's [139] rationale for moving away from the term micro-dosing is in part due to the association with taking small yet more frequent dosages of stimuli (such as drugs) that require periods of 'cycling-off' to prevent/avoid habituation. When going beyond exercise programming, however, and considering a periodised approach to training, cyclical constructs are central to how we integrate, sequence and organise training that targets a specific outcome [140]. Therefore, the application of micro-dosing may not always be appropriate or may need to be utilised in conjunction with traditional programming methods to emphasise the development of specific skills or physical characteristics.

Following the pharmacological theme presented when defining micro-dosing, it is important to understand what a dose is and the relationship a dose has with a subsequent response. In medical research, a dose refers to the amount of a therapeutic agent. The interaction between the dose and the potency of that agent provides researchers with a dose-response relationship for a given population whereby practitioners (medical professionals) can be provided with what is referred to as a therapeutic index, which represents the range in which the drug or substance is effective but not lethal. There are clear parallels in terminology when considering resistance training, with a combination of the volume (dose) and load/"intensity" (potency) providing a physiological response. The response is dictated by the training prescription used within the training zones (therapeutic index) and can be anywhere from a 'minimal effective dose', all the way up to a period of planned overreaching, with a lethal dose comparable to causing rhabdomyolysis or overtraining when consistently going beyond those training zones (Figure 4.1). It is important to understand that the 'optimal' dose-response will differ and fluctuate for each exercise, session, training cycle, program, and individual based on a multitude of factors which mitigate the athlete's internal load and adaptive responses.

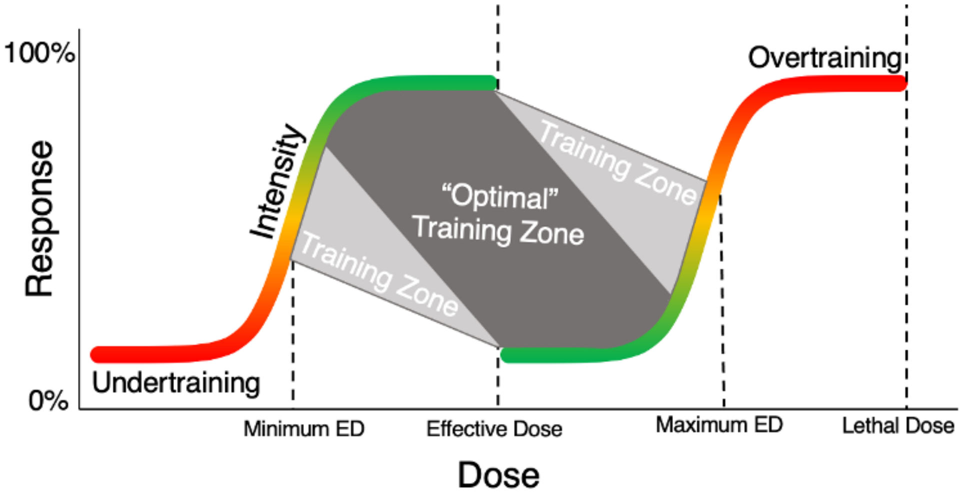


Figure 4.1. An illustration of the dose-response curve in relation to resistance training.
(ED = Effective Dose)

The purpose of this review is therefore to discuss how the concept of micro-dosing resistance training in team sports is more than just a "hipster-magnet" as described by Hansen [139]. Within each section we provide a definition of the subject area, outline the potential ways in which micro-dosing may be used as a programming strategy across four key areas (i.e., competition schedule, acute/chronic programming, motor learning and individualisation [Figure 4.2]) as well as provide inferences from current literature, and highlight areas for future research.

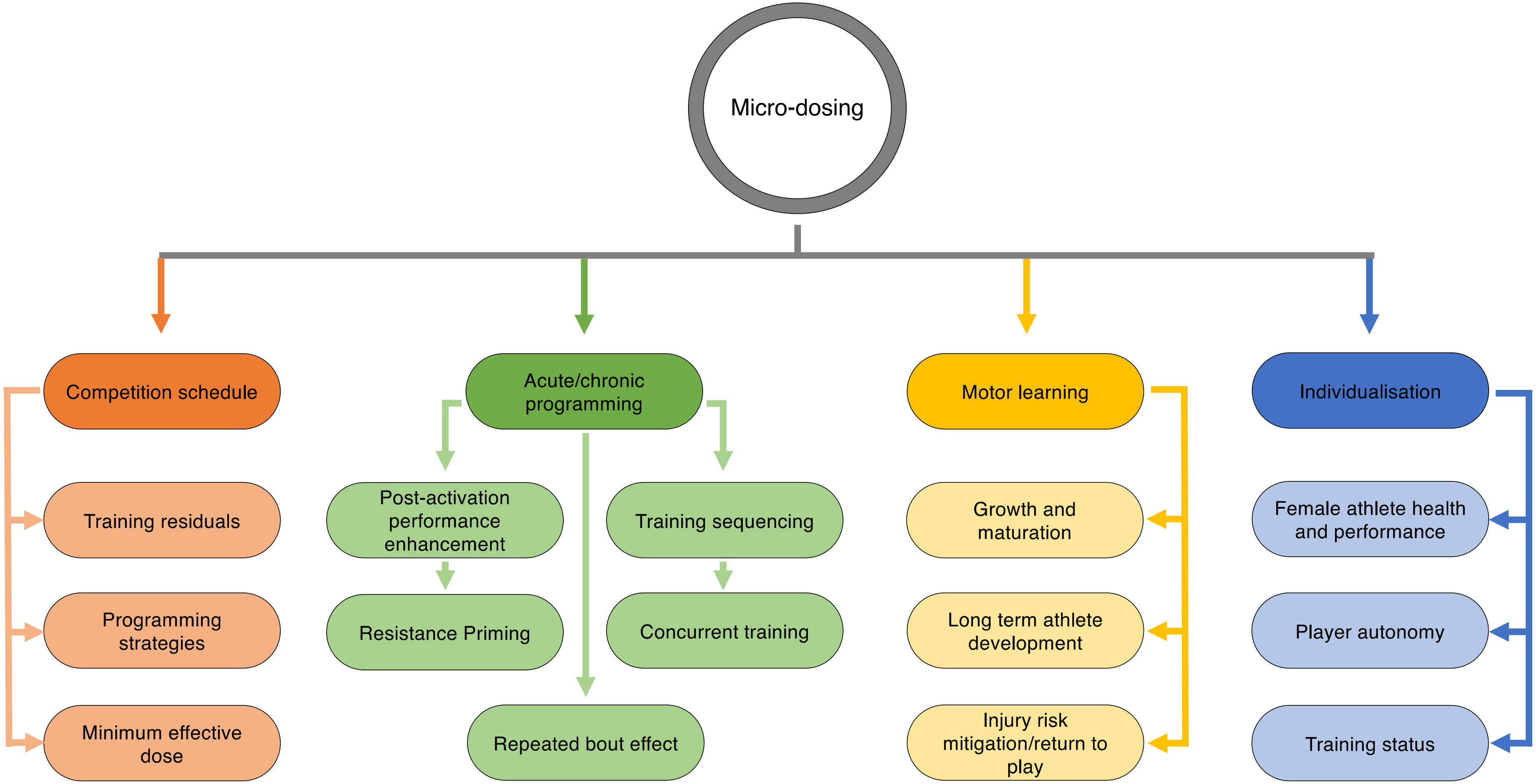


Figure 4.2. Illustration of key areas where micro-dosing resistance training may be advantageous.

4.3 Competition schedule

4.3.1 Training residuals

The residual effects of training, commonly referred to as “training residuals”, have been defined as the retention of positive physical changes following the cessation of training beyond a time period in which possible adaptations can take place [141]. Training residuals are therefore separate to any delayed training effect driven by supercompensation and are often contextualised as short-, medium-, and long-term responses [142]. Long-term residuals include ‘almost irreversible’ changes in the musculoskeletal and neuromuscular systems, such as coordinative abilities, movement skills and event-specific techniques whereby the rate of loss is several years. Medium-term residuals include those associated with the cardiovascular system such as increased capillary density, stroke volume and decreased resting heart rate, as well as neuromuscular changes such as effort regulation and force differentiation in which the rate of loss can be several months. Finally short-term residuals include increased maximal aerobic consumption and anaerobic thresholds, increased muscular strength, power, and endurance which may last for several weeks, but can also include anaerobic alactic, and glycolytic power, capacity, and efficiency which can decay in a few weeks or days (51). The rate of loss for all residuals is heavily dependent on an individuals’ training history and the volume and intensities of loading used prior to the cessation of training that targets specific foci.

The shorter-term training residuals are of primary importance for programming, especially when considering periods of competition or the use of a block ‘periodization’ approach where the focussed training of certain physical characteristics is omitted for predetermined period of time [143]. When designing periodized training programs there are a variety of competition schedules across a range of team sports, many of which have some form of in-season fixture congestion, particularly sports that are deemed as non-collision sports (e.g., soccer, basketball) (Table 4.1). There are several reasons some team sports have specific periods of in-season fixture congestion, for example, some European soccer teams will have multiple competitions running simultaneously, such as domestic leagues, domestic cup competitions and European cup competitions. Both National Basketball Association (NBA) and National Hockey League (NHL) teams play multiple games back-to-back (one night after the other) typically to reduce travel requirements. Another example is demonstrated in team sports such as baseball or rugby sevens whereby a ‘series’ is played over 2-3 days and multiple matches are played during these periods. Finally, international based tournaments, such as the World Cup in soccer and rugby, or even the Olympics for team sports such as field hockey and volleyball, also result in multiple fixtures in very quick succession with limited recovery time between each fixture.

Within short periods of fixture congestion where the duration of the congested period lasts the length of a microcycle or summated microcycle, fatigue management generally the primary priority (depending on the competition and time of the season). In contrast, international tournaments can last up to four weeks, however, as outlined by Issurin [144] within that time period the residual effects of some physical qualities such, as maximal speed, may diminish, if training targeting the development of this residual is not incorporated as part of the athlete’s training program. It is important to remember that training residuals are usually based on the complete cessation of training that targets a particular capacity, therefore competition may still provide some stimulus; however, based on the principle of specificity the magnitude of certain stimuli is likely to be below the level required to allow for maintenance, development or slowest decay (compared to opposition) of the training residual. Based on most periodization models, any period of competition is accompanied by a reduction of training volume and increase in intensity, which may result in the loss of specific training residuals. During periods of dense competition, resistance training volumes can be reduced even further to prioritise recovery, exacerbating the loss of training residuals. Micro-dosing resistance training as an approach during these periods of dense competition schedules may be a feasible option to maintain appropriate strength and/or power stimuli. This may be accomplished through dividing the training volume typically seen in a microcycle so that more frequent shorter duration training sessions are encountered. Alternatively, through the utilization of specific programming strategies, such as post-activation performance enhancement (PAPE) or resistance priming stimuli (see *resistance priming* below), the accumulated volume across the whole microcycle may be maintained whilst potentially inducing less fatigue compared with traditional approaches to programming in-season training. It is possible that a micro-dosed approach can provide a sufficient stimulus to maintain or perhaps improve physical qualities which typically deteriorate during periods of intensive competition (e.g., maximal speed [144]) due to ‘recovery’ being prioritised over the application of resistance training.

4.3.2 Programming strategies

There are various periods within certain team sports in-season where fixture congestion becomes prominent in the short term. On the other hand, the competition period for other team sports occurs over a prolonged duration (Table 4.1), with professional soccer, rugby, American football, basketball, and ice hockey all competing for large portions of the calendar year. In addition to a prolonged competitive season, a number of these team sports, including basketball and ice hockey (particularly in the NBA and NHL), are required to complete a competition schedule that is extremely dense/congested (Table 4.1). The requirement for sustained success throughout these prolonged periods is paramount to win championships or league titles. Sustaining a performance peak for prolonged periods of time is unrealistic due to the accumulation of fatigue and reductions in fitness, with these occurrences being a consistent argument as to why traditional periodization models (the transition from a high volume, low intensity general preparation phase into a specialized lower volume, higher intensity phase before leading into a competition phase) are ‘unsuitable’ for team sports [144]. It is, however, important to note that periodization is the macro-management of the training process [145] and serves as the scaffold for planning the direction of programming, making both periodization and programming two distinctly different concepts.

Table 4.1. Examples of fixture schedules in a range of team sports.

Sport	Standard/Level	Competition type	Competition/ season length	Number of games	Between game turnaround time	Length of post-season*	Number of post-season* games
American Football	Professional (NFL)	Season	18 weeks	17	4-7 days	5 weeks	3-4
Baseball	Professional (MLB)	Season/Series	~27 weeks	60	0-3 days	~5 weeks	26-43
Basketball	Professional (NBA)	Season	~26 weeks	82	0-3 days	10 weeks	4-28
Ice Hockey	Professional (NHL)	Season	~26 weeks	82	0-3 days	10 weeks	4-28
Field Hockey	Olympic Games	Tournament	2 weeks	10	0-2 days	-	-
Netball	Commonwealth Games	Tournament	10 days	6-7	0-3 days	-	-
Rugby Union	International	Tournament	~6 weeks	7	~7 days	-	-
	Domestic	Season	~40 weeks	~32-39	5-7 days	2 weeks	2
Rugby League	International	Tournament	~7 weeks	7	~7 days	-	-
	Domestic (Super League)	Season	~32 weeks	30-37	5-7 days	3 weeks	3
	Domestic (NRL)	Season	26 weeks	24	5-7 days	4 weeks	4
Rugby Sevens	International	Series	2 days	6	~3 hours	-	-
Soccer	International	Tournament	~31 days	≤ 7	4-6 days	-	-
	Domestic (EPL)	Season	~40 weeks	~38-62	3-7 days	-	-

NFL = National Football League; MLB = Major League Baseball; NBA = National Basketball Association; NHL = National Hockey League; NRL = National Rugby League; EPL = England Premier League

*Post-season in this instance describes a period of play-off games leading to and including either promotion deciders or championship games.

As Cunanan et al. [145] have highlighted, programming includes the manipulation of training variables (e.g., frequency, density, volume, load etc.) but also the use of various advanced programming strategies that can include phase potentiation [146], planned overreaching [147] and tapering [148]. On programming strategy that can be used in a periodised training plan is micro-dosing which can be applied as a standalone concept or in conjunction with several of these advanced programming strategies. For example, the use of concentrated volume loads (often termed planned overreaching [149]) that stimulates a delayed training effect, or specific training residuals can stimulate what is referred to as phase potentiation [145, 146, 150]. This concept is also aligned with the block periodization approach proposed by Issurin and Yessis [151], who referred to utilization of 'mini-blocks' to enhance specific training factors. These mini-blocks have been suggested as a strategy to prolong the residual effects of a preceding mesocycle, providing a form of micro-dosing [152].

Alternative to sequential models, emphasis periodization whereby multiple training factors such as strength, power and endurance can be included simultaneously but with varying emphasis within each mesocycle may be a more appropriate periodization strategy. Emphasis periodization models cycle between stimulating loads (those that will elicit adaptation) and maintenance loads, with the emphasis typically rotating every two weeks [153, 154]. Therefore, varying emphasis means that attributes being maintained require less dedicated training, which may be more appropriate for team sports [140, 155]. Micro-dosing may assist in the application of maintenance loads (e.g., power during a strength bias phase) which can be distributed throughout the microcycle (Figure 4.3), whilst the primary focus of the training phase (e.g., maximal strength) can be applied through longer duration sessions. In contrast, a micro-dosing approach may permit more frequent exposure to the training emphasis/bias of the phase (e.g., a power stimulus), for those foci that would benefit more from reduced fatigue accumulation (Figure 4.3). As D'Emanuele et al. [156] demonstrate, rapid force production is one of the most sensitive physical characteristics to fatigue and experiences the greatest depression following training and therefore may benefit from the decreased volume load per session as result of micro-dosing, as well as the increased frequency of stimulation to combat the short residuals associated with this characteristic.

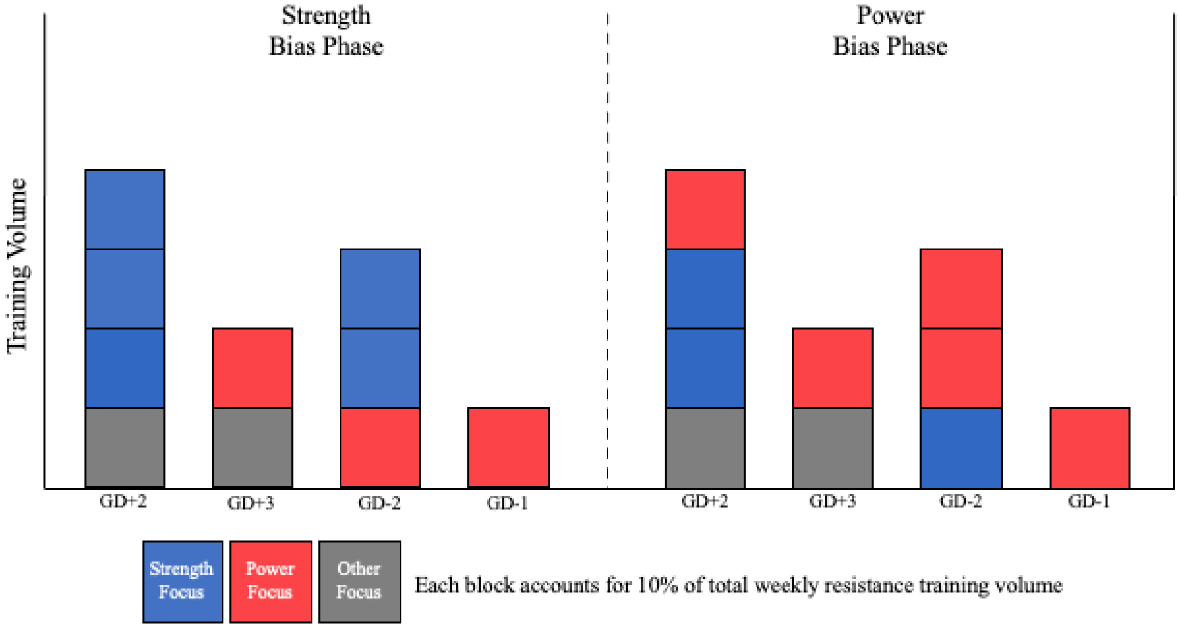


Figure 4.3. A schematic diagram illustrating an example of the distribution of resistance training volume and division of micro-dosing sessions for an in-season micro-cycle of either a strength bias or power bias.

GD = Game Day

When considering sports with both a prolonged season and dense fixture schedules, it may be more appropriate to use a combination of traditional sessions when time permits, to generate a concentrated stimulating load in a relatively short duration and integrate micro-dosed strength training sessions, where warranted, to provide an accumulation of volume without inducing excessive fatigue. This approach could be front loaded within a training week, whereby the longer duration (higher volume) sessions are performed furthest away from competition and the micro-dosing sessions performed much closer to competition to maximise recovery (Figure 4.3). Practitioners should be mindful that increased frequency of sessions may also increase monotony of training especially if suitable exercise variation is not provided.

4.3.3 Minimum effective dosing

The minimum effective dose is not synonymous with micro-dosing, as exercise prescription can be applied across a spectrum of minimum to maximum effective dosing (Figure 4.1). The utilisation of the minimum effective dose may be advantageous during periods of fixture congestion (as described in sections 4.3.1 and 4.3.2) to minimise training induced fatigue whilst maintaining physical characteristics. The length of time where the minimum effective dose is targeted with training will be heavily influenced by the presence of training residuals (section 4.3.1) and the athlete's current training status (section 4.6.3). A number of researchers have recently investigated the minimum effective dose for various populations with the view of preventing detraining [157], increasing strength [158, 159], or for hypertrophy [159]. The prescriptions outlined by Iversen et al. [159] suggests in order to improve maximal strength capacity, ≥ 4 sets per muscle group should be completed for a 4-6 repetition range at ~85% of one repetition maximum (RM) per week. Regardless of the sets, repetitions, and frequencies suggested in this research the authors concluded that working to volitional fatigue is required, which is impractical for in-season exercise prescription, particularly during dense competition schedules, and is not essential for the development of hypertrophy or strength [160, 161]. Knowledge of these loading paradigms may, however, provide guidance on the volume load (sets x repetitions x load) required for a minimum effective dose and how these loads can be divided throughout a microcycle. As suggested by Iversen et al [159], in a micro-dosed approach, without the need to induce additional fatigue by training to failure, as used in the aforementioned studies. Alternatively, guidance could also be provided for the reduction of a relative percentage of overall training for a minimum effective dose to be applied, for example Spiering et al. [162] suggested reductions in volume by 33-66% can be made whilst strength is maintained providing the load lifted remains high.

Rønnestad et al. [28] investigated the effect that frequency of strength training has on the in-season maintenance of strength and athletic performance in team sports. A comparison was made between a group performing strength training once per week and a group performing the same session once every two weeks. In effect, the latter group performed half the volume across the 12-week season. The group performing resistance training every second week demonstrated a decrease in maximal strength, while the group performing the same volume once every week maintained performance, demonstrating that once per week was the minimal effective dose for maintenance of strength over 12 weeks [28]. As an extension of this study, it may be interesting to determine if the same effect would be present had the groups' training volume been equated, with frequency remaining once per week vs once every two weeks, but whereby the more frequent group (i.e., once per week) micro-dosed the volume across the two weeks (e.g., halving the volume of each session). This of course requires further investigation; however, it may suggest that micro-dosing is not necessarily appropriate if already applying a minimum effective dose but could be used as a tool to increase the in-season volume or maintain a volume higher than that of a minimum effective dose in periods of dense competition schedules or fixture congestion (Figure 4.4). Either way, micro-dosing and minimum effective dosing are separate concepts, albeit that the minimum effective dose can be micro-dosed, despite authors of a recent commentary relating micro-dosing to minimal dosing [163]. The same authors also describe micro-dosing as 'old wine in a new bottle' directly comparing it to motor learning theory of distributed practice [163]. Whilst the authors of this current review do not disagree with the suggestion that micro-dosing is not a new concept, the links to motor learning will be outlined later in the review.

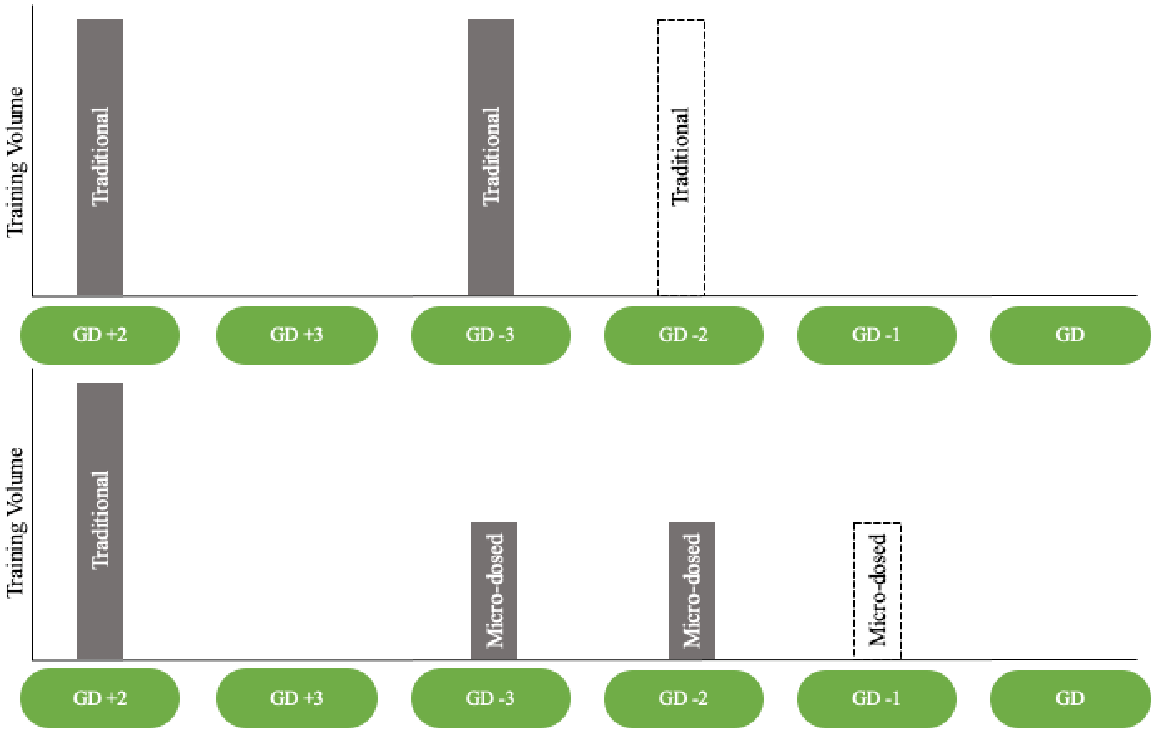


Figure 4.4. A schematic diagram illustrating a comparison of a traditional two-session resistance training week in-season, and an example a front-loaded training week whereby a higher volume, longer duration (traditional) session is performed furthest away from game day (GD) in conjunction with micro-dosed sessions closer to competition.

The dashed lines indicate the possible movement of sessions based on the configuration of rest days in a microcycle and not any additional sessions e.g., the sessions seen on GD-3 may be scheduled on either GD-2 or GD-1 for traditional or micro-dosing, respectively.

4.4 Acute/chronic programming

4.4.1 Post-activation performance enhancement

The definition of PAPE is the acute enhancements in voluntary dynamic force production after a bout (defined as a short period of intense activity) or conditioning activity (CA) typically viewed as a single prescribed exercise sometimes with as little as one set performed [164-166]. There are two ways in which the authors propose resistance training could be designed to take advantage of PAPE within a micro-dosing strategy. Firstly, dependent upon the configuration of a training day, it may be possible that the first bout of exercise is a high-intensity CA (e.g., 1 set of 3 repetitions at ~90% 1RM [167]) whereby the subsequent PAPE effect could increase the intensity of the first few actions of the following technical training session (e.g., sprint training [167]) or resistance training session [168] (Figure 4.5). Secondly, a micro-dosing session may be constructed of just two exercises as a contrast set/session (as will be highlighted in section 4.4.4), whereby the time-course in between the CA and the subsequent exercise (e.g., jumping, or plyometric task) is long enough (i.e., 3-12 mins, dependent on training status) to elicit a PAPE effect. The second option is likely to be more feasible and can be applied more frequently throughout a microcycle, with the accumulative volume of multiple CAs in addition to other micro-dosed sessions creating the overall microcycle dose.

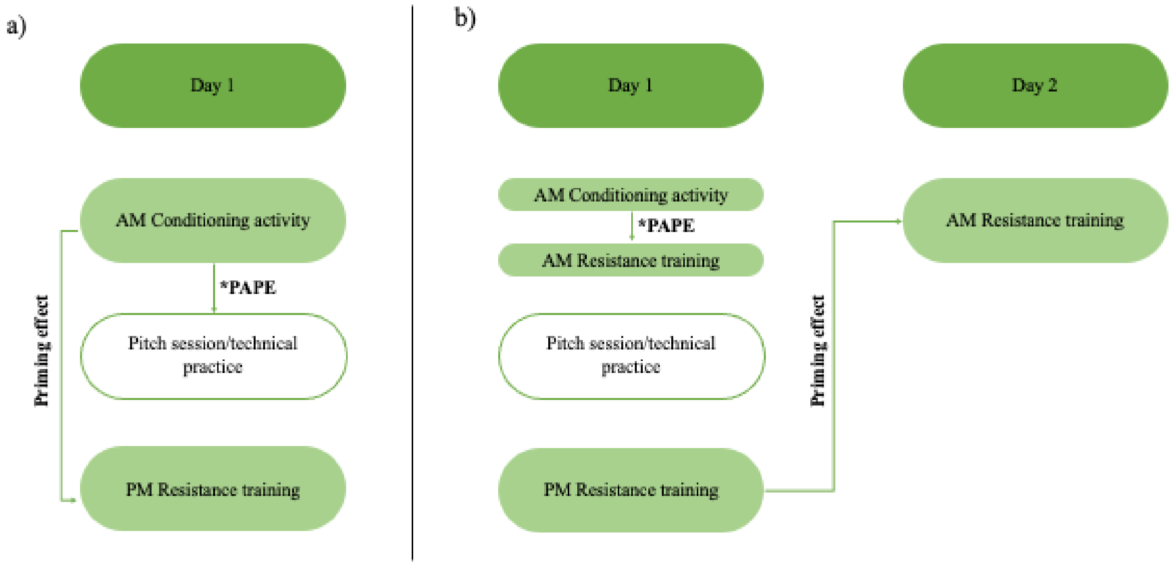


Figure 4.5. An example of two different session configurations across (a) one and (b) two days to take advantage of both post-activation performance enhancement and priming effects.

**PAPE – Post-activation performance enhancement. In this instance performance enhancement is most likely to influence the first couple of actions in the subsequent pitch session/technical practice or resistance training session.*

Prior to their being a distinction between the term PAPE and 'post-activation potentiation' (PAP) (defined as the increase in force/torque following an electrically evoked twitch contraction, rather than a voluntary contraction), PAP was used as an umbrella term for both. Although the two approaches share some similarities including enhanced contractile force, a delay in observed benefits of potentiation and a greater response in muscles with a large proportion of fast-twitch fibres, the time-course of benefits, from both PAP and PAPE, on force production and other underpinning mechanisms (myosin regulatory light chain phosphorylation compared to muscle temperature, water content and activation) differ largely, making them two distinctly different approaches [164]. For a more detailed discussion on the differences between PAP and PAPE see reviews by Blazevich and Baubault [164], and Prieske et al. [165]. In this section reference will be made to PAPE rather than PAP, regardless of the terminology used in the original articles.

There is currently no consensus on the underpinning mechanisms that provides a PAPE effect following a specific CA, with a combination of mechanisms likely providing the enhancement of performance (28,29). The proposed mechanisms span three areas: neural, mechanical, and cellular. More specifically these potential mechanisms are likely related to increased calcium ion (Ca^{2+}) sensitivity, muscle-tendon stiffness, and increased muscle temperatures [164]. It is, however, generally considered that the time-course of PAPE following a CA occurs within a window of 3-10 minutes but may also last > 15 minutes in some scenarios [164, 169]. Although this seems like a large window it is important to highlight that the recovery duration, whereby fatigue following the CA diminishes but the 'potentiation' effect remains (Figure 4.6a), can demonstrate large inter-individual variation as a result of a number of factors including training experience, strength level and myotypology [164]. This phenomenon has previously been contextualised as an acute version of the traditional fitness-fatigue paradigm (supercompensation [Figure 4.6c]) [170].

An overview of PAPE related studies that utilise a range of CAs (e.g., free weight exercises, resisted sprints, variable resistance exercises, isometric tasks and plyometrics) and their effect on a variety of different performance measures has been provided in a comprehensive review by Ng et al. [166]. Interestingly the magnitude of PAPE effects in stronger individuals may be comparable to the improvements observed following an entire phase of training (e.g., 4-week mesocycle) in stronger individuals. Even though most CAs result in small acute effects, it is important to consider that in stronger individuals, consistent increases in "intensity" via PAPE may result in a sufficient stimulus for greater chronic adaptation [171]. This may be of greater importance in well-trained individuals, as chronic adaptations to training have been reported to be smaller compared to untrained individuals [172]. In contrast, the time-course for manifestation of PAPE is longer for weaker individuals and therefore may not be realistic to permit a sufficient training stimulus to elicit a chronic adaptation, and greater focus should be spent increasing the underpinning capacities (i.e., strength) before utilising PAPE. With that in mind such practices may be more applicable for individuals of ≥ 3 years training experience as the period between CA and PAPE is shorter (~3-7 minutes) than individuals with ~1 year of resistance training (~7-10 minutes) [169]. These observations are likely due to greater relative strength in individuals with a longer training history/experience, in line with previous recommendations regarding greater and more rapid potentiation in stronger individuals [173].

The PAPE approach may be beneficial to those with a higher training status, particularly during periods of training that are either focused on the development of power (providing overall training volume does not diminish), when PAPE is not the only stimulus provided in a training week or when athletes are utilising a tapering strategy. The PAPE approach may, however, be limited or less effective with individuals of a lower training age [174, 175] whereby greater improvements will likely be observed from other approaches focused on developing the amount of force they can produce rather than trying to enhance the rate at which they produce it [88]. Micro-dosing of PAPE stimuli may, therefore, be more appropriate for those of a greater training status [169, 173], in conjunction with other resistance training sessions. Those athletes of a lower training age should utilise micro-dosing in other ways to benefit in-season resistance training without focusing on trying to induce a PAPE effect.

4.4.2 Resistance priming

'Resistance' priming, occasionally referred to as delayed potentiation, is the enhancement of neuromuscular performance following a low-volume strength (e.g., squat, 3 sets, 3 repetitions, ≥ 85% 1RM) or power (e.g., jump squats, 3-4 sets, 5 repetitions, 30-40% 1RM) CA that manifests beyond the window traditionally associated with PAPE. For example, the beneficial effects of priming have been reported to occur for periods of time lasting 6-48 hrs after the completion of the priming activity [176]. Due to the time-course of enhanced performance, adopting a micro-dosing approach with appropriate volumes and intensities will likely elicit a priming response and provide some benefit during subsequent resistance, skill-based or technical training session. In some cases, this may be between sessions during a single day, particularly in some environments where training might be split into morning and evening, or otherwise the priming effect is likely to benefit training on subsequent days (Figure 4.5). Provided the priming stimuli are repeated throughout the microcycle, as mentioned within the previous section (4.4.1), the cumulative volume can equal the planned training prescription of a more traditional approach to resistance training, in line with the definition of micro-dosing [133]. Repeatedly utilising a priming effect may also increase the intensity in which that prescribed volume is executed.

Theoretically resistance priming is a more chronic form of PAPE and acute representation of the traditional fitness-fatigue paradigm (Figure 4.6), although the underpinning mechanisms may differ to that previously described for PAPE. With the greater time-course for positive effect and dissipation (hours compared to minutes), some mechanisms such as muscle temperature and high-frequency motor neuron activation are unlikely to have an effect across a period of 48 hrs. It has also been hypothesised that acute changes in architecture and water content can contribute to an increased ability for 'muscle gearing' (see Van Hooren and Bosch [177]) which could result in an acute enhancing effect for resistance priming. Although this has predominately been demonstrated in animals, Dick and Wakeling [178] have provided a comprehensive set of in vivo data which support theorised mechanisms of muscle gearing in human subjects. There is, however, a lack of research directly examining potential mechanisms of resistance priming over the course of a 48-hr period following a CA.

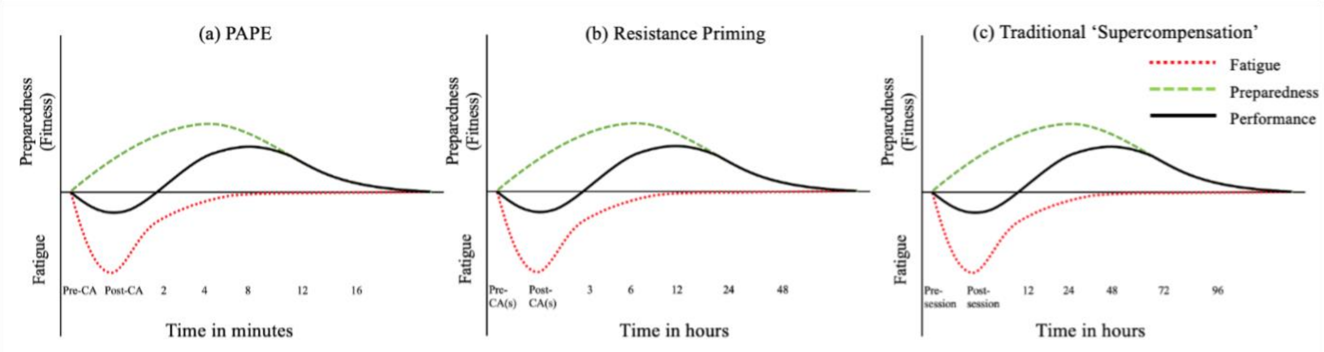


Figure 4.6. A comparison of the time-course of the fitness-fatigue paradigm following post-activation performance enhancement (PAPE), resistance priming and traditional supercompensation conditioning activities.

CA = Conditioning activity; CA(s) = Conditioning activity of multiple sets/a small number of high load, low volume conditioning activities.

Resistance priming strategies are typically implemented prior to competition to improve subsequent sporting performance [176]. The prevalence of resistance priming in a pre-competition period (most frequently within an 8-hour window) has been reported to be evident across a range of different sports, the majority being multi-directional team sports [179]. Both resistance priming and PAPE have been assessed using an outcome measure of neuromuscular performance, such as a ballistic jump, plyometric exercise, sprint, or maximum voluntary contraction. Although a resistance priming effect has been demonstrated in the outcome measures mentioned, the increases in performance may be limited to the action and number of repetitions being measured. For example, Russell et al. [180] demonstrated a priming effect in a repeated sprint protocol, however, the enhancement in performance dissipated after two sprints (out of a total of six). The dissipation of performance enhancement highlights the suitability of resistance priming on competition in strength-power sports whereby a low number of actions are completed typically with long rest periods. The authors are not suggesting that the approach is unsuitable for that of team sports, however, due to the chaotic nature, and the potential interference from aerobic stimuli, resistance priming is unlikely to benefit athletes across a whole fixture. In contrast, it may be worth considering micro-dosing resistance training in appropriate volumes that will elicit a regular resistance priming response that increases the intensity of work in subsequent training sessions/days, rather than influencing match performance. In combination with the PAPE approach described above, the micro-dosing of training volume through both resistance priming and PAPE may provide consistent enhancements in training “intensity” whilst also providing an accumulation of training volume that may allow for continued development to chronic adaptations (Figure 4.7).

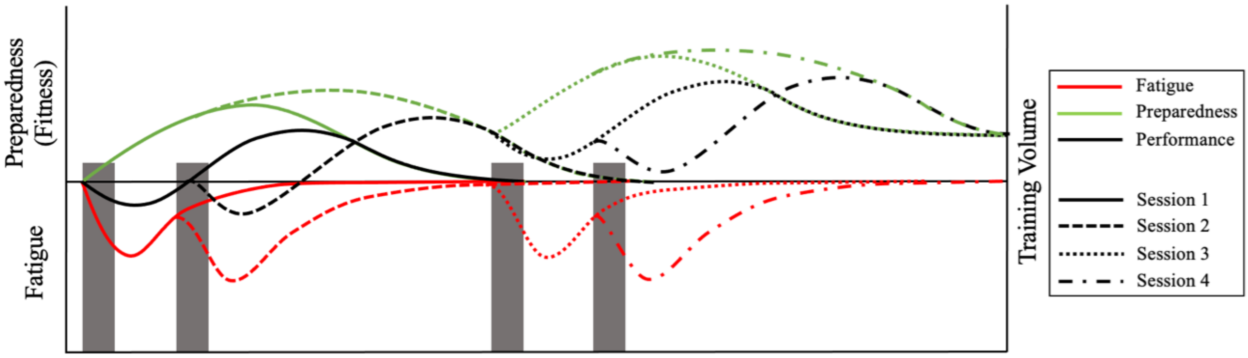


Figure 4.7. An example of the use of resistance priming on the fitness-fatigue paradigm and the theoretical benefit on increased preparedness and performance.

4.4.3 Repeated bout effect

The repeated bout effect (RBE), predominantly but not exclusively observed as a result of eccentric exercise, is a phenomenon whereby the muscle damage and subsequent symptoms caused by an initial bout of unfamiliar exercise becomes minimal when the same bout is repeated following a period of recovery [181]. Initial symptoms include loss of muscle force production characteristics, range of motion, increase in muscle proteins in the blood and development of muscle soreness that are detrimental to performance [182-184]. Although it may not be possible to completely eradicate the initial symptoms associated with the introduction of a novel stimuli, it may be possible to reduce them through micro-dosing. This approach, as discussed in section 4.3.2, is observed during emphasis periodisation approaches as all physical components are performed simultaneously which means that when the emphasis changes, the “system stiffness” associated with the change in training focus, is reduced [185]. Dividing the volume of unfamiliar and/or eccentric bias stimuli may allow for the magnitude of disruption caused to be considerably lower, whilst still providing the protective characteristics of the repeated bout effect required to increase the volumes at a later point within a training cycle [186]. As such, a new or novel stimuli may be micro-dosed when first introduced and then implemented in a traditional format allowing the smooth transition between vertically integrated and horizontally sequenced mesocycles [187, 188].

Although the initial symptoms described previously are predominantly observed following eccentric exercises, they also occur in response to concentric, concentric and eccentric combined, and isometric muscle actions and are occasionally referred to as “exercised-induced muscle damage”. Exercised-induced muscle damage has been reported to acutely affect glucose metabolism, namely decreased glucose uptake and insulin sensitivity that impairs glucose synthesis [189]. Such changes in glucose metabolism may also be detrimental to performance during periods of fixture congestion (see section 4.3). While the RBE has been demonstrated to provide a protective effect upon a subsequent bout of exercise, this does not necessarily remain task specific, whereby the protective effect only applies to the task that induced the RBE, but with specificity of the muscle group and action required. An example of this could be the eccentric action of the hamstrings during a Nordic hamstring exercise which could subsequently provide protection of an eccentric action during sprinting [190]. Although the evidence of the Nordic hamstring exercise protecting against injury is equivocal [191], appropriate prescription may provide enough of a protective effect to reduce the magnitude of exercise induced muscle damage.

Within group responses to eccentric bouts become more homogenous following the initial exposure [186, 192], which may be advantageous when working within a setting whereby individualisation is more challenging (see section 4.6). Despite many RBE protocols utilising high doses of eccentric actions (e.g., 5 sets of 10 repetitions [119]), Nosaka et al. [186] have demonstrated that performing 24 eccentric repetitions, compared to 6 eccentric repetitions, had no greater protective effect when a subsequent 24 eccentric repetitions were performed two weeks later (whereby plasma creatine kinase activity and myoglobin concentration were not significantly greater in either group), highlighting the benefits of low doses of an eccentric stimulus. Within the same study a group performed 2 eccentric repetitions which demonstrated a partial but significant protective effect, whilst producing far less damage in the initial bout. Whilst a significant protective effect has been demonstrated following a single eccentric bout, Hody et al. [184] have also described observations of a greater protective effect following several sessions. Based upon these findings, utilising a micro-dosing strategy when introducing an unfamiliar or eccentric stimulus could minimise fatigue and exercise-induced muscle damage following the initial bout, while also providing a protective effect for subsequent bouts of exercise. Following these initial micro-doses, gradual increases in volume can be prescribed without inducing the same level of muscle damage that would occur without the protection provided by the RBE. Appropriate introduction of unfamiliar stimuli in-season is essential to reduce or negate some of the negative effects (actual or perceptual) on performance. Considering the study conducted by Nosaka et al. [186], the micro-dosing strategy can be applied to eccentric exercises whereby the total volume equates to the larger volumes of ≥ 6 repetitions but divided into smaller doses across a week (e.g., 15 repetitions once per week vs 5 repetitions 3 times per week). This example may allow the manifestation of a greater RBE while minimising symptoms that are detrimental to performance.

4.4.4 Training sequencing

The principles of training sequencing, be that acutely (i.e., within-session), chronically (i.e., between mesocycle), or anywhere within that continuum, appear to be consistent but with differing terminology. For example, Marshall et al. [171] reviewed acute training sequencing, investigating both the acute responses as well as the chronic responses from acute strategies (sequencing of sets and exercises) such as contrast and complex training. When considering contrast and complex training further along the acute-chronic continuum, parallels can be drawn to the principles of PAPE and priming as described in the sections prior to this when looking at the sequencing of training sessions. Even further along the continuum, with the sequencing of microcycles, approaches such as a conjugated successive system and weekly undulations in training volume (as opposed to load where the focus on developing a specific physical capacity varies each week) can also be compared to that of complex and contrast training, respectively (see Figure 4.8).

Another sequencing method highlighted by Marshall et al. [171] is cluster training. Cluster training is a global term for a number of different set structures that include basic cluster sets, equal work-to-rest ratio and the rest pause method, and is defined as a set structure that includes the normal inter-set rest periods but involves pre-planned rest intervals within the set [193]. When performing traditional sets, movement velocity and therefore power output, tend to decline as more repetitions are performed [194]. Cluster training facilitates superior maintenance of repetition velocity and power output, whilst also allowing for the potential to perform a greater number of repetitions, increased loads, or a combination of the two through minimising the effect of accumulated fatigue per 'bout' [195, 196]. All variations highlighted as a form of cluster training on an acute scale (i.e., within-set) can also be applied in principle on a chronic scale, as micro-dosing (Figure 4.9). If the division of volume across a microcycle allows for superior maintenance of movement velocity and power, or even increased load (suggested above by [195, 196]), as with cluster training it would be theorised that greater improvements in strength and power may be achieved chronically when compared to a traditional approach. Häkkinen and Kallinen [197] demonstrated that the division of resistance training volume into 2 daily sessions over a 3-week period significantly improved strength in female athletes. Further evidence of this strategy providing faster recovery responses and higher training intensities has also been outlined by Bartolomei [198] with a 4 hour rest period between sessions.

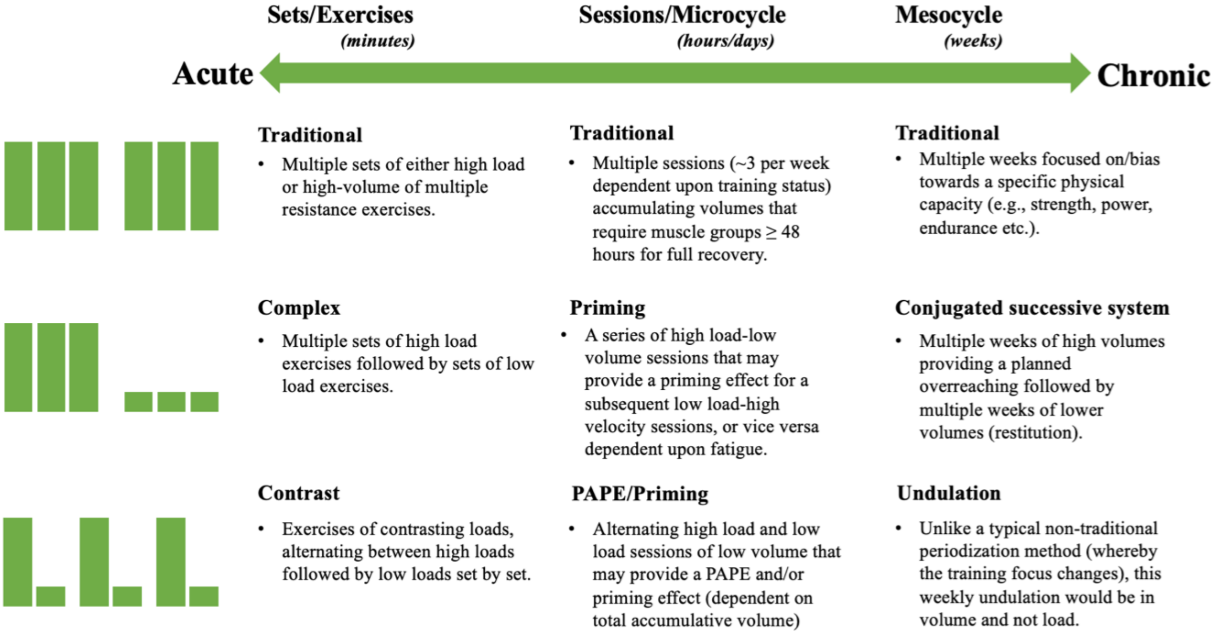


Figure 4.8. A comparison of terminology used for different set, session, microcyle and mesocyles across the acute-chronic continuum.

When considering micro-dosing, the pre-planned rest periods may vary (much like in cluster training) dependent upon the chosen variation, to gain the benefits discussed within the PAPE and resistance priming sections, highlighting the links demonstrated in Figure 4.8. Variations in volume per session is also likely to occur in order to best exploit possible PAPE, resistance priming effects and even a RBE, with the definition of micro-dosing provided by Cuthbert et al. (section 3.3.5 [133]) as frequent, short duration, repeated bouts and not that these bouts are required to be equal. This approach may also allow for reduced volumes closer to match-day as highlighted in section 4.3.2. Providing that the entire training volume prescribed is completed, findings from a recent systematic review and meta-analyses demonstrates that higher training frequencies do not negatively impact strength adaptations providing volume is equated [133]. The use of micro-dosing, however, in a variety of sequences (e.g., complex, contrast, PAPE or priming) may allow for the enhancement of various training stimuli to allow for a greater training response because of reduced amounts of fatigue following each session as highlighted in section 4.3.2.

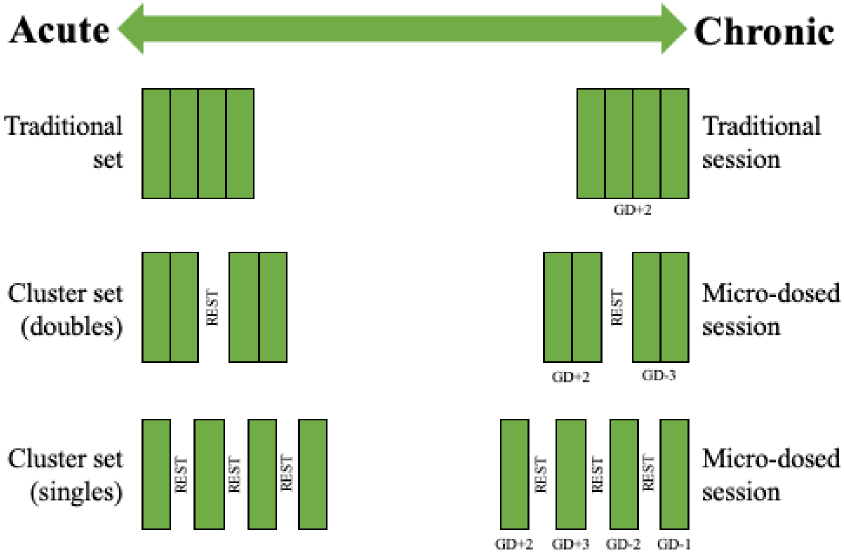


Figure 4.9. A comparison of the structure of cluster training and micro-dosing and where they fit across the acute-chronic continuum.

GD = Game Day

4.4.5 Concurrent training

Concurrent training is the combination of resistance training and aerobic exercise in a single program/training cycle, and is observed particularly in multidirectional team sports, due to the importance of developing aerobic fitness congruently with strength and power, particularly in-season [129]. Concurrent performance of aerobic and resistance training has been suggested to create an ‘interference phenomenon’ or ‘interference effect’ where adaptations to resistance training are compromised due to either excess fatigue, a greater catabolic state, differences in motor unit recruitment patterns or possible conflicts in fibre type shifts [199, 200], and inhibition of the mTOR pathway [129]. The potential benefit of micro-dosing during unavoidable concurrent training could be the increase in number of exposures to strength/power stimulus which may reduce the inhibition of mTOR pathways (although the evidence of this in human populations is equivocal [201]) and emphasise motor unit recruitment and fibre types towards the desired adaptations. The reduction in session volume (but not total volume) observed in micro-dosing may also combat the compromises of excess fatigue, as energy depletion has been described as a contributing to the impairment of the mTOR signal pathway mentioned previously [129].

Vechin et al. [202] have presented an updated model of the interference effect which describes how interference between aerobic and resistance training can be reduced or negated through the use of high intensity interval training (HIIT), in line with previous findings regarding the beneficial effects of HIIT in minimising an ‘interference effect’ [203]. The HIIT protocols are based upon work by Buchheit and Laursen [204] who refer to velocity at maximal oxygen consumption ($v\dot{V}O_2$ max), which is referred to as maximal aerobic speed when completed in the field rather than in a laboratory setting. The protocols include long duration (> 60 s, ~90-110% $v\dot{V}O_2$ max), short duration (< 60 s, ~110-130% $v\dot{V}O_2$ max), repeated-sprint (3-10 s, ~140-170% $v\dot{V}O_2$ max) and sprint interval (30-40 s, > 170% $v\dot{V}O_2$ max). The suggestion based upon the interference model is that long duration HIIT sits within an ‘interference zone’ due to conflicting peripheral adaptations, particularly when little to no recovery is given between the HIIT protocol and resistance training. Long duration HIIT, being within the interference zone, may lead practitioners to assume that small-sided games and associated technical drills are encompassed within that category, as they are typically 3-5 minutes in duration. It is important to understand, however, that although different for each individual, within the 3–5-minute duration, there will be multiple short duration high intensity efforts (e.g., accelerations and decelerations) with periods of active rest in between. A duration ≥ 6 hrs, however, has been demonstrated to negate this conflict in a study that investigated 0 hrs, 6 hrs and 24 hrs [205], meaning the duration required could be less but further research would need to be conducted to demonstrate this. Vechin et al. [202] have also suggested that short duration HIIT may be included within a ‘slight interference zone’, but further research needs to be conducted to affirm that statement. The other two protocols would be recommended if the interference effect is required to be completely avoided.

The interference effect has been reported mainly in relation to strength and hypertrophy bias training due to an apparent lack of data around power training. In contrast to this view, however, Wilson et al. [129] concluded in a meta-analysis investigating concurrent training studies that power is the major variable affected by concurrent training. The conclusions in an updated meta-analysis [206] published recently concurs with the findings of Wilson et al. [129], suggesting that “combining aerobic and strength training in close proximity attenuates adaptations in explosive strength regardless of exercise order”. The attenuation of explosive strength in season is problematic as most sports require rapid force production for efficient acceleration/deceleration type actions and there is therefore a need to develop this quality throughout the season. It has also been concluded that there is little to no interference effect on maximal strength [206]. When considering implementing a micro-dosing strategy, if an athlete requires additional long duration aerobic stimuli, it is likely to be more beneficial to schedule those on days where there is a greater strength training stimulus. An example of this can be observed in Figure 4.3, whereby the aerobic stimulus could be added on matchday (MD) +2 and MD-2 (match day may be referred to as game day in some sports) during the strength bias phase to allow isolation of the power stimulus. In terms of a power bias phase, micro-dosing could assist in alleviating some of the interference effect, allowing the potential for a greater rest period between the resistance training and additional aerobic work due to the reduction in session duration.

4.5 Motor learning

Increased frequency of a stimuli with appropriate rest intervals, as induced via a micro-dosing approach, is the primary theme throughout this section (4.5), similar to the concept of distributed learning over time or “the spacing effect” whereby better learning and retention of skilled tasks is achieved compared to “massed” practice [163, 207]. Based on a long term athlete development (LTAD) perspective Moody et al. [208] have recommended 2-3 structured integrated neuromuscular training sessions to allow recovery and prevent disinterest from over exposure to formalised training, however, some of these effects may be related to the lack of variation in the application of stimuli. We propose that this could potentially go further than just 2-3 structured sessions for numerous reasons including attention retention, regularity of feedback and skill recall.

4.5.1 Growth and maturation

Although both growth and maturation and LTAD typically go hand in hand, the authors want to highlight that LTAD should span the whole journey that an athlete needs to navigate. Growth and maturation should therefore be viewed as an important part of the journey that needs greater appreciation and emphasis on motor learning during the period of childhood through to adolescence due to interferences in motor skill execution [209]. The use of micro-dosing during these important periods could provide a solution to enhance motor learning, by increasing the frequency of motor skill development and therefore increase the opportunities and availability of feedback which has been demonstrated to aid both performance and learning [210] without simultaneously increasing the total volume. Unfortunately, it is common that when frequency increases, so does the volume. An example can be observed in a recent 6-month intervention investigating the effect of neuromuscular training frequencies on motor skill competencies, strength and power in male youth [211]. Within the intervention, a group performing two sessions per week (one gym-based and one pitch-based) were compared to a group performing one session per week (pitch-based), which, in effect, doubled the weekly volume and did not truly investigate the frequency of exposures as the title suggests [211]. With the same total volume load across a microcycle being maintained through micro-dosing, there would be a reduction in daily volume load which is sometimes necessary during this stage of development as we discuss below.

Within the National Strength and Conditioning Association's LTAD position stand, growth is clearly defined as the increase in the size attained by specific parts of the body, or alternatively the body as a whole [212]. Growth has also been described as non-linear in nature, with periods of rapid growth development interspersed with periods of plateau [213]. One problem typically experienced approximately six months prior to an adolescents' "peak height velocity" (the maximum rate of growth in stature) is a phenomenon known as "adolescent awkwardness" [214]. Adolescent awkwardness is the temporary disruption of basic motor skills execution because of a growth spurt rather than any training induced performance decrements. Although the recommendation has been made to modify training volume loads during this phase of rapid skeletal growth, to avoid excessive loading, there also needs to be ample opportunity provided for individuals to relearn motor skills and reintroduce some physical literacy to limit the potential for injuries due to technical deficiencies [209].

The definition provided for maturation is progression toward a mature state which varies in timing, tempo and magnitude dependent upon the different biological systems (i.e., skeletal or sexual) [212]. Lloyd et al. [209] have highlighted the importance of assessing biological maturity, particularly when considering appropriate exercise prescription in order to provide performance benefits that are greater than the expected natural development. For instance, prior to puberty the primary mechanism underlying improvements in muscular strength and related characteristics is through neural adaptations [215]. Myer et al. [216] have summarised how the formulation and fine tuning of specific skills during childhood corresponds with the high degree of plasticity in neuromuscular function and brain development via synaptic pruning, in which critical subsystems (cognitive, sensory, emotional, perceptual, and motor control) are developing optimally. Considering that increases in strength during childhood are typically neurological, training prescription should be focused on higher relative loads with ‘mean intensity (% of 1RM)’ being highlighted as demonstrating a significantly positive correlation with gains in motor performance skills in a meta-analysis by Behringer et al. [217]. Micro-dosing may not only allow for increased frequency of sessions whilst maintaining acceptable volumes, but due to the subsequent reduction in duration, micro-dosing may also allow for smaller groups and therefore a higher supervision ratio. Particularly during childhood whereby regular constructive feedback is required, working with smaller groups more frequently may provide greater opportunities for feedback, with Gentil and Bottaro [218] demonstrating greater strength increases in both upper and lower-body muscles under a high supervision ratio (1:5) compared to low (1:25).

Following the onset of puberty and typically after peak height velocity, improvements in strength are not only attributable to neurological changes but also structural and architectural (increases in muscle cross-sectional area and pennation angle) [219]. The structural and architectural development in skeletal muscle occurs due to rapidly increased circulating testosterone and growth hormone [220]. At this point it is thought that strength training (the focus during pre-adolescence) can begin to be interspersed with bouts of hypertrophy-based training to maintain increases in both strength and overall performance [221]. During these bouts of hypertrophy-based training, micro-dosing may not necessarily be appropriate. Considering that hypertrophy is predominately driven by volume, traditional resistance training sessions may end up being more suitable, particularly for large groups of athletes and bearing in mind age-related commitments in terms of education and potential participation in several sports. It is, however, worth considering that much like cluster-training (see section 4.4.4), micro-dosing can be an opportunity to use high loads, considered optimal for increasing strength, whilst also incurring hypertrophic effects.

4.5.2 Long term athlete development

Long term athlete development has been defined as the habitual development of health and fitness characteristics that contribute to enhanced physical performance, reduction of injury risk, and improvement of overall “athleticism” [212]. Proposed LTAD models have typically been outlined for youth populations [221], focussing on the development of three key fundamental movement skills (FMS); (i) locomotion, (ii) stabilization, and (iii) manipulation, in conjunction with phased and integrated strength and power development where appropriate. More recently, Radnor et al. [222] expanded the FMS concept, outlining the use of athletic motor skill competencies, which breaks the three FMS categories into eight, more specific skills. Regardless of the model used, effective motor skill execution, governed by the combination of efficient cognitive processing, movement patterns and force production, is paramount [208]. Although covered in greater detail in the previous section, one of the reasons that the LTAD models typically focus on the youth populations is that older populations are less susceptible to learning new motor skills due to the non-linear reduction of grey matter in the brain [223]. As a result, high frequency exposure to motor learning is not commonly utilised to develop and refine skilled movements applied in resistance training; however, micro-dosing may provide more focused and frequent opportunities to enhance motor learning during such tasks [224].

Once athletes reach the end of adolescence (~20 and 21 years for females and males, respectively), they are typically within professional or elite environments, however, this should not be the end of their LTAD. In the authors' opinion, a focus on LTAD should remain an integral part of the athlete's development across their entire athletic career. The LTAD model highlighted previously [221] does give a general indication of focus for adulthood (21+ years) which of course differs from the bias towards the motor skill competencies described for children and adolescents (section 4.5.1). There is a requirement for adults to constantly refine movement patterns to move towards mastery. The refinement may be to master skills specific to their sport, it could be mastery of exercises that elicit improvements in the underpinning physical capacities for those sport specific skills, or potentially skills that aid in the transfer between the two. Micro-dosing of resistance training may provide solutions for the development of physical capacities and potential enhancement of adaptation in comparison to traditional methods as described in previous sections. There is an argument that for the most part this can be achieved with the range of movements associated with the earlier stages of LTAD (e.g., squat, lunge, hinge, jumping, landing etc.) as athletes become masterful of these foundation movements, more complex tasks are required to further challenge learning. There are also certain circumstances throughout a career, such as injury, that may require adjustment to a previously developed motor skill or to rebuild the physical capacities, much like with untrained individuals, without incurring too much fatigue.

Another benefit to micro-dosing is the increased frequency of feedback, through dividing resistance training volume throughout a week, athletes will gain a greater number of opportunities to receive feedback be that intrinsic or extrinsic. As described in section 4.5.1, micro-dosing can also aid in reducing the coach to athlete ratio which means those who benefit from greater extrinsic feedback may also benefit in this instance. In addition, whether athletes are within a full-time organisation or not, there will be an increased demand on their time, be that other departments (e.g., technical/tactical), media commitments or life outside of their sporting environment, which may mean that the utilization of micro-dosing (i.e., an increased frequency, but more importantly reduced duration of sessions) could also benefit the required motor learning as this approach may aid greater compliance to the prescribed protocols.

4.5.3 Injury risk mitigation/return to play

Typically, injury risk mitigation and return to play are viewed as entirely different entities, however, principally they both aim to stimulate positive adaptations to musculoskeletal structures (e.g., muscle cross-sectional area, pennation angle, fascicle length etc.) and increased neuromuscular control [225]. For those practitioners who separate injury risk mitigation (or "prevention") stimulus into a separate category of training, the definition provided for micro-dosing simply mention the division of total volume, so that could be considered as total volume of a planned dose of whatever stimuli has been planned for. In this regard, if a traditional approach to resistance training is appropriate, micro-dosing can still be of benefit when it comes to accessory stimuli that comes under an injury risk mitigation banner. Herrington [226] has demonstrated this approach with regular, short duration progressive jump-training that produce positive benefits in terms of injury risk mitigation via improved motor control. Micro-dosing in this instance may therefore provide more opportunities for motor learning, much like sections 4.5.1 and 4.5.2 but also allow a greater amount of time either for other sessions, such as traditional resistance sessions, or for recovery between sessions/training days. A form of injury risk mitigation has also been covered in section 4.4.3 where the micro-dosing of unfamiliar or novel stimuli will provide an acute protection from similar stimulus following a period of recovery through the RBE. The micro-dosing of the RBE could also benefit return to play protocols with the introduction of new exercises but also some exercises executed during return to play are potentially atypical of those usually completed by athletes prior to injury, and therefore will be a novel stimulus.

In terms of return to play, Taberner et al. [227] have outlined a process for rehabilitation described as the 'control-chaos continuum', with that there is a progression from highly controlled and structured actions/behaviours/movements all the way to highly chaotic and unpredictable actions/behaviours/movements that appear to be both random and reactive. Although originally proposed for pitch-based protocols, resistance training can provide stimuli towards one end of the continuum that is highly controlled in nature and directly translates to the increased capacity of tissues required to produce or tolerate the forces required during chaotic and unplanned situations described by Dos'Santos et al. [228]. One reason for applying a micro-dosing approach in a return to play/rehabilitation situation would be to allow the doses of highly controlled but potentially fatiguing actions to be divided in a way that the fatigue levels during the highly chaotic actions are lower than if they were to follow a larger volume of controlled work. This in turn will allow exercises to be performed across the full spectrum throughout each microcycle when at an appropriate stage of an athletes return to play.

4.6 Individualisation

4.6.1 Female athlete health and performance

The authors believe it is important to recognise that there is much more to female athlete health and performance than the menstrual cycle and also understand the current disparity in current sports science literature [229]. There may therefore be numerous other areas to explore from a female athlete health perspective in relation to micro-dosing particularly when considering some of the points from section 4.0 regarding motor learning. We have, however, focussed our attention on the implications of the menstrual cycle on training in this section, due to the high variation in duration of the menstrual cycle and associated phases, severity/presence of physical symptoms, and psycho-social experiences between individuals and therefore potential requirement for individualisation of training [230]. Although a recent systematic review and meta-analyses presented a trivial effect of the menstrual cycle on performance, no general guidance was provided for modulating exercise across the cycle [231]. The between-study variance and poor methodological quality of the included studies resulted in the lack of guidance regarding manipulation of training. McNulty et al. [231], however, did recommend that a personalised approach should be taken based on individual responses to the menstrual cycle and the subsequent effect on performance. Whilst it is recommended that symptom management should be the priority, with the utilisation of a micro-dosing approach, if training is required to be modified for a particular athlete, then depending on how the sessions are micro-dosed the athlete may only miss or reduce the planned training for a smaller percentage of the total weekly volume. For example, if two traditional resistance training sessions were micro-dosed equally into four sessions, rather than missing 50% of the weekly volume, only 25% would be missed/adapted. Although relatively low absenteeism in training has been reported previously [230], within the week leading up to menses evidence indicates that some individuals do require adjustments to training [232].

Further to just the menstrual cycle, Nimphius [233] has highlighted previously that, although strength and neuromuscular adaptations are broadly similar in male and female athletes of comparable training status [234] the influence that sporting and societal systems have on motor skill development/attainment may ultimately influence the transfer of improved strength to sport-specific skills. Despite some of these issues, due to the disparity of literature tailored to female athletes, more research needs to be carried out to understand whether some of the previously highlighted benefits of micro-dosing, such as PAPE and priming would also benefit female populations. Considering both PAPE and resistance priming are thought to benefit athletes with a higher training status, it is important to know if these results are present with females, particularly considering that both Russell et al. [180] and Cook et al. [235] have discussed the potential resistance priming effect to be due to hormonal changes.

4.6.2 Player autonomy

Based on several meta-analytical observations [106, 107, 133], as previously highlighted, there are no meaningful differences between training frequencies when volume load is equated. One factor that is likely to make a difference between the success of both traditional and micro-dosing methods is the intent and motivation of the athletes completing the programme. Micro-dosing may offer an alternative approach to assist in the enhancement of some athletes' intent/motivation within a group. Motivation is reported to be a key element of an athletes' success in sports [236] and has been clearly described as the internal (intrinsic) and/or external (extrinsic) forces that influence the initiation, direction, intensity, and persistence of a person's behaviour [237]. Intrinsic motivation refers to performing an activity for the pleasure and satisfaction derived from participation and with no other apparent rewards [238] and has been shown to be an important determinant of sport performance [239]. Although a lot of team sport athletes will be intrinsically motivated when it comes to the technical and tactical development of their sport, not all athletes will experience the same motivation when it comes to resistance training and may require a greater level of extrinsic motivation. Extrinsic motivation has been proposed to be either self-determined (e.g., internal acceptance of the value of resistance training for sports performance and engaging out of choice even if it perceived as unpleasant [237, 239]) or non-self-determined (e.g., feeling obligated or pressured to take part in resistance training either externally by a coach or internally through a feeling of guilt [237]). Extrinsic motives can therefore either be imposed and coercive or fully endorsed by the athlete [239].

One possible method of enhancing the intrinsic and self-determined extrinsic motivation, or altering non-self-determined motivation is through autonomy support. Autonomy-supportive environments allow individuals to feel that a behaviour or activity originates from and expresses their true selves rather than being a response to external pressures or demands [240]. Mageau and Vallerand [237] have proposed a list of coaching behaviours that allow for autonomy support, the first of which is “providing as much choice as possible within specific limits and rules”. Athletes’ choice in sport is generally quite limited due to coaches planning and prescribing their training programs and schedules. Coaches could therefore potentially provide several options, that include a traditional and micro-dosing approach(es), which players can choose from, that are still within the coaches’ control to maintain appropriate planning and periodisation. Optionality could also give the players a greater level of ownership based on what their preferences are to maximise the quality, intent, and overall compliance of their weekly outputs. For example, a player may have the attitude that they would rather get all the work done in larger less frequent chunks and follow more of a traditional approach (see option *a* in Table 4.2). Alternatively, if a player has a preference towards spending less time in the gym on each training occasion but is willing to attend more frequently, the use of micro-dosing may be more appropriate based on their own preferences (see Option *B* in Table 4.2). Providing an alternative approach, to increase player autonomy, may also have benefits within organisations that work in a decentralised format whereby athletes are either spread across a country, or even across countries and motivation becomes key if they are not in face-to-face contact with their coach’s day in, day out. It is worth considering, however, that dependent upon the training status of the athletes Option *B* in Table 4.2 will potentially increase the number of warm up sets executed across a training cycle which will increase training load. This may not be a negative consequence, as it may be a way of providing additional volume for weaker/lesser trained athletes without explicitly programming it, or alternatively the additional warm up sets could be viewed as additional power training [241].

Table 4.2. An example three variations of traditional and micro-dosed approaches to a strength training block.

Training Day	**Option A**	**Option B**	**Option C**
Monday (Game day +2)	Back Squat (3x5) Push Press (3x5) Bulgarian Split Squat (3x5) Romanian Deadlift (3x5) Depth Jump (3x5) Calf Raise (3x5)	Back Squat (1x5) Push Press (1x5) Bulgarian Split Squat (1x5) Romanian Deadlift (1x5) Depth Jump (1x5) Calf Raise (1x5)	Back Squat (3x5) Romanian Deadlift (3x5)
Wednesday (Game day -3)		Back Squat (1x5) Push Press (1x5) Bulgarian Split Squat (1x5) Romanian Deadlift (1x5) Depth Jump (1x5) Calf Raise (1x5)	Bulgarian Split Squat (3x5) Calf Raise (3x5)
Thursday (Game day -2)		Back Squat (1x5) Push Press (1x5) Bulgarian Split Squat (1x5) Romanian Deadlift (1x5) Depth Jump (1x5) Calf Raise (1x5)	Push Press (3x5) Depth Jump (3x5)

Intensity at 80-85% 1RM

4.6.3 Training status

Unlike the other sections included in this review whereby micro-dosing is utilised as a method that should ultimately enhance the effectiveness, feasibility or flexibility of resistance training in-season, training status is more likely to dictate how micro-dosing is best utilised with a given athlete. Peterson et al. [242] has identified that the rate of improvement in muscular strength following a given training stimulus decreases with greater training status and previous level of muscular strength. Rhea [130] also highlights that smaller magnitudes of improvement should be expected in athletes of a higher training status. As a result of the findings by Peterson et al. [242], the potency (intensity) or dose (volume) of an exercise, or in some cases both, must increase to elicit a similar magnitude of adaptation over a chronic period of training (i.e., progressive overload). In-season, when the training focus is likely to be weighted towards increasing the intensity of exercises rather than the total volume, micro-dosing with athletes of a higher resistance training status may be more appropriate for many of the reasons covered in previous sections such as eliciting a PAPE or resistance priming response. Outside of the competitive season, however, the volumes that those of higher training status require will likely make a traditional approach to training more appropriate as time constraints are not as limiting.

Within team sports there can be a large variation in the training status of a squad, particularly in sports such as soccer, where the culture around physical development can differ greatly. Although there may be some players who have come up through an academy system or attended a well-resourced school, some players may move to an organisation having limited experience in resistance training and be of a much lower training status, despite being extremely proficient at their sport. Micro-dosing may provide a greater opportunity to divide the team into smaller groups that train more frequently, particularly for those of a lower training status to benefit from concepts highlighted previously such as the RBE, a reduced amount of fatigue per session, and greater number of learning opportunities.

4.7 Conclusion

Micro-dosing is not necessarily a new concept, even within resistance training, or at least it is derived from and an amalgamation of numerous other strategies and models. Within this review, however, the ways in which micro-dosing of resistance training could influence the enhancement of athletic development and performance have been outlined, as a conceptual framework. Although micro-dosing may not be a new concept, there are still many aspects of the framework provided that need further investigation to determine whether micro-dosing works in certain situations or populations, so practitioners can understand when it is and is not appropriate to utilise this programming strategy. In addition, this review has focussed on team sports, but it is also worth considering how the concept would apply to individual athletes or for tactical strength and conditioning (military or emergency response personnel). Whether the term micro-dosing is here to stay or not, the underpinning theories provided to solve constraints around competition scheduling, or enhance the acute/chronic programming, individualisation, and motor learning of athletes will remain applicable, and micro-dosing is a convincing strategy to navigate these challenges.

4.8 Commentary 3

Going through the process of producing chapter 4 has allowed us to be far more divergent in our thinking as to where micro-dosing as a concept could be appropriate, and where further research could follow, once we have laid the foundations and demonstrated how it works overtime, in-season, using a simple approach. As highlighted in section 4.4.3, the RBE is one method in which micro-dosing could have a fairly acute benefit in-season whilst still working towards positive adaptations over time. In order to identify if a RBE is present in micro-dosing of hamstring strength exercises such as the NHE highlighted in chapter 2, we needed a method of hamstring strength assessment that was sensitive enough to accurately track changes in strength day to day. This entire thesis was supported by The Football Association which is the national governing body of soccer in England, who are also responsible for the England national teams. Due to the players associated with the national teams only attending training/fixture camps or tournaments for short, condensed periods of time, we were unable to use any of those athletes for interventions, which meant we were then required to do any reliability testing in the populations we were subsequently going to use within our planned intervention. Due to utilising a professional squad of athletes from a domestic league club, the test also needed to be easily applied in the field. Chapter 5 highlights this process and the associations between the chosen tests.

5 Chapter 5: Reliability of and associations between a variety of field-based hamstring strength measurements in professional female soccer players.

5.1 Abstract

Background: The 'gold standard' method of assessing hamstring strength has been viewed as some form of isokinetic dynamometry, however, the cost and time implications of using such equipment makes this method unrealistic for most team sports. A series of other field-based hamstring strength assessments, both eccentric and isometric have been used recently to determine acute and chronic changes in force production. The reliability of those measures are yet to be compared and assessed within a female soccer population. ***Objective:*** The aim of this study was to identify within- and between-session reliability and determine associations between an eccentric and three isometric hamstring strength assessments. ***Methods:*** Twenty-three female soccer players performed one eccentric and three isometric hamstring strength assessments on two separate occasions, 72 hours apart. Three trials were completed for each test, and on each leg for the unilateral tests, with absolute and relative reliability calculated within- and between-session. Null hypothesis significance testing was completed using permutation tests with 5000 bootstrap samples and used alongside Hedge's *g* effect sizes to determine the differences between test occasions. Minimum detectable change (MDC) was also used to assess the sensitivity, with Spearman's rho calculated to assess associations between tests. ***Results:*** Good to excellent relative and acceptable absolute reliability (ICC ≥ 0.792 and CV ≤ 7.69) were observed in all hamstring tests both within- and between-session. Trivial to small differences ($g \leq 0.23$) were present between-session for all tests, with only the isometric assessments performed with a 90° knee angle showed significant differences ($p \leq 0.011$). Small to moderate correlations were observed between all isometric exercises and the Nordic hamstring exercise ($r = 0.195$-0.596). MDC was 18.64-24.04% for all tests, with the lowest isometric test being the 30° isometric supine knee flexion (18.65%). ***Conclusions:*** The Nordic hamstring exercise should be used to monitor chronic adaptations whereas the 30° isometric supine knee flexion test is potentially more appropriate to monitor day to day changes in hamstring force production but will require additional familiarisation before being used for decision making.

5.2 Introduction

Athletic tasks such as sprinting and jumping are key performance indicators within many sports, including both individual events and multidirectional team sports [88]. The function of the hamstrings, as a biarticular muscle group, during these tasks is to decelerate the shank during the late swing phase of sprinting gait [243] and to assist with forceful extension of the hip, acting as a synergist for the gluteal muscles. During high velocity running, or sprinting, the hamstrings work eccentrically to decelerate the lower shank during the terminal swing-phase of the sprint gait cycle just before touch-down. Decelerating the shank is an important factor in reducing injury risk of the hamstrings as this is where the muscle is at its longest and most vulnerable [244]. Hamstring strain injury

(HSI) has been reported as being 17% of all injuries reported by 17 top-flight European soccer teams [17] with 57% of HSIs reported as being sustained during running activities [34]. The hamstrings also prevent anterior tibial translation during this decelerative action (e.g., change of direction or landing from a jump) which combined with ankle eversion and knee valgus has been identified as an injury risk factor, particularly for an ACL injury [245]. The hamstrings also assist in performance, playing a significant role in ground reaction force production during sprinting [246]. Specific hamstring strength training interventions should therefore increase performance in athletic tasks and elicit adaptations that include increases in strength and fascicle length and reductions in pennation angle, in the biceps femoris long head [57, 74]. These adaptations have been shown to decrease risk of HSI [247]. Increases in hamstring strength has also been demonstrated within more holistic strength training interventions [248].

Isokinetic dynamometry (IKD) has long been viewed as the gold standard for measuring and screening hamstring strength [249]. A plethora of variables can be derived from an equally diverse range of protocols, which can include assessing peak torque at a range of angular velocities [64], concentric and eccentric muscle actions, ratios between limbs and ratios between reciprocal muscle groups [250]. Aagaard et al. [251] recommended that alongside absolute maximal hamstring strength, assessment of both conventional hamstring to quadriceps (H:Q) ratio (the ratio between maximal hamstring muscle strength relative to maximal quadriceps muscle strength) and functional H:Q ratio (the ratio between maximal eccentric hamstring muscle strength and concentric quadriceps muscle strength) should be utilised to assess knee joint function, the capability of the hamstrings to counteract the quadriceps, and reduce anterior tibial translation. Despite this being a gold standard approach, Green et al. [252] highlighted, through meta-analytic data, no associations between eccentric knee flexor strength and HSI risk. This has also been echoed earlier in the research, with both concentric and eccentric isokinetic strength testing at 60 and 180 degrees/second being demonstrated to be a poor predictor of HSI in Australian football players [253]. Ratios between reciprocal muscle groups also has its limitations due to variation based upon, sex, age, and activity the athletes participate in. Similar to the magnitude of peak torque, angular velocity also has an influence over these ratios, with an increase in the ratio alongside increases in angular velocity during concentric actions [250]. During eccentric actions, however, higher angular velocities decrease peak torque and therefore the ratio will change as a result. Caution should also be taken when comparing ratios with previous literature as not all studies correct for the effect of gravity and without considering the effect of gravity, erroneous conclusions will be made [254]. With the additional financial costs of the equipment paired with the time-consuming nature of testing, there needs to be alternative field-based assessment methods of testing the hamstring muscles that is valid for monitoring, screening, and assessing performance in team sports whereby the number of players needing testing, and the regularity of those testing sessions, are accounted for.

More recently, the Nordic hamstring exercise (NHE) has been used to assess eccentric hamstring strength, via the use of strain gauges. The strain gauges permit assessment of bilateral and unilateral eccentric knee flexor force production, quickly and easily within a portable unit, making its implementation within team sports more efficient. No correlation between the force during the NHE and torque from IKD assessments has been shown, meaning although the two methods are assumed to measure the same strength quality, they do not [83]. This is most likely due to the differences in body position and metrics measured, with IKD being unilaterally in a seated (hip flexed) position whereby torque is measured, compared to the bilateral kneeling position (hip extended) in which force is assessed during the NHE. The angular velocity when using a IKD is also constant throughout the movement, whereas the opposite is true for the NHE. Unlike the IKD, which demonstrated poor predictions of HSI, the NHE has been successfully used to identify HSI risk in players with inferior eccentric hamstring strength [47, 120]. There are, however, some limitations associated with the NHE as an assessment of hamstring strength. The sampling frequency of most strain gauges available for this type of use are very low, despite initially sampling at 1000 Hz when the initial device was first tested [255], the NordBord in particular, at the time or recording only sampled at 50 Hz, this meant that only peak force, and no time related force data could be taken from it reducing its potential to be used as a device to monitor fatigue. In addition to this, the supramaximal eccentric nature of the exercise has been observed to cause delayed onset muscles soreness (DOMS) [60]. This means regular monitoring, particularly in terms of acute injury risk due to fatigue is largely inappropriate, unless the NHE is already part of a strength training programme and there is already an element of protection from further DOMS due to the repeated bout effect [192]. In this instance the prescribed repetitions could be completed using the strain gauges.

An alternative to testing eccentric muscle actions during both the NHE and IKD is to use isometric hamstring assessments. Isometric muscles actions are shown to cause minimal or no structural muscle damage, meaning the approach will cause less fatigue and the time in-between testing occasions can be much shorter without having any negative impact on performance [256]. There are a number of variations of isometric hamstring tests, these include being in a standing position [257], lying in a supine position [256], kneeling on all fours [258], or in a prone position, all with varying angles of knee flexion, including 0°, 20°, 30° and 90° and variation in the corresponding hip angles depending on the initial body position. Body position is not the only variation, with investigators using sphygmomanometers, strain gauges, or force plates under/over the heel of participants to measure force production. The sphygmomanometer was initially used in a case study, whereby the subject was lay in a supine position, both legs resting on a box with hip and knee at 90°, the subject then pushed down maximally onto the sphygmomanometer on one leg at a time to obtain a quantified maximum voluntary contraction [259]. The same approach has since been adapted slightly, with only the testing leg being placed upon the box and the passive leg resting on the ground beside it, with the slight adaptation still presenting high reliability for both a 90° hip and knee angle (ICC ≥ 0.83), and 30° knee angle (ICC ≥ 0.87) [260]. Since publication of the case study by Schache et al. [259] numerous researchers [256] have used this approach with a force platform instead of sphygmomanometer, this potentially allows for a more accurate measurement of force. McCall et al. [256] were amongst the first to investigate this method as a potential measure for assessing the magnitude of reductions in hamstring strength as a result of competition. The investigators concluded that both the 90° and 30° knee flexion angle variations were reliable and sensitive enough to detect reductions in isometric hamstring strength and may be suitable in identifying players “at risk” of injury. The testing protocols were executed a week apart to assess the reliability and both pre- and post-competitive match-play to assess sensitivity, and to determine whether the reduction in isometric peak force following a 90-minute competitive fixture is greater than the minimal difference identified through the reliability testing. Not all teams have access to force platforms to complete these tests, however, so alternative tests need to be investigated and compared to these protocols using the same cohort.

Due to the different ‘field based’ methods of assessing hamstring strength reported across the literature, the aim of this study was to: (1) identify within- and between-session reliability of four different field-based hamstring assessments in female soccer players, to determine their ability to assess changes in hamstring strength across time, and (2) to determine the associations between the peak force during the NHE, which is reported to be a predictor of HSI risk, and three field-based isometric protocols.

5.3 Methods

5.3.1 Participants

Twenty-three professional female soccer players (age: 21.1 ± 4.5 years; height: 168.3 ± 5.9 cm; body mass: 64.2 ± 6.5 kg) took part in at least two of the exercises included in this study on two occasions. Participants were required to have had no hamstring related injuries for six months prior to taking part. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent to participate in the study. Ethical approval (HSR1819-037) was granted by the institutional ethics committee in accordance with the declaration of Helsinki.

5.3.2 Experimental Design

A cross-sectional design was used to examine the within- and between-session reliability of and associations of between four field-based hamstring assessments including a supine 30° knee flexion (KF), supine 90° KF and kneeling 90° KF and a field-based eccentric hamstring strength test (the NHE). Participants completed the tasks prior to their normal training day on two occasions 72 hours apart. The first session was carried out 48 hours after a competitive fixture, following their recovery day.

5.3.3 Procedures

5.3.3.1 Isometric hamstring strength tests

The three isometric assessments were performed prior to the eccentric assessment, due to the isometric tests being less fatiguing and less likely to result in muscle damage. The kneeling 90° KF assessment was performed on a NordBord (Vald Performance, Brisbane, QLD, Australia), whilst the other two 30° and 90° KF were tested using a force plate (Kistler Type 9286AA: Kistler Instruments Inc, Amherst, NY, USA). For the kneeling 90° KF test, participants were instructed to position themselves on all fours, with a 90° angle of flexion at hip and knee whilst their hands and knees to provide stability during the test, participants were then be instructed to flex their knees as hard as they could for 3-5 seconds, pulling their heels up against the strain gauges embedded in the ankle attachments (Figure 5.1c). The same protocol was applied to the remaining isometric tests (30° and 90° KF), these were measured using the force platform, placed upon a box at an appropriate height for each participant, which was determined by participants lying in a supine position with their hip and knee at 90° or 30° of flexion at the knee depending on the test, their heel resting on the box (Figure 5.1a-b). These two tests were applied unilaterally with the non-testing leg being placed fully extended next to the box. Three trials for each leg were executed with the participants driving their heel down into the force platform for 3-5 seconds following three submaximal trials, similar to the previous tests.

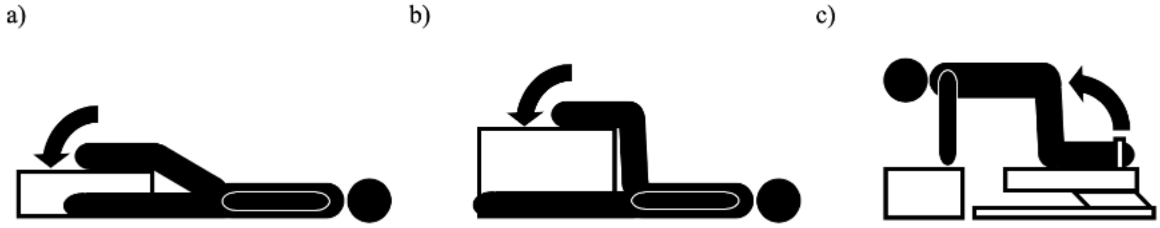


Figure 5.1. A depiction of a) 30° knee flexion, b) 90° knee flexion and c) kneeling 90° knee flexion tests.

5.3.3.2 Eccentric hamstring strength test

The eccentric hamstring test was performed using the NordBord whilst performing the NHE. Participants knelt on a padded board with individual ankle attachments and integrated uniaxial load cells for force capture as described by Opar et al. [255]. Three submaximal efforts of the NHE were performed followed by a 1-minute rest. Participants were then asked to execute three maximal repetitions of the NHE, where they were instructed to lean forwards slowly, whilst maximally resisting the forward motion, maintaining a neutral hip position and extending through the knee joint. Force (N) and time (s) data were then extracted from the NordBord for further analysis.

5.3.3.3 Data analysis

Raw force-time data for each trial was analysed using a customised Microsoft Excel spreadsheet (version 2019, Microsoft Corp., Redmond, WA, USA). Peak force was identified for each trial of all four exercises, with a mean average of the three taken and used for further analysis.

5.3.3.4 Statistical analyses

All statistical analyses were conducted using SPSS for Windows version 24 (IBM SPSS Inc, Chicago, IL) and Estimationstats.com [261]. Data are presented as the mean ± standard deviation (SD) with the assumption of normality verified using the Shapiro-Wilk's test. An *a priori* alpha level was set at < 0.05. Absolute reliability was calculated using coefficient of variance (CV), with acceptable reliability < 10%. Relative reliability was calculated using intraclass correlation coefficients (ICC) and interpreted as poor < 0.39, fair 0.4 – 0.69, good 0.7 – 0.89 and excellent > 0.9 based on the lower bound 95% confidence intervals (CI) [262]. Null hypothesis significance testing was carried out using a series of permutation tests for each comparison. Five thousand bootstrap samples were taken as part of the permutation tests with the *p* value reported as the likelihood of observing the effect size reported if the null hypothesis of zero difference was true [261]. The magnitude of differences was calculated using Hedges *g* effect sizes and the 95% CI. Effect sizes were interpreted based on the recommendations of Cohen [263]: 0-0.19, trivial; 0.2-0.49, small; 0.5-0.79, moderate; ≥ 0.8, large. The minimal detectable change (MDC) was calculated as follows: ((SEM 1.96) x √2), with SEM was calculated as: SD of difference in scores (i.e., session 2-session 1) divided by √2. Associations between the NHE and isometric tests were calculated using Pearson’s correlation or the non-parametric equivalent (Spearman’s rho) for data not normally distributed. Correlations were interpreted using the scale 0-0.09 trivial; 0.1-0.29, small; 0.3-0.49, moderate; 0.5-0.69, large; 0.7-0.89, very large; 0.9-0.99, nearly perfect; 1.0, perfect [80].

5.4 Results

5.4.1 Within- and between-session reliability of isometric and eccentric strength assessments

Relative reliability for all four exercises was good to excellent (ICC ≥ 0.792) both within- and between-session, acceptable variance between-sessions was also observed (CV ≤ 7.69) for both isometric and eccentric exercises (Table 5.1, Figure 5.2). The magnitude of difference between sessions has also shown trivial to small effect sizes ($g \leq 0.23$) with the 90° KF and Kneeling 90° KF with significant differences ($p \leq 0.011$). A non-significant decrease in force was observed for the NHE ($p = 0.61$), and no significant differences between session for the 30° KF ($p = 0.071$). The MDC was observed to be lowest in the NHE (18.46%) and of the isometric assessments, the 30° KF assessment demonstrated a similar level of sensitivity (1.865%).

Table 5.1. Within- and between-session reliability of four field-based hamstring exercises.

Test	Session 1		Session 2		Between-Session				
	Mean (SD)	ICC (95% CI)	Mean (SD)	ICC (95% CI)	*p*	CV %	ICC (95% CI)	*d*	MDC %
30° KF	195.47 (8.46)	0.887 (0.828 – 0.930)	200.64 (7.00)	0.923 (0.878 – 0.953)	0.071	5.43	0.858 (0.747 – 0.920)	0.16	18.65
90° KF	217.16 (10.12)	0.854 (0.767 – 0.912)	224.84 (12.92)	0.834 (0.712 – 0.905)	0.011	7.41	0.784 (0.614 – 0.879)	0.23	22.55
Kneeling 90° KF	274.95 (19.18)	0.792 (0.689 – 0.870)	275.01 (18.22)	0.827 (0.733 – 0.894)	< 0.001	7.69	0.818 (0.669 – 0.899)	0.14	24.04
NHE	331.77 (15.15)	0.882 (0.721 – 0.946)	323.19 (14.09)	0.823 (0.712 – 0.901)	0.61	4.07	0.871 (0.739 – 0.937)	-0.11	18.46

SD = Standard deviation; ICC = intraclass correlation coefficient; CI = confidence interval; CV = coefficient of variation; d = Cohen’s d effect size; MDC = minimal detectable change; KF = knee flexion; NHE = Nordic hamstring exercise

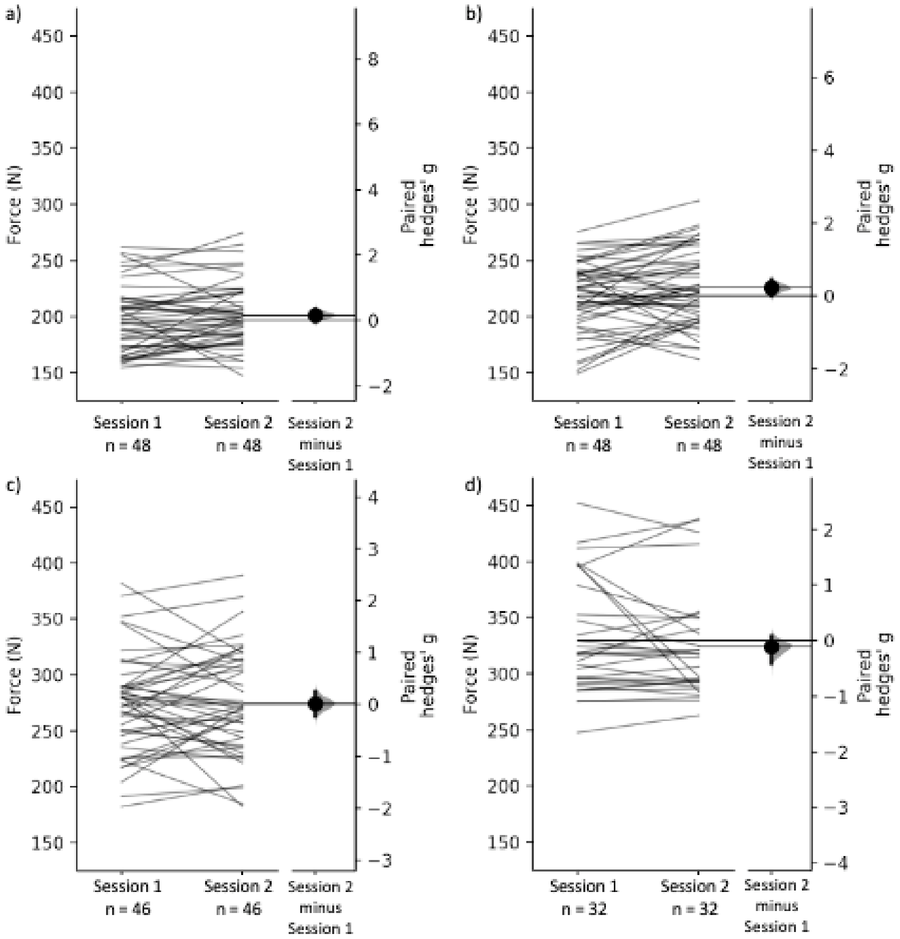


Figure 5.2. Individual between-session comparisons for (a) 30° knee flexion, (b) 90° knee flexion, (c) kneeling 90° knee flexion and (d) Nordic hamstring exercise and Hedge's g effect sizes.

5.4.2 Associations between isometric and eccentric strength assessments

Due to the non-linear distribution of the NHE data collected, Spearman's rho was calculated with the results highlighting significantly moderate correlations ($p \leq 0.001$, $r = 0.556$ and 0.596) between the NHE and the 30° and 90° KF tests, respectively. Small and non-significant correlations ($p = 0.27$, $r = 0.195$) were observed between the NHE and kneeling 90° KF (Figure 5.3).

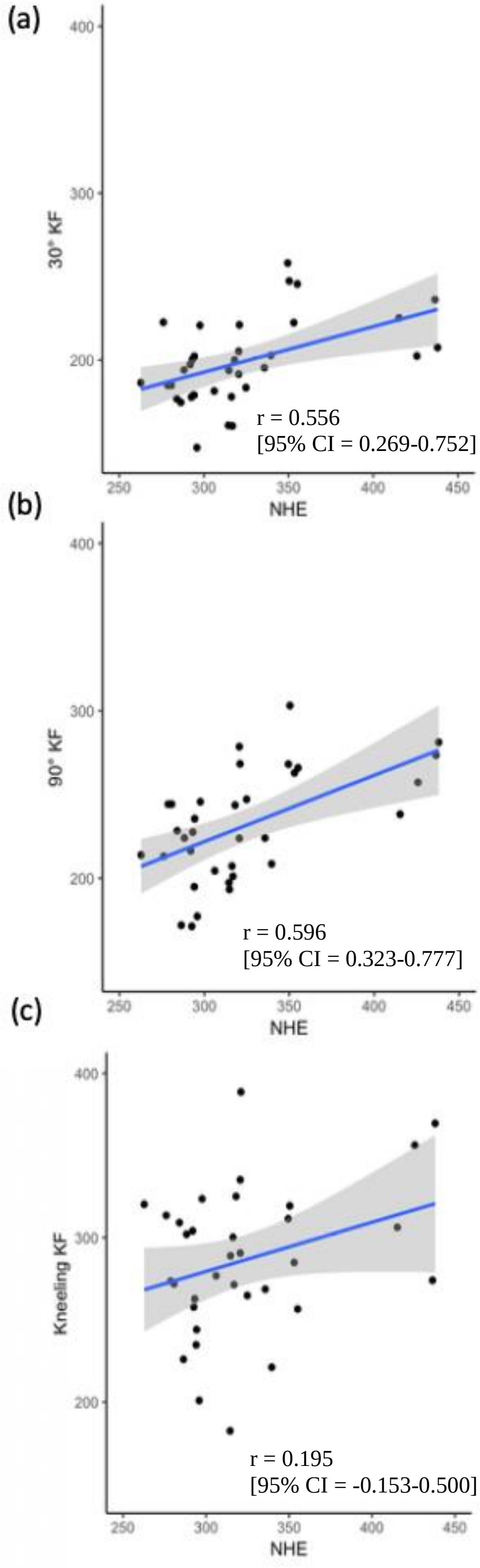


Figure 5.3. Correlations between the Nordic hamstring exercise and isometric hamstring strength assessments in Newtons.

NHE = Nordic hamstring exercise; KF = Knee flexion; CI = Confidence interval

5.5 Discussion

The aim of this study was to investigate within- and between-session reliability of four field-based hamstring strength assessments and to determine associations between the the eccentric and isometric assessments. Based on the criteria stipulated in the methodology, ICC's presented good to excellent relative reliability both within- and between-session with acceptable variance (absolute reliability) between the sessions. Moderate correlations were also observed between the NHE, 30° KF and 90° KF tests, as well as between the NHE and kneeling 90° KF.

Three of the four field-based assessments within this study have all been reported within previous literature to be reliable [255, 256], with McCall et al. [256] suggesting that the 'sensitivity' of the 30° and 90° KF is accurate enough to detect reductions in isometric force of the posterior lower limbs following a competitive fixture to assess the level of match-induced fatigue and identify those players who may be "at risk". The results of the current study indicate that between-session reliability for the isometric tests were good to excellent, however, the MDC was high ($\geq$ 18.65%) especially when compared to McCall et al. [256] who identified MDC of ~8-12%. The high MDCs highlight that substantial changes in peak force are required to indicate any real change, meaning that in order for any decisions in terms of training load changes for athletes can be made, big fluctuations in hamstring strength would need to be observed across a training week, which is unlikely to occur consistently. A possible reason for the high MDC could be due to a lack of familiarisation, with McCall et al. [256] carrying out two familiarisation sessions prior to the single testing occasion. When inspecting the ICCs demonstrated in session 2 (Table 5.1), these have increased for both 30° and kneeling 90° KF, with values similar to that reported by McCall et al. [256]. Despite a level of variation between-sessions, highlighted in Figure 5.1, the general trend is a slight increase in force output. With an increased regularity of testing, significant increases in force production may not occur, but the reliability of peak force may increase and variability decrease. With an increase in competency of the assessments it may be possible to analyse force-time related variables to include force produced at different time points within the assessment as a 'sensitive' measure related to neuromuscular fatigue.

Knowing that these field-based assessments are reliable both within- and between-session, and therefore able to be replicated at different time points within a season, it is important to then understand which is most appropriate or whether a choice can be made simply based upon equipment availability and/or preference of the practitioner. For example, the kneeling 90° KF assessment was used in this investigation as a potential alternative to those practitioners who may have access to the appropriate strain gauges but not to force platforms. It is therefore important to understand the relationship between the isometric assessments utilised within this study and the NHE (due to force measured during the NHE having been shown to be a predictor of HSI [47]), to investigate whether there is a possible interaction that may provide a greater rationale to choose one exercise compared to another. The results of the correlations demonstrated that there is a significant and moderate relationship ($p \leq 0.001$, r = 0.556 and 0.596) between the NHE and the 30° and 90° KF assessments, respectively. Comparing these moderate correlations to that of the kneeling 90° KF test, which demonstrated small and non-significant correlations (r = 0.195, p = 0.27) suggests that the two force plate assessments are potentially more appropriate. This however could be due to the difference in sampling frequency, as data collection using the force platforms were carried out at 1000 Hz, whereas the NordBord only sampled at 50 Hz, having said that, the NHE in which it has demonstrated poor correlation with is also completed using the NordBord sampling at the same frequency.

Further analysis of the muscle activation during the remaining tests should allow practitioners to understand which test recruits which of the hamstring muscles preferentially and to what extent, to make an informed decision as to the most appropriate form of assessment. The NHE and both 30° and 90° KF assessments have been investigated in previous literature [56, 264] to assess the magnitude of hamstring muscle activation. During the NHE it is clear that the medial hamstrings have the greater activation (101.8% of maximum voluntary isometric contraction (MVIC)) compared to the biceps femoris (71.9% MVIC). The limitations of this study were mainly due to the lack of familiarisation, this could explain the variance in some individuals seen in Figure 5.2, suggesting the use of these tests sporadically with no form of familiarisation may not allow the identification of true change in hamstring strength. The lack of familiarisation in this instance was due to access to the athletes around their in-season fixture requirements, in the future this could have been incorporated into resistance training warmups, or even content in resistance training sessions. Future research should, therefore, aim to identify the familiarisation process for practitioners to understand the length of time their athletes will need to familiarise themselves with the test prior to application.

Based on the criteria set within this study, the ICC's have shown that although the reliability within- and between-session was good to excellent, with acceptable variance (CV $\leq$ 7.69). Moderate correlations were observed between the NHE and kneeling 90° KF, and between the NHE, 30° KF and 90° KF tests. The NHE demonstrated the greatest between-session reliability, suggesting in terms of testing for adaptations to strength training, this is likely to be the most appropriate. Out of the isometric tests, the 30° KF showed the greatest between-session reliability, which increased from good to excellent ICC's between session 1 and 2, and showed the lowest variability. This increase in reliability, suggests that with further familiarisation, the 30° KF is likely to be the most appropriate test to use for regular hamstring monitoring. The 30° KF test has also shown previously to elicit similar activation across both biceps femoris and medial hamstrings [264], giving more of a global hamstring strength measure, rather than being medially or laterally biased.

5.6 Conclusion

Based on the findings of this study, practitioners should consider using the NHE as a tool to monitor chronic adaptations to training and the isometric tests to monitor neuromuscular function on a more regular basis. The recommendation would be to use the test with the lowest MDC as a meaningful change is more likely to be observed between testing occasions. According to the MDC presented, the isometric test of choice would be the 30° KF as meaningful changes will be detected with an increase/decrease in force of anything greater than a 18.65%. This value may also reduce over time as the athletes become more familiar with the test.

5.7 Commentary 4

Unfortunately, due to access with the athletes, and being in the midst of their competitive season, we were unable to follow up the two testing occasions included in Chapter 5 to understand if a learning effect would take place in order to reduce the large minimal detectable changes observed. It was therefore inappropriate to follow this reliability study with an investigation into the RBE. A strong rationale for using the NHE as the test of choice for the planned training intervention was a positive. We still wanted to investigate the acute performance of the NHE across a microcycle, however, to understand whether any differences occur between frequency groups and when performing the exercise on consecutive days as any detriment in performance across a microcycle will likely be further exacerbated over several weeks which would be inappropriate for a team whilst trying to compete in-season. Chapter 6 therefore investigates two different training frequencies and performance of the NHE on consecutive days during an individual microcycle replacing the originally planned RBE study.

6 Chapter 6: A comparison of force-time characteristics of two, volume-equated, Nordic hamstring exercise microcycle prescriptions, in-season.

6.1 Abstract

Background: The prevalence of hamstring strain injuries has been reported in several team sports and the incidence rates increasing. Strength has been identified as a modifiable risk factor for hamstring strain injuries, with improvements in hamstring strength reported to have a 4- to 5-fold reduction in injury risk. The Nordic hamstring exercise (NHE) has been demonstrated as an effective tool to induce positive strength adaptations due to its supramaximal eccentric nature. Despite the results of numerous studies highlighting the positive effects of the NHE, the compliance to injury prevention programmes that include the exercise are low, typically because the high volumes prescribed can induce delayed onset muscle soreness. In addition to reducing the prescribed volumes, micro-dosing the total weekly volume may be an additional method to increase compliance whilst still providing long term positive adaptations. **_Objective:_** The aim of this study was to assess differences in force-time characteristics of two volume equated training frequencies across a microcycle in-season, whilst also investigating the effect of performing the NHE on consecutive days. **_Methods:_** Thirty-one female soccer players performed 18 NHE repetitions across a microcycle in-season. A traditional group completed the repetitions over two days whereas the micro-dosing group performed 30% less each training occasion but performed the total volume over three days, two of which were on consecutive days. All repetitions were performed on the device used to assess eccentric strength of hamstrings with peak and mean force, impulse and repetition time collected for further analysis. Both absolute and relative reliability were calculated, with a series of paired samples t-tests and Hedge's *g* effect sizes calculated to determine differences between groups. **_Results:_** Peak and mean force demonstrated acceptable relative and absolute reliability. Trivial to small non-significant differences were observed between between groups (g = -0.52 to 0.52; $p \geq 0.915$). No significant differences were observed for peak force between consecutive days, with only a small significant reduction in mean force observed between repetitions on the second day (g = 0.24; p = 0.039). **_Conclusions:_** No meaningful differences between frequency groups, or performing the NHE on consecutive days, means that practitioners have the ability to be flexible with the programming of eccentric exercises providing that the volumes are appropriate.

6.2 Introduction

The ability to produce high magnitudes of force both rapidly and for sustained durations, is the underpinning of both the performance of sporting tasks and reduction non-contact injury risk [88]. The hamstrings, in particular, are associated with a higher risk of injury compared to other lower limb muscles, with weakness a contributing factor to injury risk [48, 265]. Hamstring strain injury (HSI) has been reported as contributing to 15% of injuries in Rugby and Australian football [31, 266], and 12% of all injuries in soccer, with 32% of all muscular injuries being classified as a HSI [17, 19]. The number of HSIs in soccer has also reportedly been rising over the last 20 years [18]. It is therefore important to gain an understanding of methods used to combat the modifiable risk factors associated with HSIs, in order for a holistic approach to hamstring training be adopted by practitioners, helping to reduce the risk of HSIs occurring [267]. One such method is the use of a supramaximal eccentric knee flexion exercise, known as the Nordic hamstring exercise (NHE). The NHE has previously been demonstrated to increase strength of the hamstrings, in Australian football players, which reduced the risk of HSI 4-fold, providing athletes exceed a 279 N threshold, or 5-fold when a relative threshold of 3.45 $N.kg^{-1}$ is surpassed [47].

The positive effects that NHE has on eliciting adaptations that are known for reducing the risk of HSI has been well established [57, 59, 69, 72-77], with such findings resulting in the inclusion of the NHE within injury prevention protocols, such as the FIFA 11+ [268]. Since the publication of these protocols/interventions there has still been an increase is HSI [18], therefore it has been argued that the NHE alone may not necessarily be an effective method of prevention [267]. The lack of reduction in HSI, however, is more likely due to low compliance rates of NHE interventions [269, 270], or a lack of inclusion of the NHE in programming all together, particularly in soccer [61]. One reason for low compliance in NHE interventions, including that of the FIFA 11+ could be that the prescribed volume is very high for such a high intensity eccentric exercise. Although eccentric exercises have been reported not only to have chronic benefits on strength and hypertrophy but also provide a protective effect from muscle soreness and exercise induced muscle damage, usually referred to as the repeated bout effect [54, 249, 271]. High volumes of eccentric exercises, however, are likely to result in delayed onset muscle soreness (DOMS) and muscle damage. As such, DOMS is likely to negatively affect compliance, particularly in-season for team sports, where the turnaround between games is quick and therefore time for recovery is usually reduced [272]. As highlighted in Chapter 2, high volumes are not always necessary to elicit the desired adaptations (increased strength and fascicle length).

In-season demands of soccer usually result in some form of fixture congestion particularly at higher levels due to commitments in domestic leagues, both domestic and international club/cup tournaments, as seen in European soccer and international tournaments (e.g., World Cup). Not only is there likely be a larger emphasis placed on recovery, but technical/tactical aspects of the sport also tend to be prioritised [273]. The short turnaround between competition can therefore have a large impact on how players can develop physically throughout a season, without performance decreasing. Reductions in strength has been demonstrated to occur within 2-3 weeks of resistance training cessation with subsequent losses in power, and even greater losses in both strength and power over a 10-16 week period [274]. The decrease in performance may be due to accumulated fatigue which is the rationale for inclusion of a periodised approach to training [275], or in many cases over longer periods of time there is a potential for a detraining effect to occur. Regardless of the mechanism, reductions in performance can also then increase the risk of injury. Despite competition providing some training stimuli, this is not always sufficient, for example in pitch-based team sports, some players will experience regular exposure high-speed running/sprinting, which could have a training effect on the hamstrings [276] but this does not necessarily occur for every player during every fixture at high enough intensities. Silva et al. [277] have also provided evidence to suggest that other indicators of performance such as countermovement jump and sprint performance and are not able to be maintained from match play alone, throughout an entire season, suggesting therefore the importance of incorporating strength and power training into the microcycle. In a number of meta-analyses researchers have investigated the effect of training frequency on strength [106, 107], suggesting that volume is more likely to be the driving stimulus behind adaptations, as suggested in Chapter(s) 3 and 4 the concept of “micro-dosing” could be a possible programming solution.

For a supramaximal exercise like the NHE, the micro-dosing concept could allow for more regular inclusion of the exercise throughout a season and subsequently increasing compliance. Increasing the frequency of doses may lead to a requirement for the NHE to be performed on consecutive days, depending on the structure of the microcycle. This may mean that even low dosages could be detrimental to performance on subsequent training and competition days due to accumulated fatigue. Consequently, it is important to understand the effect of NHE prescription throughout a microcycle. Therefore, the aim of this study was to (1) compare force-time characteristics between two different, volume equated, training frequencies (traditional [2 days per week] vs. micro-dosed [3 days per week]) across a microcycle, in-season, and (2) investigate the effect of performing the NHE on consecutive days, on the force-time characteristics. It was hypothesised that the micro-dosing group would demonstrate greater force over longer durations due to less fatigue accumulated across the whole microcycle. It was also hypothesised that there would be difference performing the NHE on consecutive days, with decreases in force-time characteristics observed on the second day.

6.3 Methods

6.3.1 Participants

Thirty-one female soccer players (age: 17.3 ± 0.8 years; height: 168.9 ± 3.8 cm; body mass: 64.7 ± 7.6 kg) playing within a Women's Super League academy, with experience of resistance training for a minimum of two seasons, volunteered to participate in this study. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent, or parental/guardian assent where required, to participate in the study. Ethical approval (HSR1819-037) was granted by the institutional ethics committee in accordance with the declaration of Helsinki.

6.3.2 Experimental design

A between subject's cross-sectional design was used to examine the difference between a traditional approach (n=17) and micro-dosing approach (n=14) to the prescription of the NHE across a microcycle. A within-subjects cross-sectional design was used to assess the effect of performing the NHE on consecutive days for subjects in the micro-dosing group, where training was performed on consecutive days. This occurred over two microcycles following the same weekly protocol. Data was therefore pooled resulting in 31 subjects of data. Participants were randomly allocated into the two groups using a random computer-generated assignment tool, they were all then assessed the week prior to the study being conducted, as part of their normal resistance training sessions, to determine peak values from a normal training week. The last session of their training week was a minimum of 48 hours prior to the start of the testing microcycle.

6.3.3 Procedures

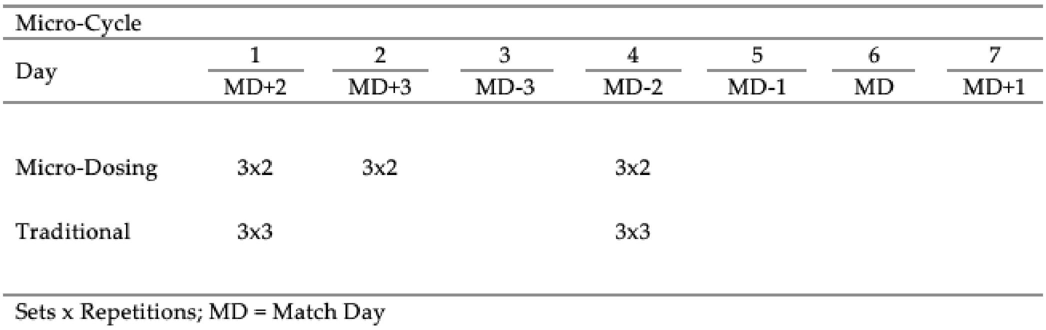
6.3.3.1 *Nordic hamstring exercise*

Participants performed the NHE repetitions on the NordBord (Vald Performance, Brisbane, QLD, AUS), they were required to kneel on the padded board with individual ankle attachment points and integrated uniaxial load cells captured the force produced during the movement [255], with the sampling frequency set at 50 Hz. Participants were asked to execute every NHE repetition maximally, following a thorough warm up, whereby they were instructed to lean forwards slowly (via knee extension alone), whilst resisting the forward motion with both lower limbs, maintaining a neutral hip position, and extending through the knee joint. Force (N) and time (s) data was extracted from the NordBord for further analysis in a bespoke Excel spreadsheet (version 2019, Microsoft Corp., Redmond, WA, USA).

6.3.3.2 *Training protocol*

Figure 6.1 depicts the outline of the NHE prescription for both the traditional and micro-dosing groups across the microcycle. The NHE was already a staple exercise within the training programme of these participants so there was no need for familiarisation. Both the traditional and micro-dosing groups completed 18 NHE repetitions within the microcycle as this was the low-volume prescription agreed with their club. The micro-dosing group performed 30% less per set and per session. Force-time data from all repetitions were recorded during the testing microcycle, and the microcycle prior which established a baseline for between group comparisons.

Table 6.1. An overview of the microcycle structure for the micro-dosing and traditional groups.



Micro-Cycle							
Day	1 MD+2	2 MD+3	3 MD-3	4 MD-2	5 MD-1	6 MD	7 MD+1
Micro-Dosing	3x2	3x2		3x2			
Traditional	3x3			3x3			

Sets x Repetitions; MD = Match Day

6.3.3.3 *Data analysis*

Raw force-time data for each trial was analysed using a customised Microsoft Excel spreadsheet. The onset of movement was identified when force exceeded 5 times the standard deviation (SD) of the mean of the residual force and peak force was identified as the maximum force produced during the exercise (similar to that used by McMahon et al. [278] during countermovement jump analysis). Mean force (N) was the average force produced from onset of movement to the end of active resistance, repetition time the duration in seconds of the same period. Impulse ($N.s^{-1}$) was then derived from both the mean force and repetition duration. In order to make comparisons between groups, due to differences in strength of the groups, the values for both traditional and micro-dosing groups across the microcycle were presented as a percentage of their maximum from the previous weeks baseline test.

6.3.3.4 Statistical analysis

All statistical analyses were conducted using SPSS for Windows version 24 (IBM SPSS Inc, Chicago, IL). Data is be presented as the mean ± SD, with normality verified using the Shapiro-Wilk's test. An *a priori* alpha level was set at < 0.05. Between-session reliability measures were assessed using day 1 and day 4 for the micro-dosing group and day 2 and day 4 for the traditional group (See Table 6.1). Absolute reliability was calculated using coefficient of variance (CV), with acceptable reliability < 10% [279]. Relative reliability was assessed by calculating intraclass correlation coefficients (ICC) using a two-way mixed model of absolute agreement and interpreted based on the lower bound confidence intervals (CI) (ICC; poor < 0.39, fair 0.40 – 0.69, good 0.70 – 0.89 and excellent > 0.90) [262]. Those variables that show acceptable absolute reliability and do no demonstrate poor relative reliability will be used for further analyses. A series of paired samples T-tests were completed to assess differences between test occasions used for between-session reliability. Differences between-groups for the analysis of both the whole microcycle (micro-dosing vs. traditional) and consecutive days (day 1 vs. day 2) were evaluated using a series of repeated measures analysis of variance, with Bonferroni post hoc analysis. Comparisons repetition by repetition between groups of the whole micro-cycle were analysed using a series of Welch's t-tests due to unequal sample sizes, whereas a series of paired samples t-tests were used when comparing repetition by repetition between the consecutive days. The magnitude of differences was also be calculated using Hedges *g* effect sizes and interpreted based on the recommendations of Cohen [263]: 0-0.19, trivial; 0.2-0.49, small; 0.5-0.79, moderate; ≥ 0.8, large. Additionally, data are presented in, with individual data plots including the mean difference and 95% CI, using an adapted version of Weissgerber et al. [280] template.

6.4 Results

6.4.1 Between-session reliability

Individual plots between reliability sessions for peak force, mean force, repetition time and impulse are presented for both the micro-dosing and traditional groups are presented in Figure 6.1. Based on the thresholds outlined, peak and mean force demonstrated acceptable absolute reliability with fair to good relative reliability in both the testing groups. Repetition time and impulse, however, were not acceptably reliable, with repetition time only demonstrating acceptable absolute reliability in one group (micro-dosing) and good relative reliability in the other (traditional). Impulse did not demonstrate acceptable absolute reliability, but the relative reliability was similar to peak and mean force with fair to good. Due to both impulse and repetition time not meeting the reliability criteria, no further analysis was executed for these variables. Figure 6.1 illustrates the paired mean difference with 95% CI for each, whilst highlighting the CV, ICC, statistical differences, and effect size between reliability sessions.

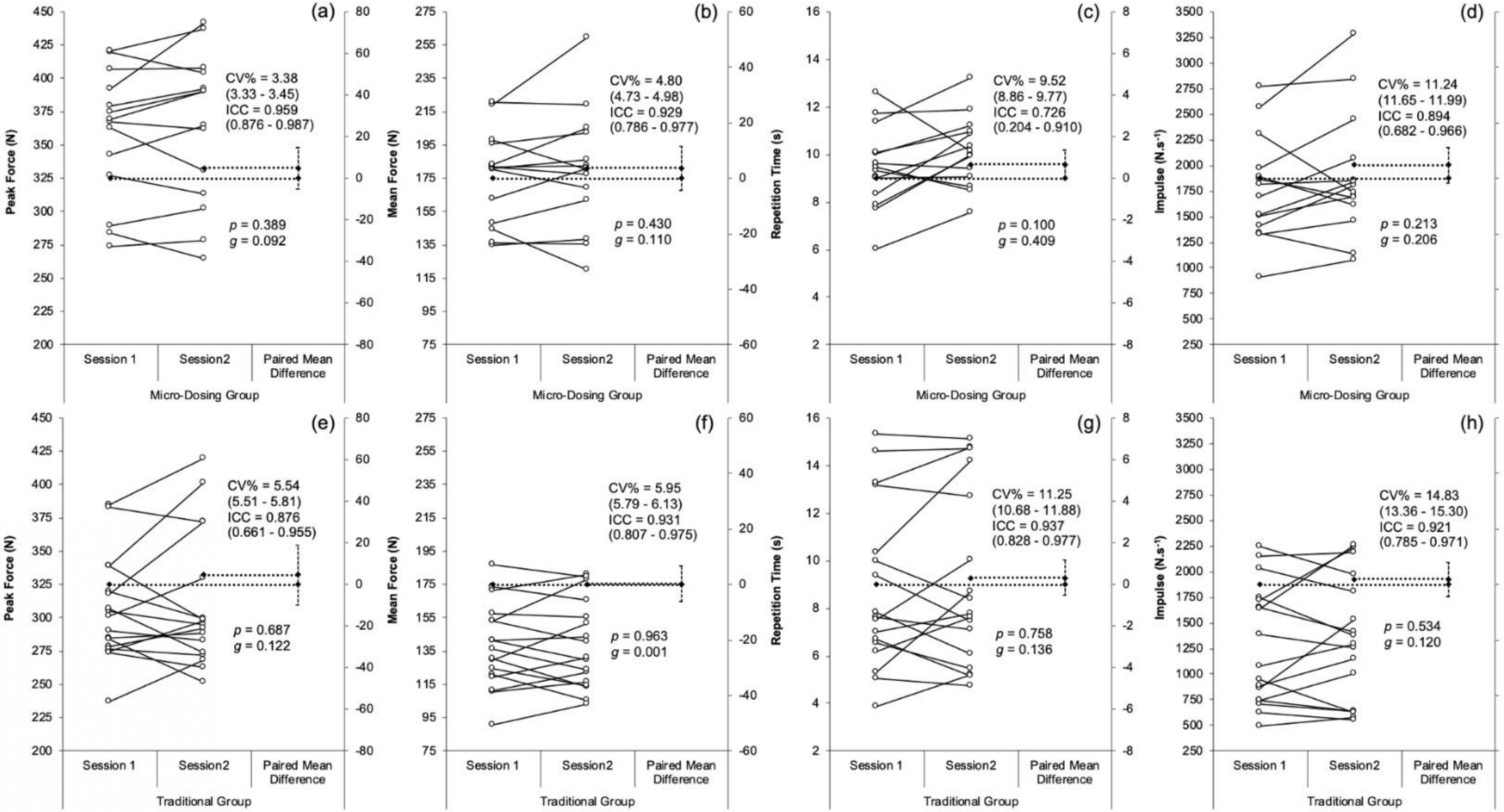


Figure 6.1. Individual plots of the reliability and paired mean differences of the Nordic hamstring exercise variables between-session.

CV = Coefficient of variation; ICC = Intraclass correlation coefficient; N = Newtons; s = seconds; N.s^{-1}= Newtons per second

Table 6.2. Comparison of between-group mean ± SD and effect sizes across the microcycle.

Peak Force (% of previous weeks peak)																		
Repetition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Micro-dosing (Mean ± SD)	97 ± 8	94 ± 6	96 ± 5	95 ± 10	95 ± 8	92 ± 7	97 ± 8	93 ± 9	94 ± 9	97 ± 15	94 ± 8	94 ± 11	95 ± 7	96 ± 4	92 ± 10	94 ± 5	94 ± 6	93 ± 5
Traditional (Mean ± SD)	94 ± 8	92 ± 12	93 ± 11	94 ± 8	95 ± 6	94 ± 8	93 ± 10	92 ± 10	93 ± 8	92 ± 7	92 ± 8	93 ± 7	94 ± 6	94 ± 8	91 ± 5	93 ± 5	92 ± 6	93 ± 8
g	-0.37	-0.26	-0.31	-0.10	< 0.01	0.22	-0.38	-0.15	-0.14	-0.39	-0.17	-0.11	-0.12	-0.32	-0.17	-0.13	-0.29	-0.14
Mean Force (% of previous weeks peak)																		
Repetition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Micro-dosing (Mean ± SD)	87 ± 17	87 ± 9	94 ± 8	86 ± 14	92 ± 13	86 ± 12	93 ± 14	87 ± 12	90 ± 13	89 ± 19	88 ± 11	88 ± 17	84 ± 12	91 ± 8	84 ± 11	84 ± 12	85 ± 9	84 ± 12
Traditional (Mean ± SD)	92 ± 11	89 ± 13	89 ± 9	91 ± 8	91 ± 11	91 ± 11	87 ± 11	87 ± 13	84 ± 10	89 ± 10	88 ± 11	87 ± 11	91 ± 14	91 ± 13	84 ± 12	88 ± 12	86 ± 11	85 ± 11
g	0.29	0.17	-0.53	0.50	-0.07	0.39	-0.43	0.06	-0.52	0.04	-0.02	-0.03	0.52	0.03	0.06	0.27	0.13	0.04

SD = Standard deviation

6.4.2 Differences between groups for repetitions across the microcycle

There were trivial to moderate, yet non-significant differences observed between the micro-dosing and traditional groups in peak force (*g* = -0.37 to 0.22; *p* = 0.870), mean force (*g* = -0.53 to 0.52; *p* = 0.523) for each repetition individually (Table 6.2). Only three repetitions demonstrated a moderate difference, and these three repetitions were not consistently in favour of either the traditional or the micro-dosing groups.

6.4.3 Consecutive days

Analysis of the micro-dosing groups repetitions performed on consecutive days (Table 6.3) demonstrated no significant difference between absolute scores during day 1 and day 2 for peak force (*p* = 0.993). There was, however, a small and significant decrease observed during day 2 when comparing between the fifth repetitions of both day 1 and day 2 for mean force (*g* = -0.24; *p* = 0.039). Individual plots for mean force both on day 1 and day 2 are illustrated in Figure 6.2.

Table 6.3. Comparison of force-time characteristics across consecutive days for the micro-dosing group.

Peak Force (N)						
Repetition	1	2	3	4	5	6
Day 1 (Mean ± SD)	353.31 ± 53.99	346.80 ± 52.96	352.86 ± 50.65	350.39 ± 53.95	350.37 ± 47.30	346.90 ± 48.07
Day 2 (Mean ± SD)	349.00 ± 57.76	343.89 ± 55.92	347.63 ± 59.41	347.50 ± 54.11	343.71 ± 52.48	346.76 ± 53.47
g	-0.08	-0.05	-0.09	-0.03	-0.06	-0.06
Mean Force (N)						
Repetition	1	2	3	4	5	6
Day 1 (Mean ± SD)	173.62 ±35.26	169.75 ± 34.58	174.35 ± 36.51	167.00 ± 35.06	178.70 ± 30.84	168.45 ± 31.31
Day 2 (Mean ± SD	170.55 ± 45.79	167.58 ± 44.18	167.90 ± 36.79	162.82 ±38.84	170.78 ± 33.59	166.67 ± 37.34
g	-0.07	-0.05	-0.17	-0.11	-0.24*	-0.05

SD = Standard deviation

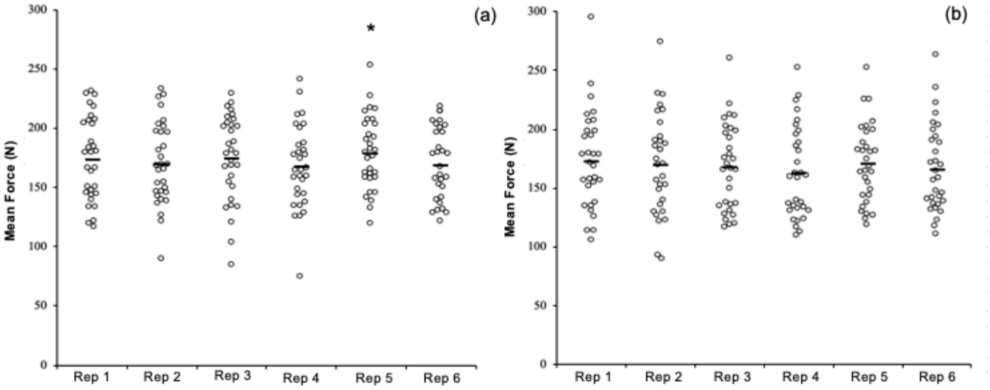


Figure 6.2. Individual plots for mean force between consecutive days.

6.5 Discussion

The aim of this investigation was to assess the differences in force-time characteristics of the NHE across two different volume-equated training frequencies (traditional [2 days per week] vs. micro-dosed [3 days per week]) during an in-season microcycle. Due to the regular scheduling of the microcycle, the effect on the force-time characteristics when performing the NHE on consecutive days was also investigated. Despite a 30% reduction in the number of NHE performed in each set and each bout, trivial to moderate and non-significant differences (g = -0.53 to 0.52; p = 0.870 and 0.523) were observed in peak and mean force between the two groups. There was also no significant difference in peak force between the two consecutive days performed by the micro-dosing group overall (p = 0.993). When the same repetition by repetition analysis was applied to the consecutive days, the only significance was observed in mean force for repetition 5 (p = 0.039).

6.5.1 The microcycle

When comparing the overall microcycle between the micro-dosing and traditional groups, it is evident that only trivial to small differences are present to a non-significant level, with only three repetitions demonstrating moderate differences in mean force between the two groups. This suggests that neither approach was superior, despite as previously highlighted, the 30% difference per set and per day. The potential benefits of no meaningful difference between approaches, coupled with the growing knowledge around lower training volumes still eliciting both strength and architectural adaptations (Chapter 2 [74, 281]), means that practitioners are likely to be able to use a number of different training frequencies based upon changes to schedules, or planned around periods of congested fixtures. Due to the two groups being volume equated, it was possible to compare each repetition between the two groups to gain further insight into whether the way both groups were prescribed made a difference. Although ‘interset rest intervals’ have been investigated at 1 and 3 minutes [282], further research should investigate numerous set configurations as well as the possible benefits of both cluster sets and rest redistribution methods which may remove the occurrence of moderately different repetitions [283].

6.5.2 Consecutive days

Due to periods of fixture congestions or based upon the way some sports teams schedule their training weeks, applying a micro-dosing approach to certain aspects of resistance training may mean that some high intensity and potentially fatiguing actions are required to be performed on consecutive days. It is important to understand if there are any negative implications associated with this to know what exercises in what dosages are appropriate to do so with. The results of this study indicating that even though day 1 was superior in all six repetitions, peak force was not significantly greater than day 2, with only one repetition of mean force showing any level of significance, in addition the magnitude of difference was trivial to small. No meaningful differences demonstrate that with the appropriate dosage, such as the six total repetitions included within this study, the NHE could be completed on consecutive days without any negative effects on performance of the tasks, suggesting that training adaptations are still likely to occur. If players are able to complete a small number of repetitions, with greater regularity and not incur as noticeable reductions in performance and increases in fatigue, the positive implications on compliance could then mean greater benefits in the adaptations associated with completing the NHE [269, 281].

6.5.3 Limitations and areas for future research

Due to this study only investigating the acute effects of two different training frequencies, limiting our knowledge on actual adaptations or maladaptation as a result, further research needs to be applied longitudinally to understand whether similar adaptations occur due to the lack of difference observed within one microcycle. In addition, the way in which the microcycle was structured within the team tested for this study, there was a requirement for the NHE to be executed on consecutive days. Although performing the NHE on consecutive days did not prove to be detrimental, which could make it the most optimal option in some situations, it may not be best practice. Further investigation should therefore consider the configuration of a microcycle, as there may be a potential for some form of repeated bout effect or slight supercompensation if adequate recovery is provided between bouts. Future research should also focus on the within set prescription as the micro-dosing group demonstrated with just two repetitions per set (Table 6.3) there appears to consistently be a decline in all metrics for the second repetition of a set, suggesting that the rest redistribution should be investigated as opposed to using cluster sets to get the best performance in each repetition.

6.6 Conclusion

No meaningful differences were observed in peak force and all but three repetitions for mean force, between a traditional group performing the NHE twice per week and a micro-dosing group performing the same volume across 3 sessions per week, despite a reduction of 30% in each set and day completed. The lack of difference for the majority of the prescription provides practitioners with the ability to divide the total prescribed NHE volume for a given microcycle over at least two or three bouts. With neither approach demonstrating superiority based on the force-time characteristics, the approach taken can be based upon which is most appropriate in relation to competition scheduling and potentially on the need/compliance of players. There were also no differences in peak force or in all but one repetition for mean force between repetitions when completed on consecutive days, suggesting that although it may not be viewed as optimal for adaptation, within periods of fixture congestion, or based on player-availability, performing low volume repetitions of the NHE on consecutive days is unlikely to be detrimental.

6.7 Commentary 5

Most likely due to the appropriately prescribed volumes, no meaningful differences were observed between the two groups across a microcycle, and neither frequency appeared detrimental to the groups. The small relative difference between session volume prescriptions may have aided in there being no meaningful difference. These findings, however, allowed us to carry on further to a 9-week intervention, to try and ascertain whether the lack of meaningful difference that occurred in chapter 6 was maintained across a longer period of training. It was decided that due to no meaningful differences being present in peak and mean force, and the unacceptable reliability observed for impulse and repetition time, we would only investigate peak and mean force rather than any time related variables during the intervention, particularly as it was strength focused so we wanted to understand changes in force production.

7 Chapter 7: A comparison of eccentric strength in response to 9-weeks of traditional vs. micro-dosing Nordic hamstring exercise prescription, in-season.

7.1 Abstract

Background: Hamstring strain injuries account for 17% of all injuries reported by top-flight European soccer teams. The hamstrings also play a critical role in the in the prevention of ACL injuries during deceleration tasks, as well as assisting sprint performance. A range of interventions have demonstrated the effectiveness of the Nordic hamstring exercise (NHE) in increasing strength, yet compliance has been reported to be low amongst soccer players particularly in-season. One potential method of increasing compliance is micro-dosing the total weekly volume to permit additional recovery between bouts. It is not yet known, however, if this approach can apply in-season and whether the increased recovery between bouts will result in greater intensity and in turn a greater adaptation. ***Objective:*** The aim of this study was to compare the change in hamstring force production following a volume equated 9-week intervention between two groups of different weekly training frequencies (two and three times per week). ***Methods:*** Seventeen female academy soccer players were divided into two groups and completed a 9-week intervention, each group were prescribed 18 repetitions per week, with the traditional group completing the prescription equally across two days and the micro-dosing across three and performing 30% less volume per bout. Peak and mean force production data during the NHE were collected pre- and post-intervention. Null-hypothesis significance testing was completed using permutation tests, with 5000 bootstrap samples, alongside Hedge's *g* effect sizes to determine the magnitude of differences between the two groups. ***Results:*** Both groups demonstrated a small increase (*g* = 0.38-0.45) in peak force and moderate increases (*g* = 0.69-0.75) in mean force pre- to post-intervention, no meaningful differences were observed between the groups for either variable (*g* = 0.04-0.11). There was only a small difference between the groups in terms of compliance, however, the individuals who completed > 75% of the total volume observed a large difference (g > 0.85) compared to those who completed < 75%, regardless of group. ***Conclusions:*** Provided that volume prescribed is subsequently completed, the frequency at which it is completed does not appear to have an effect when seeking increases in hamstring strength, allowing flexibility based on the training schedules in-season. Due to the requirement of high compliance rates (> 75%), this flexibility in execution of planned training volume could aid the increase in compliance.

7.2 Introduction

The hamstrings are a muscle group that have had particular attention in scientific literature, due to the high prevalence of hamstring strain injury (HSI) incidence amongst team sport athletes, particularly in soccer [17]. Despite the increased attention, HSI rates remain high with a reported 4% annual increase over a 13-year period [18]. The importance of reducing HSI is not only to reduce the financial burden, where the average cost of a first team soccer player being injured for 1 month is ~ €500,000, but to be successful, teams require their best players to be consistently available for selection [284]. From a developmental perspective, not all HSI's occur in senior players, and for youth athletes greater training availability will permit consistent opportunities to develop physically as well as technically and tactically. One reason for a lack of reduction in HSI's has been hypothesised as a disconnect between the evidence-based research and practice [285]. This has been highlighted by reports that, despite the Nordic hamstring exercise (NHE) being suggested to reduce HSI's by ~ 50% [83], only 11% of elite clubs surveyed [61] utilised a NHE protocol outlined by Mjølsnes et al. [57]. The prescription within the aforementioned protocol has already been highlighted as entailing inappropriate or excessive volumes (Chapter 2), particularly for training in-season.

Although methods used to assess the effectiveness of the NHE has come under some scrutiny [191], it is clear that the exercise is an efficient method of increasing hamstring strength which is a primary risk factor for HSI, among many (e.g., age, fatigue, previous HSI etc. [48]), and is why it should be used as part of a holistic approach to hamstring training [267]. One reason outlined for the poor uptake of NHE protocols in elite clubs is the muscle soreness experienced [61]. Of course, the reduction in volume as suggested in Chapter 2 should help reduce muscle soreness to some extent, however, being a supramaximal eccentric exercise there is still the potential for some soreness to be present following exposure. This is especially true if the NHE exposures are not consistent, as the benefits of the repeated bout effect in reducing the magnitude of impairment will not be present or as prevalent [186]. Also, the hamstrings as a muscle group appear to have a very short residual effect of training, whereby a detraining effect can occur in maximum strength within a four-week period following the cessation of hamstring strength training [74, 286, 287] and detraining effects associated with architectural changes occurring after only 14 days [286, 287]. All these factors provide evidence for how important compliance rates are required to be, with a systematic review and meta-analyses suggesting that compliance of > 50.1% has a positive effect on reducing the occurrence of future HSI with a 139% increase in preventative effect when compliance was > 75.1% [288]. Despite this importance, Ripley et al. [288] reported a lack of detailed reporting of compliance within the literature.

One proposed method for increasing the compliance of appropriate NHE prescription in-season would be to use micro-dosing. Micro-dosing has been defined as "the division of total volume within a micro-cycle, across frequent, short duration, repeated bouts" (Chapter 3), and would allow the distribution of hamstring training across a microcycle (as seen in Chapter 6). Considering the suggestion of programming lower NHE volume overall, provided that sufficient recovery is accounted for, particularly prior to competition, dividing the volume further may allow an increase in compliance due to ease of application, and flexibility of when the stimulus is applied. For example, if each training day 25% of the total NHE volume was planned to be micro-dosed, and changes were made to the schedule, players would either miss a smaller portion of the total prescribed volume compared to a traditional approach, or that 25% could be moved/added to another training day.

Although variations in training frequencies of muscle groups have been previously investigated (Chapter 4) [106, 107], there has not been a specific focus on the hamstrings, particularly following a supramaximal eccentric exercise (i.e., the NHE), during a competitive season. The aim of this study is to compare the changes in hamstring force production between a traditional group (twice per week), and a micro-dosing group (3 times per week) performing 33% less volume per session, across a 9-week, volume matched (based on the planned training volume), intervention. Despite previous researchers having suggested that changes in frequency, when volume matched, will have little effect, it was hypothesised that the micro-dosing group would demonstrate greater improvements in force production due to higher compliance.

7.3 Methods

7.3.1 Participants

Seventeen female soccer players playing within a Women's Super League academy, with experience of resistance training for a minimum of two seasons, volunteered to participate in this study. An *a priori* power calculation was performed using G*Power [289] to determine the minimum number of participants (n = 32; *16 per group*) required for a statistical power ≥ 0.8 at an alpha level < 0.05 with a large effect size (*d* = 0.92), based on the results from a study of similar duration inlcuded in Chapter 2 [59]. Fourteen players (age: 17.4 ± 0.8 years; height: 168.5 ± 3.6 cm; body mass: 63.2 ± 5.1 kg) completed the study due to three players incurring long term injuries. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent, or parental/guardian assent where required, to participate in the study. Ethical approval (HSR1819-037) was granted by the institutional ethics committee in accordance with the declaration of Helsinki.

7.3.2 Experimental design

A between subject's cross-sectional design was used to examine the difference between a micro-dosing approach (n = 6) and traditional approach (n = 8) to the prescription of the NHE across a 9-week intervention. Participants were randomly allocated into the two groups using a random computer-generated assignment tool, they were all then assessed the week prior to the study being conducted, as part of their normal resistance training sessions, to determine their baseline strength.

7.3.3 Procedures

7.3.3.1 Nordic hamstring exercise

To assess eccentric hamstring strength, participants performed the NHE repetitions on the NordBord (Vald Performance, Brisbane, QLD, AUS), they were required to kneel on the padded board with individual ankle attachment points and integrated uniaxial load cells captured the force produced during the movement, with the sampling frequency set at 50 Hz. Participants were asked to execute every NHE repetition maximally, following a thorough warm up, whereby they were instructed to lean forwards slowly (via knee extension alone), whilst resisting the forward motion with both lower limbs, maintaining a neutral hip position, and extending through the knee joint. Force (N) and time (s) data was extracted from the NordBord for further analysis in a bespoke Excel spreadsheet (version 2019, Microsoft Corp., Redmond, WA, USA).

7.3.3.2 Training protocol

A 9-week intervention was applied to both the traditional and micro-dosing groups, who completed 18 NHE repetitions within each microcycle. The micro-dosing group performing 30% less per set and per session but performed the sessions over 3 days compared to 2 for the traditional group. Out of the completed sessions, 80% were carried out on the NordBord due to the equipment being available for use, and force-time data from all repetitions of the players present were recorded during those training sessions. The typical microcycle configuration can be seen in the Chapter 6 (Table 6.1), with slight variations in the scheduling of the additional micro-dosing sessions, due to movement of fixtures and/or training sessions.

7.3.3.3 Data analysis

Raw force-time data for each trial was analysed using a customised Microsoft Excel spreadsheet. The onset of movement was identified when force exceeded 5 times the standard deviation (SD) of the mean of the residual force, peak force was identified as the maximum force produced during the exercise. Mean force (N) was the average of the force produced from onset of movement to the end of active resistance. To make comparisons between groups, percentage difference pre- to post-intervention was calculated.

7.3.3.4 Statistical analyses

Due to the low sample size, a series of permutation tests were performed as null hypothesis significance testing for comparisons pre- to post-intervention and percentage change between the two groups. As part of the permutation tests, five thousand bootstrap samples were taken for each group with the *p* value reported as the likelihood of observing the effect size reported if the null hypothesis of zero difference was true [261]. An *a priori* alpha level was set at ≤ 0.05. Hedge's *g* effect sizes were calculated with 95% confidence intervals and bias-corrected to determine the magnitude of changes both pre- to post-intervention and between both the traditional and micro-dosing groups. Effect sizes were interpreted according to recommendations by Cohen [263]: (≤ 0.19, trivial; 0.20-0.49, small; 0.50-0.79, moderate; ≥ 0.80, large).

7.4 Results

7.4.1 Eccentric hamstring strength

Changes pre- to post intervention for the peak and mean force of both groups are outlined in Table 7.1 with individual data plots presented in Figures 7.1. Both the micro-dosing and traditional groups demonstrated small increases in peak force ($g = 0.38$ and 0.45, respectively) and moderate increases in mean force ($g = 0.69$ and 0.75, respectively). A comparison of the percentage change between the two groups, also highlighted in Table 7.1, illustrates that no meaningful difference was present for both peak ($g = 0.11$) and mean ($g = 0.04$) force.

Table 7.1. Pre- to post-intervention changes in peak and mean force, and between-group differences.

	Micro-dosing (n = 6)		Traditional (n = 8)		Difference (%)	
Peak force (N)	Pre	Post	Pre	Post	Micro-dosing	Traditional
Mean	316.11	334.45	302.79	325.18	4.53	6.30
SD	38.81	49.41	43.12	51.62	0.12	0.10
p	0.45		0.12		0.82	
g [95% CI]	0.38 [-0.26, 1.47].		0.45 [-0.10, 0.94]		0.11 [-1.14, 1.25]	
Mean force (N)						
Mean	146.87	176.18	139.68	165.05	14.21	14.87
SD	34.09	43.34	33.67	30.04	0.20	0.16
p	0.20		0.05		0.92	
g [95% CI]	0.69 [-0.03, 1.74]		0.75 [-0.10, 1.72]		0.04 [-1.11, 1.31]	

SD = Standard deviation; CI = Confidence interval

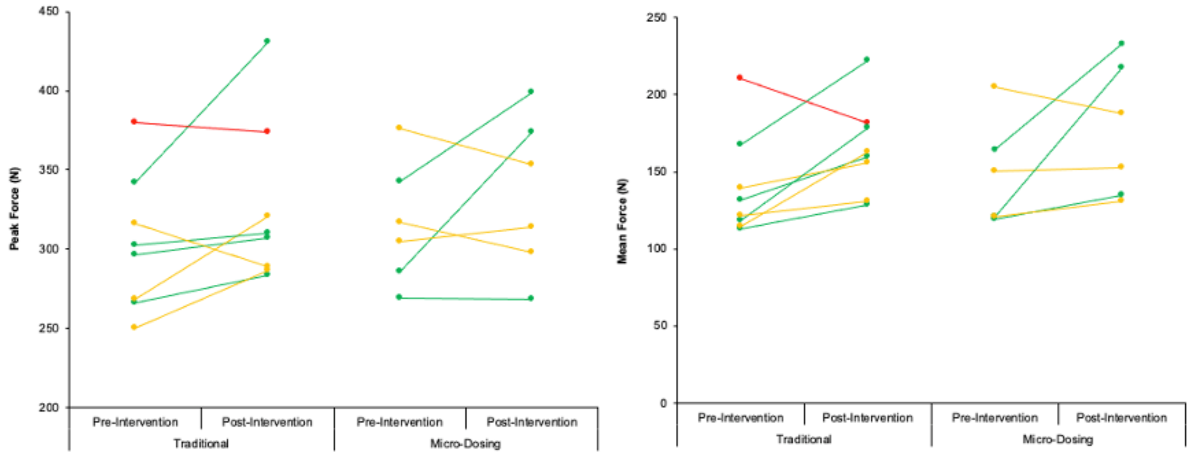


Figure 7.1. Individual plots for peak and mean force pre- and post-intervention in both the micro-dosing and traditional groups.

Red lines < 50% compliance; Amber lines = 50.1-75% compliance; green lines > 75% compliance.

7.4.2 Compliance

Figures 7.1 also depict the pre- to post-intervention change for individuals based on three compliance thresholds (< 50%, 50.1-75% and > 75%). Between the micro-dosing (75.3 ± 7.7) and traditional groups (68.8 ± 15.8), compliance was greater in the micro-dosing group albeit a small effect (g = 0.47) (Figure 7.2). When pooling the data in regard to compliance rates, those who completed > 75% of the prescribed training volume, experienced a greater improvement in both peak and mean force (g = 0.85 and 1.40, respectively) compared to those who performed < 75% (Figure 7.3).

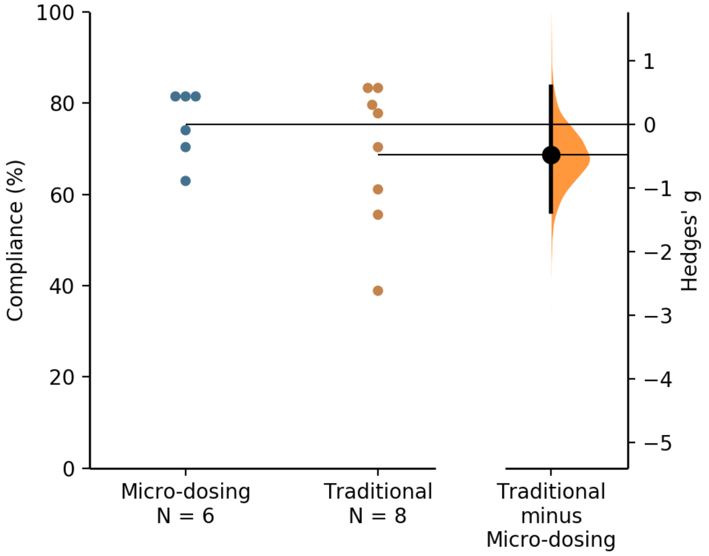


Figure 7.2. Individual comparison of compliance between the micro-dosing and traditional groups.

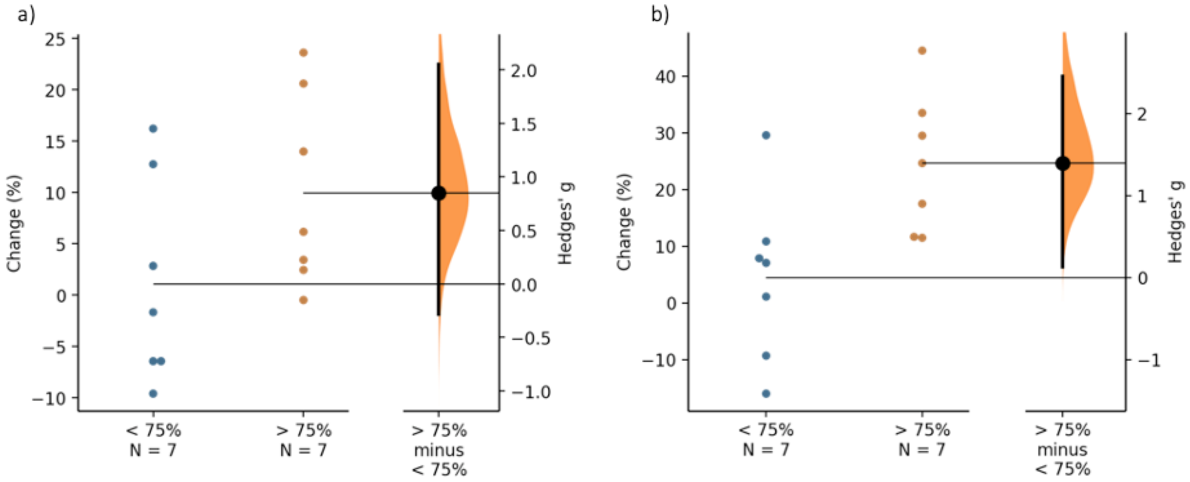


Figure 7.3. Pooled percentage change for individuals < 75% and > 75% compliance for (a) peak and (b) mean force.

7.5 Discussion

The aim of this investigation was to compare the effect of dividing a low volume traditional hamstring strength prescription, into micro-dosed sessions, on hamstring force production following a 9-week intervention. The findings indicate that although small and moderate increases pre- to post-intervention were observed in peak and mean force, respectively, there was no meaningful difference between the two groups despite a slightly greater compliance rate in the micro-dosing group.

During the competitive season it is important to at least maintain, if not develop, physical characteristics, particularly in team sports whereby the competitive seasons span over several months. Although the hamstrings have numerous injury risk factors [48], hamstring strength is a modifiable risk factor that can be accounted for during in-season training, but strength losses can also be observed quickly when hamstring training is not accounted for [74, 286, 287]. Previous NHE interventions have included a large range of volumes and durations (Chapter 2), and none of the interventions included within a recent systematic review and meta-analyses have used volumes as low as the current study across the same duration. Ishøi et al. [59] completed a study over a similar duration (10 weeks) and demonstrated large (*g* = 0.91) increases in hamstring peak force production pre- to post-intervention based on the criteria used within this study and there was little difference in baseline strength between Ishøi et al. [59] and the current study. One clear reason as to why, in comparison, only small increases in peak force were observed in the current study was the difference in prescribed volume. The study from Ishøi et al. [59] included 700 repetitions across the 10-week intervention, compared to 162 repetitions in the current study. Although Ishøi et al. [59] completed their intervention in-season, only 60% compliance was reported, which is still allowed for over 400 repetitions to be completed by the participants. Considering within this study those who completed > 75% of the repetitions experienced comparably large increases in peak and mean force compared to those of lower compliance, further evidence has been provided here that lower prescriptions in-season can be just as effective providing the consistent execution of the prescribed repetitions in agreement with previous conclusions (Chapter 2).

In line with the results from previous training frequency meta-analyses (Chapter 3) [106, 107] there was no meaningful difference between the two frequency groups in this study. The main reason for the trivial difference, in this instance, is likely to be due to the small difference in compliance, meaning there was a very similar total volume completed by each group. Another consideration between the two groups would be their baseline strength pre-intervention. Although the differences between the groups were trivial, the traditional group did increase their strength slightly more in comparison to the micro-dosing group, however, the traditional group was slightly weaker (*g* = 0.31) at baseline so potentially have a greater propensity for adaptation.

Due to the intervention being executed in-season, three players were required to drop-out due to injuries which occurred during match-play. As a result of the injuries, the already small squad was reduced further, resulting in a small sample size overall which is a clear limitation to this study. Another limitation could have been that despite there being a 30% reduction in volume performed per set and per session in the micro-dosing group, due to the already small volume prescriptions the difference was only 1 less repetition per set, meaning a greater difference may have been observed if there were a greater number of sessions in which the total volume was micro-dosed across. Alternatively, if the distribution of volume is to have a greater benefit in this instance, then it may be insightful to investigate a greater total volume, albeit still a dramatically lower volume when compared to the original NHE protocols [57]. Future research should also look to utilise a cross-over design. With no meaningful difference between the two groups, a small increase in both pre- to post-intervention, and considering the length of competitive season for a lot of team sports, a consistent increase in peak force in theory will result in a greater magnitude of change across a season. Future research should, therefore, also look to investigate these two approaches over much longer durations.

7.6 Conclusion

Consistent with previous literature, no meaningful differences between the two frequency groups were observed following the 9-week intervention period. Despite no differences being present between the groups, small to moderate increases in peak and mean force occurred pre- to post-intervention in both groups. For those who had a compliance rate > 75%, large increases in peak and mean force were observed compared to those who completed < 75%. Although it was hypothesised that the micro-dosing group would see greater improvements due to a greater compliance, it can be concluded that providing the prescribed volume is completed, the intended outcome (in this instance, increases in hamstring strength) will be achieved, even in-season. Therefore, an approach that allows flexibility based on the individuals should be utilised by practitioners to allow for maximising compliance of a programme.

7.7 Commentary 6

The findings of chapter 7 were much like those observed in chapter 6 with no meaningful differences between the groups over a 9-week intervention period. The findings of both these chapters mean that when considering a single exercise for a single muscle group, coaches/practitioners can be flexible in the frequency in which they programme. Even when considering a supramaximal exercise such as the NHE. Following chapters 6 and 7, we then needed to observe whether the same patterns are present when applying the principle to a full lower body strength training intervention and not just a hamstring strength exercise. The next two chapters (8 and 9) include the strength training intervention that has been expanded to include the full lower body with a reliability study preceding. Although these remaining chapters could easily have formed one study, the reliability chapter (chapter 8) allows us to delve deeper into some of the statistical methodologies, without distracting from the overall aim of the thesis.

8 Chapter 8: Pre-intervention between-session reliability of force production characteristics and performance measurements in academy soccer players.

8.1 Abstract

Background: There are different ways in which performance measurements can be used to inform practice in sports science/strength and conditioning including monitoring of acute and chronic changes in numerous metrics to make inferences around adaptations and readiness. Regardless of the measurement or metric used there is a requirement to understand the reliability within a given population for inferences to be taken and for conclusions/decisions to me made. It is important to have a strong rationale for the method of analyses which can strengthen the scientific rigour in which findings are determined. ***Objective:*** The aim of this study was to identify the reliability of measurements for a battery of performance tests and the associated reliable metrics for a subsequent training intervention. ***Methods:*** Nine male academy soccer players completed a battery of force production and performance tests including the countermovement jump (CMJ), isometric mid-thigh pull (IMTP), Nordic hamstring exercise (NHE), 20 metre sprint, and 505 change of direction test, on two occasions a week apart. Null-hypothesis significance testing using permutation tests with 5000 bootstrap samples and Hedge's g effect sizes were calculated to determine differences between test occasions. Absolute and relative reliability (coefficient of variation [CV] and interclass correlation coefficient [ICC]) was calculated for all variables between-session. Minimal detectable change was also calculated to help determine meaningful changes following a subsequent intervention. ***Results:*** Trivial to small differences ($g \leq 0.48$) were present between testing occasions for all variables apart from those associated with IMTP ($g = -0.63$ to -0.92). All CMJ variables (CV ≤ 8.39%, ICC ≥ 0.822) apart from reactive strength index modified (RSImod) (CV = 10.10%, ICC = 0.815) indicated acceptable reliability. Relative peak force during both the IMTP and NHE, and the 20 m sprint as well as the corresponding splits (i.e., 5 and 10 m) were also reliable (CV ≤ 9.86%, ICC ≥ 0.701). The only reliable variable associated with the 5-0-5 change of direction test was total time to completion (CV ≤ 1.87%, ICC ≥ 0.668). Minimal detectable change for all reliable variables was < 27.32%. ***Conclusions:*** All maximum sprint, peak force production, CMJ variables (minus RSImod), and 5-0-5 time to completion were determined to show acceptable reliability between-session amongst a cohort of male academy soccer players. The reliable variables can be utilised for assessment of any pre- to post- adaptations resulting from performance interventions.

8.2 Introduction

Performance measurements have been collected, interpreted, and utilised in several ways by sports science/strength and conditioning practitioners. Effectively understanding current performance levels of athletes can help inform programming, monitor acute changes in performance during training, evaluate chronic adaptations or maladaptation from a previous training phase, allow comparison to normative data, or even potentially monitor fatigue (i.e., a reduction in neuromuscular function) [290]. Monitoring and evaluating changes in performance measures can and should inform decision making, however, it is imperative that both the validity and reliability of any measure is fully understood before making decisions that could impact athletes acutely or chronically [291]. From a research perspective this could also impact the efficacy of a treatment/intervention, as data which is not reliable or possesses a large measurement error will then cause misinterpretation of the findings and decisions regarding acute or chronic changes to interventions will be ill informed. Whilst measures of validity can often be generalised across populations [292], the reliability of measures should be determined using each practitioners own testing equipment and within each population as opposed to relying on previously published reliability data [290]. If reliability is poor and measures are too variable, especially between sessions, then interpreting the subsequent data and making decisions, assessments, or conclusions based on the information could be sub-optimal or in some cases completely wrong. Reliability is defined as the consistency of measurements and absence of measurement error, although realistically there is always likely to be some amount of error (be that through the measurement device, the investigator, or even just the inherent mechanical/biological variation of the subject). Reliable measures are therefore those that are within an acceptable range for effective practical use [291].

There are two types of reliability, relative and absolute [292]. Relative reliability takes into consideration the degree to which individuals within a sample maintain their position following a repeated measures approach and is typically assessed using some form of correlation coefficient. Atkinson and Neville [291] suggest that the bivariate Pearson's correlation coefficient has been the most common technique, however, this approach has been criticised for being dependent on a large range of values in the sample [293] and only permits comparisons between two trials or time-points. An alternative is the univariate intraclass correlation coefficient (ICC), which has the advantage of being able to be utilised for multiple retest comparisons providing the correct method of calculation is used out of the possible six calculations [292]. The ICC (derived from a mixed model [ICC 3,1] [262]) has been demonstrated to be unbiased for any sample size unlike the Pearson's correlation, however, it is still prone to the same constraints of being affected by sample heterogeneity [294]. When considering sample heterogeneity (the spread of values), if the sample is not heterogeneous and in fact homogenous, the individuals scores may appear artificially scattered randomly as this replicates a small subsample of a heterogenous population [294]. Despite this disadvantage, the reporting of ICCs has still been recommended for reliability studies [262, 295] but not as the sole statistic [291].

In contrast to relative reliability, absolute reliability has been defined as the degree to which repeated measures vary for individuals either trial to trail (i.e., within-session) or between-session. The most common method of estimating absolute reliability is using the standard error of measurement (SEM), expressed as either the actual unit of measure, or as a proportion of the measured values (e.g., percentage), for example the coefficient of variation (CV%) [291]. The benefit to using a form of SEM is that it is considered to be a fixed characteristic, regardless of the sample of subjects investigated [295]. The most common method of estimating the SEM is the group standard deviation multiplied by the square root of 1 minus the ICC [291, 292, 295]. We have already highlighted, however, some of the potential pitfalls of ICCs as a calculation. Hopkins [294] has suggested an alternative calculation of SEM, termed 'typical error', whereby standard deviation of the difference in scores is divided by the square root of 2 for between-session reliability. This calculation accounts for the fact that both testing occasions will have some level of measurement error, rather than just simply observing whether the second score falls outside of the CI of the first [295]. The absolute reliability through SEM can also be used as an index to define the difference needed between testing occasions to determine a 'real' change (e.g., minimal detectable change [MDC]). The MDC has been described as a value in which true change can be confidently interpreted due to surpassing the 95% confidence interval either above or below the subjects previous score.

Despite the importance of determining reliability of measurements between testing occasions in each population, and the subsequent calculations to determine what would be considered as a ‘real change’, of the ten intervention studies included within Chapter 3 the majority failed to identify any measures of between-session reliability [109, 111, 113-115, 117]. Of those studies that did provide a between-session reliability measure, the majority described ICCs that had been previously collected in their laboratory and not in the study population [112, 118, 122]. Not only were these measures not reported with reference to the population they were calculated in, the method of ICC calculation was also not stated. Atkinson and Neville [291] suggest that extreme caution should be taken when extrapolating between-session correlations that have been deemed acceptable to a new and possibly more homogenous sample of individuals.

The aim of this study was therefore to identify both relative and absolute between-session reliability of force-time characteristics during the countermovement jump (CMJ), isometric mid-thigh pull (IMTP) and the Nordic hamstring exercise (NHE), and performance characteristics observed during a 20 m sprint and 505 change of direction (COD) test in a group of youth soccer players. The calculation of MDC was also included to help identify the most appropriate measures to detect change in individuals. The investigation of both reliability and measurement error will aid in the identification of appropriate variables to assess individuals in a subsequent training intervention within the same cohort. It was hypothesised that all variables would be demonstrate acceptable reliability, apart from the time related IMTP variables due to the athletes’ resistance training experience.

8.3 Methods

8.3.1 Experimental design

This study used a within-subject repeated measures research design, whereby the between-session reliability of the CMJ, IMTP, NHE, 5-, 10- and 20 m sprint and 505 change of direction test were completed with a group of academy soccer players. Each test was performed on two-separate occasions 7 days apart. Testing took place in-season, mid-week, to be the furthest time-point away from the preceding and following fixture of each week. The CMJ, IMTP, 20 m sprint, 505 COD and NHE were completed, in that order, on both testing occasions.

8.3.2 Participants

Nine participants, consisting of academy soccer players playing from a Category 2 English Football League Academy volunteered to participate in this study (age: 17.11 ± 0.78 years; height: 1.82 ± 0.85 cm; body mass: 72.11 ± 7.15 kg) and completed the assessments at each of the three timepoints. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent, or parental/guardian assent where required, to participate in the study. Ethical approval (HSR1819-089) was granted by the institutional ethics committee in accordance with the declaration of Helsinki.

8.3.3 Procedures

Prior to testing, a non-fatiguing standardised warm-up was performed by all participants which consisted of body weight squats, forward, reverse and side lunges, single leg Romanian deadlifts and submaximal countermovement jumps. The order of testing was as follows: CMJ, IMTP, 20 m Sprint, 5-0-5 COD test, and the NHE. Testing was completed at the same time of day (09:00-11:00) for all time points and prior to any other activities.

8.3.3.1 Countermovement jumps

The CMJs were assessed using dual force platforms (Hawkin Dynamics, Maine, Portland, USA) sampling at 1000 Hz with a 50 Hz cut-off filter (as determined by the Hawkin Dynamics software package), to permit the assessment of force-time characteristics. Variables included jump height (derived from the velocity of the centre of mass at take-off, based on the impulse momentum relationship [278]), and time to take-off (TTT) as the duration (in seconds) from the onset of movement until the participant leaves the force platform. Reactive strength index modified (RSImod) was calculated as jump height divided by contraction time (i.e., TTT), countermovement depth was the distance (in cm) the athletes centre of mass travelled downwards in the countermovement, mean propulsive force was the average force produced (in Newtons) during the propulsive phase and propulsive phase duration (in seconds) was also calculated. The force platform was placed upon a hard solid, flat surface and zeroed prior to the instructions being given to participants. Participants were instructed to stand on the force platform, as still as possible with their hands on their hips for at least one second of quiet standing before being instructed to jump as high and as fast as possible. Three repetitions were completed by each participant.

All of the force-time data was calculated using the software provided by Hawkin Dynamics and exported for further statistical analyses, however, it is still important to provide a detailed summary of calculations used. Jump height was calculated from velocity of centre of mass at take-off, with centre of mass velocity determined by dividing vertical force data (minus body weight) by body mass and then integrating the product using the trapezoid rule, based on the impulse momentum theorem [278]. The trapezoid rule is simply an integration method of calculating area under the curve by dividing that area into a number of trapezoids. Whilst the impulse momentum theorem is logically equivalent to Newton' second law and states that the change in momentum of an object is equal to the impulse applied to it. The start of the CMJ was identified based on a decrease in force > 5 standard deviations of the force during the 1 second period of quiet standing with a backward search to bodyweight, and take-off identified when vertical force decreased below 20 N. Time to take-off was determined as the duration between the onset of movement and the instant of take-off. RSImod was calculated by dividing jump height by TTT [278]. The propulsion phase was identified as the period between the start of when positive centre of mass velocity was achieved, through to take-off, with propulsion phase duration and mean propulsive force subsequently calculated.

8.3.3.2 *Isometric mid-thigh pull*

The IMTP was assessed in a custom isometric rig (Absolute Performance, Cardiff, Wales, UK) using dual force platforms (Hawkin Dynamics, Maine, Portland, USA) again sampling at 1000 Hz with a 50 Hz cut-off filter to permit the assessment of peak force and time-related variables. The force platforms were zeroed before participants were instructed to stand on them and adopt the posture assumed for the second pull phase of a clean, (knee angle of 125-145° and a hip angle of 140-150°, and an upright trunk). The participants hands were strapped to a fixed cold rolled steel bar with angles at the hip and knee were assessed using a handheld goniometer (IDASS Fitness Ltd, Devon, UK). Prior to each trial participants were instructed to 'push as hard and fast as possible' against the force platforms [296]. Two warm-up trials were performed at 50% and 75% perceived exertion, separated by 1-minute of rest. Three maximal trials were performed, interspersed by 2-minutes of rest. Acceptable trials were taken provided there was (1) at least one second of quiet standing prior to the pulling that represented bodyweight (with less than 50 N of pre-tension), (2) they did not exhibit a countermovement based on visual inspection of the force-time trace, and (3) trials were within 250 N of each other based on the peak force [296]. Subsequently force at 150-, 200- and 250 ms were determined.

Analysis of the force time data was carried out using the Hawkin Dynamics software and exported for further statistical analyses. The peak force was determined as the highest force achieved (minus body mass). The onset of force production (initiation of the pull) was defined as an increase in force > 5 standard deviations of force during the period of quiet standing, with a backward search to bodyweight [297]. All trials were ratio scaled (force / body mass) as the tests are to be used for a subsequent intervention study where body mass could change over time.

8.3.3.3 *Nordic hamstring exercise*

Eccentric hamstring strength was assessed by performing three repetitions of the NHE on a NordBord (Vald Performance, Brisbane, QLD, AUS). Participants were required to kneel on the padded board with individual ankle attachment points resting superior to the malleolus and integrated uniaxial load cells captured the force produced during the movement [255], with the sampling frequency set at 50 Hz with no cut-off filter. Participants were asked to execute all three NHE repetitions maximally, following a thorough warm up, whereby they were instructed to cross their arms over their chest (until break point), maintain a straight posture (maintaining a neutral hip position), and lean forwards slowly via knee extension alone, whilst resisting the forward motion with both lower limbs. The rest intervals between each trial were 1 minute. Peak force (N) data was extracted from the Vald Performance software and ratio scaled (force / body mass) again as the tests are to be used for a subsequent intervention study where body mass could change.

8.3.3.4 *20 m sprint*

20 m sprints tests were performed with 5- and 10 m splits, using Brower timing cells (model number BRO001; Brower, Draper, UT, USA) on artificial turf at an indoor facility. Participants performed two warm-up trials at

50% and 75% effort, with three maximal trials being performed, interspersed by 1-minute of rest. Participants started 0.5 m behind the photocell gates, to prevent any early triggering of the initial start gate, from a 2-point staggered start. All participants performed sprints prior to a pitch-based session using timing cells setup at 0-, 5-, 10- and 20 m. Timing cells were placed at the approximate hip height for all participants to ensure that only one body part, such as the lower torso, broke the beam.

8.3.3.5 505 Change of direction test

Change of direction performance was assessed utilising a traditional 505 test on the same surface as the sprint trials (artificial turf). All participants performed three trials for each leg, with a 2-minute rest between trials. Participants started 0.5 m behind the photocell gates, again to prevent any early triggering of the initial start gate, from a 2-point staggered start. Timing gates were also placed at the approximate hip height for all participants. Participants were instructed to sprint to a line marked 15 m from the start line, placing the instructed foot on the line, turn 180° and sprint back 5 m through the finish. The time to completion (in seconds) for the whole 505 test as well as the turn time (final 5 m and back) was used for further analysis. Change of direction deficit was also calculated by subtracting the mean 10 m time from the turn time [298].

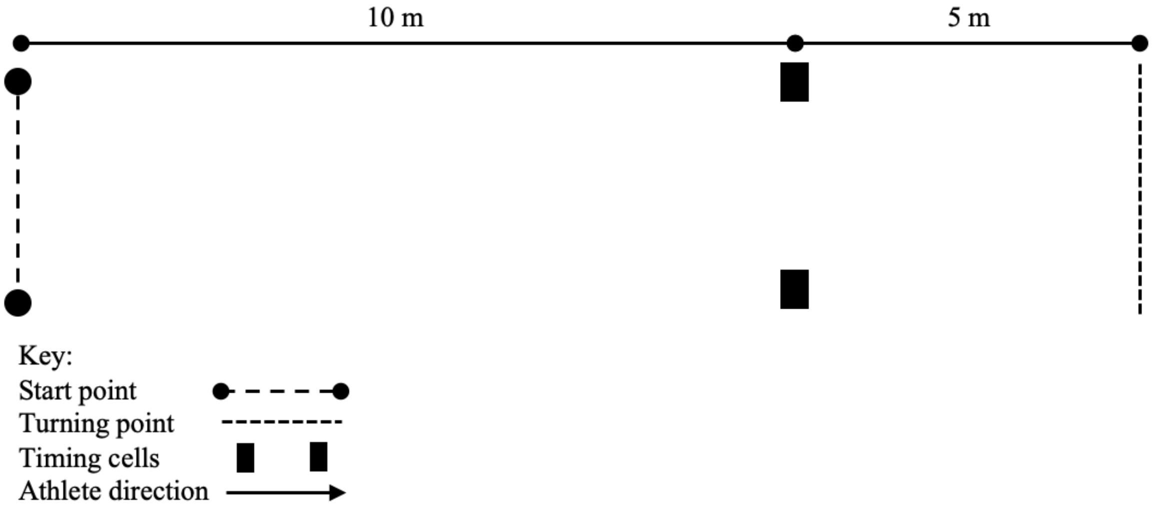


Figure 8.1. A depiction of the 505 change of direction test.

8.3.3.6 Statistical analyses

Statistical analyses for reliability were conducted using SPSS for Windows version 24 (IBM SPSS Inc, Chicago, IL) and EstimationStats.com [261] with data presented as the mean ± SD. Null hypothesis significance testing was carried out using a series of permutation tests for each comparison pre- to post-intervention as well as for the percentage change between groups. Five thousand bootstrap samples were taken for each group as part of the permutation tests with the *p* value reported as the likelihood of observing the effect size reported if the null hypothesis of zero difference was true [261]. An *a priori* alpha level was set at ≤ 0.05. Effect sizes were calculated using Hedge's *g* with the 95% confidence interval (CI) to determine the magnitude of change pre- to post-intervention and magnitude of difference between the traditional and micro-dosing groups. Effect sizes were interpreted according to recommendations by Cohen [263]: (≤ 0.19, trivial; 0.20-0.49, small; 0.50-0.79, moderate; ≥ 0.80, large), The SEM was calculated as the SD of difference scores (i.e., session 2 – session 1) divided by √2. Absolute reliability was calculated using percentage (CV%), whereby the SEM was divided by the average of group means and expressed as a percentage (multiplied by 100), with acceptable reliability < 10% [279]. Relative reliability was assessed using intraclass correlation coefficients [ICC 3,1] with 95% confidence intervals (CI) and interpreted as (< 0.50) poor, (0.5-0.74) moderate, (0.75-0.90) good and (> 0.90) excellent. Although Koo et al. [262] have previously recommended interpreting ICC's based on the lower bound CI, the homogeneity of the group will likely result in a large range in the CI and therefore the thresholds were based on the ICC and not the lower bound 95%CI. The MDC was calculated as follows: ((SEM x 1.96) x √2), with SEM calculated as the SD of difference in scores (i.e., session 2-session 1) divided by √2. Variables were interpreted as acceptably reliably providing the ICC was not poor and the CV was below the 10% threshold outlined.

8.4 Results

8.4.1 Force-time characteristics

Means (± SD) and 95% CI for all force-time related variables during both testing sessions can be seen in Table 8.1, alongside the between-session means (± SD) and reliability statistics. All CMJ variables, other than RSImod and TTT, demonstrated excellent relative reliability (ICC ≥ 0.934) and acceptable absolute reliability (CV ≤ 6.78%). RSImod, which showed greater variability (CV = 10.10%), despite having a 'good' level of relative reliability (ICC = 0.815). Good relative reliability was also observed in TTT (ICC = 0.822). The TTT, countermovement depth, mean propulsive force, and propulsive phase duration also demonstrated an acceptable level of absolute reliability (CV = 8.39%). Trivial to small differences between testing sessions were observed for all CMJ variables (*g* = -0.38 to 0.19). The only IMTP variable exhibiting acceptable relative and absolute reliability was relative peak force (ICC = 0.701; CV = 5.05%). Force at different time points demonstrated poor relative reliability (ICC ≤ 0.007) and did not exhibit acceptable absolute reliability (CV ≥ 12.23%). Moderate to large differences (*g* = -0.92 to -0.63) between the testing sessions, in favour of session 1, was observed for all IMTP variables. All NHE variables demonstrated good relative reliability (ICC ≥ 0.745) and acceptable absolute reliability (CV ≤ 9.86). Moderate differences (*g* = -0.46 to -0.42) between testing occasions, again in favour of session 1, was observed in all NHE variables. Although there are no criteria for the interpretation of MDC, in this study the outcome measures for CMJ and IMTP such as jump height and relative peak force appear to be realistic values (< 15%) to surpass following a training intervention.

Table 8.1. Between-session reliability of force-time characteristics.

	Session 1	Session 2	Between-Session					
Countermovement jump	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)	CV% (95% CI)	ICC (95% CI)	MDC%	*p*	*g*
Jump height (m)	0.34 ± 0.04 (0.31, 0.37)	0.33 ± 0.04 (0.30, 0.36)	0.34 ± 0.04 (0.16, 0.66)	3.55 (1.81, 6.96)	0.939 (0.740, 0.986)	9.84	0.12	-0.22 (-0.51, 0.11)
Time to take-off (s)	0.62 ± 0.10 (0.55, 0.70)	0.64 ± 0.09 (0.57, 0.71)	0.63 ± 0.09 (0.32, 1.24)	8.39 (4.28, 16.44)	0.822 (0.237, 0.960)	23.26	0.49	0.19 (-0.35, 0.71)
RSImod	0.57 ± 0.13 (0.47, 0.67)	0.53 ± 0.07 (0.46, 0.58)	0.55 ± 0.10 (0.28, 1.08)	10.10 (5.16, 19.81)	0.815 (0.268-0.957)	28.01	0.16	-0.38 (-0.79, 0.14)
Countermovement depth (cm)	-0.24 ± 0.07 (-0.19, -0.30)	-0.25 ± 0.07 (-019, -0.30)	-0.25 ± 0.07 (-0.13, -0.48)	7.58 (3.87, 14.85)	0.968 (0.746, 0.986)	-21.01	0.91	-0.02 (-0.30, 0.20)
Mean propulsive force (N)	1681.68 ± 312.28 (1441.63, 1921.72)	1668.69 ± 2365.71 (1427.40, 1909.97)	1675.18 ± 313.09 (854.68, 3283.35)	4.03 (2.06, 7.90)	0.978 (0.906-0.955)	11.18	0.79	-0.04 (-0.34, 0.11)
Propulsive phase duration (s)	0.20 ± 0.04 (0.17, 0.23)	0.20 ± 0.04 (0.17, 0.23)	0.20 ± 0.04 (0.10, 0.40)	6.78 (3.46, 13.28)	0.934 (0.546-0.971)	18.78	0.68	0.06 (-0.26, 0.41)
Isometric mid-thigh pull								
Relative peak force (N/kg)	36.55 ± 3.24 (34.06, 39.06)	32.93 ± 4.17 (29.75, 36.14)	34.74 ± 3.70 (17.72, 68.08)	5.05 (2.58, 9.91)	0.701 (-2.610, 0.937)	14.01	< 0.01	-0.92 (-1.42, -0.53)
Relative force at 150 ms	21.62 ± 2.33 (19.83, 23.39)	18.95 ± 3.23 (16.47, 21.44)	20.29 ± 2.78 (10.35, 3.76)	14.98 (7.64, 29.36)	-0.128 (-0.527, 0.478)	41.53	0.10	-0.90 (-1.96, 0.27)
Relative force at 200 ms	24.99 ± 2.54 (23.02, 26.96)	22.47 ± 3.50 (19.76, 25.18)	23.73 ± 3.02 (12.11, 46.51)	13.62 (6.95, 26.70)	-0.095 (-0.548, 0.523)	37.76	0.14	-0.78 (-1.87, 0.37)
Relative force at 250 ms	26.57 ± 2.27 (24.82, 28.32)	24.52 ± 3.80 (21.60, 27.42)	25.55 ± 3.03 (13.03, 50.07)	12.23 (6.24, 23.97)	0.007 (-0.533, 0.612)	33.90	0.20	-0.63 (-1.57, 0.34)
Nordic hamstring exercise								
Relative Bilateral Force (N/kg)	9.61 ± 1.51 (8.45, 10.78)	8.92 ± 1.35 (7.89, 9.96)	9.26 ± 1.43 (4.73, 18.16)	8.55 (4.36, 16.75)	0.776 (0.124, 0.948)	23.69	0.10	-0.46 (-1.05, 0.10)
Relative Left Force (N/kg)	4.95 ± 0.92 (4.24, 5.67)	4.53 ± 0.68 (4.03, 5.06)	4.74 ± 0.80 (2.42, 9.28)	9.86 (5.03, 19.32)	0.745 (0.033, 0.940)	27.32	0.09	-0.48 (-1.19, 0.02)
Relative Right Force (N/kg)	4.67 ± 0.70 (4.11, 5.20)	4.35 ± 0.72 (3.80, 4.89)	4.51 ± 0.71 (2.30, 8.83)	8.17 (4.17, 16.01)	0.826 (0.280, 0.960)	22.64	0.08	-0.42 (-0.88, 0.11)

SD = Standard deviation; CI = Confidence interval; CV = coefficient of variation; ICC = Intraclass correlation coefficient; SEM = Standard error measurement; MDC = Minimal detectable change; RSImod = Reactive strength index modified

8.4.2 Sprint and change of direction performance

The means (± SD) and 95% CI for all sprint and COD variables for testing occasions are included in Table 8.2. The relative reliability observed for all split times during the 20 m sprint had moderate to good relative reliability (ICC = 0.702-0.843) and acceptable absolute reliability (CV $\leq$ 3.26%). Sprint times for both testing sessions have been outlined to demonstrate the variability in rank order which resulted in the large confidence intervals observed (Figure 8.2). Time to completion for both left and right legs during the 505 COD test were moderately reliable from a relative perspective (ICC = 0.668-0.723) with acceptable absolute reliability (CV $\leq$ 1.87%). Change of direction deficit, however, was observed to have good relative reliability but unacceptable absolute reliability (CV $\geq$ 10.90%). All sprint and change of direction variables demonstrated trivial to small differences (g = -0.21 to 0.28) between testing occasions. All split times for the 20 m sprint and the time to completion for the 505 COD test also demonstrate a proportionate MDC (< 10%) that appears realistic when considering improvements following a training intervention.

Table 8.2. Between-session reliability of sprint and change of direction performance measurements.

	Session 1	Session 2	Between-Session					
20 m Sprint	Mean ± SD (95% CI)	Mean ± SD (95% CI)	Mean ± SD (95% CI)	CV% (95% CI)	ICC (95% CI)	MDC%	*p*	*g*
5 m (s)	1.06 ± 0.06 (1.02, 1.11)	1.08 ± 0.04 (1.05, 1.10)	1.07 ± 0.05 (0.55, 2.10)	3.26 (1.67, 6.40)	0.702 (-0.321-0.933)	9.05	0.45	0.23 (-0.50, 1.23)
10 m (s)	1.81 ± 0.06 (1.76, 1.86)	1.80 ± 0.05 (1.76, 1.84)	1.81 ± 0.06 (0.92, 3.55)	1.71 (0.87, 3.36)	0.843 (0.318-0.964)	4.75	0.55	-0.17 (-0.61, 0.43)
20 m (s)	3.08 ± 0.09 (3.02, 3.15)	3.10 ± 0.08 (3.04, 3.17)	3.09 ± 0.08 (1.59, 6.06)	1.57 (0.80, 3.07)	0.802 (0.157-0.955)	4.34	0.44	0.21 (-0.22, 1.11)
505 COD test								
Left time to completion (s)	4.10 ± 0.12 (4.00, 4.19)	4.13 ± 0.10 (4.05, 4.20)	4.11 ± 0.11 (2.10, 8.06)	1.76 (0.90, 3.45)	0.723 (-0.164, 0.937)	4.88	0.40	0.28 (-0.32, 1.13)
Right time to completion (s)	4.12 ± 0.11 (4.04, 4.20)	4.09 ± 0.11 (4.01, 4.18)	4.11 ± 0.11 (2.10, 8.05)	1.87 (0.95, 3.67)	0.668 (-0.530, 0.926)	5.18	0.54	-0.21 (-0.94, 0.45)
Left COD deficit (s)	0.45 ± 0.12 (0.40, 0.50)	0.46 ± 0.09 (0.41, 0.50)	0.45 ± 0.11 (0.23, 0.88)	10.90 (5.56, 21.37)	0.894 (0.528, 0.976)	30.22	0.60	0.10 (-0.39, 0.59)
Right COD deficit (s)	0.41 ± 0.09 (0.37, 0.46)	0.43 ± 0.07 (0.40, 0.47)	0.42 ± 0.08 (0.22, 0.83)	11.39 (5.81, 22.32)	0.798 (0.165, 0.954)	31.56	0.34	0.26 (-0.32, 0.83)

SD = Standard deviation; CI = Confidence interval; CV = coefficient of variation; ICC = Intraclass correlation coefficient; SEM = Standard error measurement; MDC = Minimal detectable change; COD = change of direction

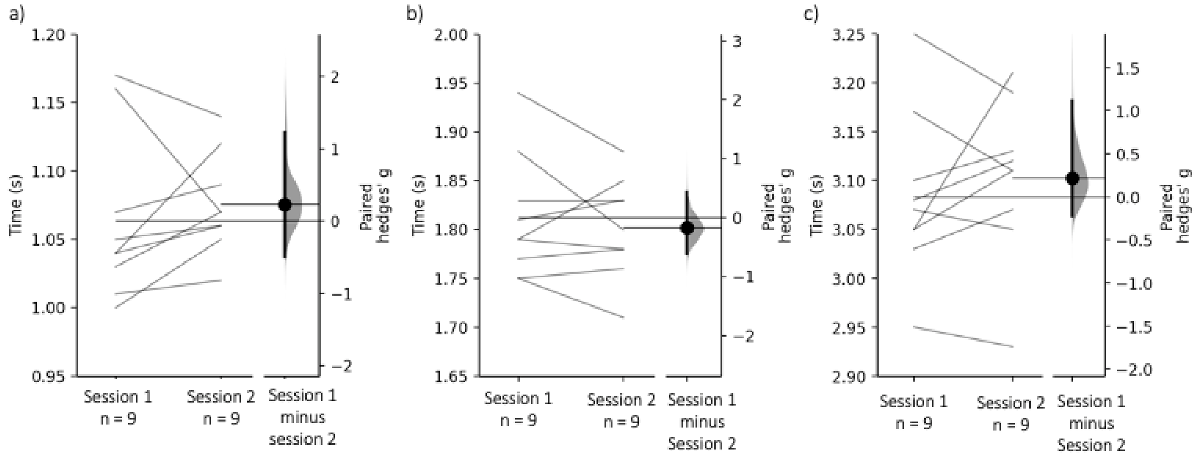


Figure 8.2. A comparison of individual (a) 5 metre, (b) 10 metre, and (c) 20 metre sprint times during both reliability sessions. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between testing occasions.

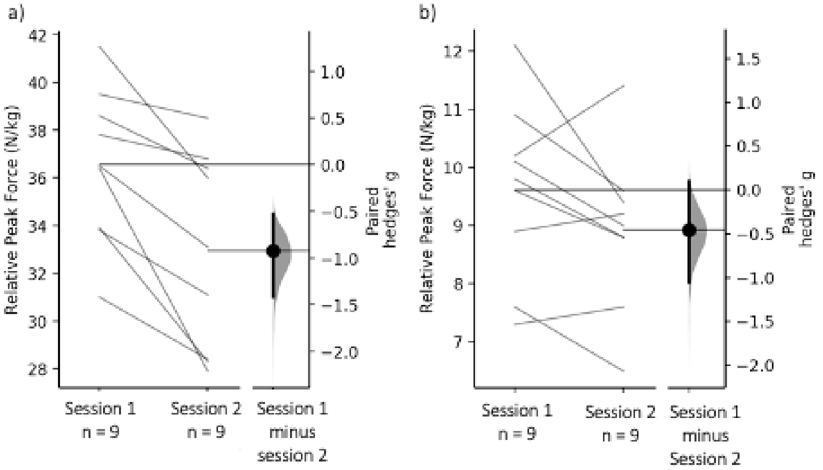


Figure 8.3. A comparison of individual (a) isometric mid-thigh pull and (b) Nordic hamstring exercise relative peak force during both reliability sessions. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between testing occasions.

8.5 Discussion

The aim of this study was to determine the between-session reliability of force production and performance characteristics in academy soccer players. Based on absolute reliability, the findings of this study indicate that all CMJ variables, other than RSImod, demonstrated acceptable reliability, while relative peak force was the only acceptably reliable variable from the IMTP. All NHE and sprint variables demonstrated acceptable reliability, as well as the time to completion for change of direction performance. In contrast change of direction deficit was not reliable. Of those variables that demonstrated acceptable absolute reliability, the corresponding relative reliability was moderate to excellent (ICC ≥ 0.668).

As previously outlined, there are distinct differences between absolute and relative reliability [292]. It is useful and often recommended to calculate and assess both absolute and relative reliability because a large ICC has the potential to mask poor trial-to-trial consistency (absolute reliability). Due to the homogenous and small sample in this current study, a low ICC can also be observed with low trial-to-trial consistency (acceptable absolute reliability) making it difficult to differentiate between subjects. Therefore, as highlighted in the statistical analyses variables are interpreted as acceptably reliable providing the ICC was not poor and the CV was below the 10% threshold outlined in the methods Another reason that more emphasis has been placed on absolute reliability being acceptable, as well as the homogenous sample, is that with a training intervention the magnitude of individual differences pre- to post-intervention will be assessed, which means it is important to understand the variability test to test within the group and there is less interest in the rank order of the individuals. Relative reliability, therefore, may be more appropriate when looking to create leader boards or benchmarks within a particular group. Based on the results of this study, the variables that are acceptably reliable and should be utilised to assess changes in a subsequent intervention include all CMJ variables, apart from RSImod, relative peak force for both the IMTP and NHE, sprint times at all splits, and total time to completion for the 505 change of direction.

In the current study, absolute reliability of CMJ height appeared to be good (CV = 3.6%), with an MDC of < 10% meaning an improvement of ~3.5 cm would be classed as a meaningful change, which does not appear to be unrealistic. In comparison to previous literature that includes youth academy soccer players, a similar absolute reliability for CMJ height on a force platform and Optojump system has also been reported (CV = 3.3% and 4.8%, respectively) [299, 300], also with an MDC < 10%. Beyond jump height, there are limited studies investigating the underpinning variables reported within the current study, particularly in soccer. There have been examples in other team sports, however, including basketball [301] and Australian football [302] whereby all jump variables included in the current study were reported to be reliable across multiple test occasions (CV < 10%). TTT, countermovement depth, mean propulsive force and propulsion duration were all observed to have acceptable absolute reliability, although the MDC was much higher for these variables (> 11.18%). Due to the inflated MDC, it would be advised that jump performance only be determined as a meaningful change pre-to post-intervention when the outcome measure (in this case, CMJ height) exceeds the MDC and the other variables collected be used to determine how or why that meaningful change occurred.

Peak force values for both the IMTP and the NHE were expressed relative to body mass. Providing no meaningful changes in body mass between the two testing occasions occurred, the reliability would not be influenced, as observed in previous literature that have reported both [303]. When inspecting the results of previous literature investigating a similar population absolute reliability (CV = 4.61% [95% CI 3.28, 7.72] [304]) appears to be similar to the current study (CV = 5.05% [95% CI 2.58, 9.91). Dos'Santos et al. [304] did, however, report a lower MDC (8.5%) in comparison, although this is likely due to their calculation of MDC (in which they have termed smallest detectable difference) as they utilised the SEM calculation highlighted within the introduction that included the ICC, rather than using the typical error calculation [294]. In the study by Dos'Santos et al. [304] the force variables at different time points were also found to be reliable, unlike in this current study. This difference could have been related to Dos'Santos et al. [304] also assessing power clean one repetition maximums, which suggests that although the population were of a similar age group and playing level, those in the study by

Dos’Santos et al. [304] could have been more familiar with the posture adopted for the IMTP or may have even possessed a greater ability to consistently generate force rapidly. Absolute reliability of peak force during the NHE was also similar to previously published literature [255], although this was not relative to body mass and the MDC calculated was reported as Newtons and not a percentage which makes comparisons difficult.

The reliability of ‘speed’ tests highlighted in a systematic review shows a range of sprint distances tested in many different populations both intraday and interday (i.e., within- and between-session) [305]. Very few of the studies included within this review which carried out between-session reliability reported absolute reliability, with the focus being on ICCs. The same review also investigated COD tests; however, no between-session reliability was reported for the 505. In the current study the sprints at all split times demonstrated acceptable reliability (CV ≤ 3.26%) which meant the MDC was also realistic (MDC ≤ 9.05%). The total time to completion for the 505 COD test also demonstrated similar reliability compared to the sprint times for both the left and right leg, although when COD deficit was calculated, the reliability became unacceptable and the MDC was inappropriate (MDC ≥ 30.22%) to detect any change following a training intervention.

One major limitation of the current study was the small sample size, alongside the homogeneity of the group which was highlighted repeatedly when outlining the rationale for reliability statistics used. Although homogeneity is a limitation it is unavoidable when using a single squad of athletes as there is always likely to be similarities in ability, training history, and exposure to previous testing occasions. Another limitation was due to the reliability testing occasions being completed in-season, there were no opportunities to determine apply any familiarisation or additional testing sessions to identify any learning effects through multiple testing bouts. The in-season nature of this study may have also been the cause of moderate to large differences between the testing sessions, as fatigue may have accounted for the lower scores in session 2.

8.6 Conclusion

Based on the findings from this study, all maximum sprint and peak force production variables including the NHE and IMTP are reliable between testing occasions in a group of academy soccer players and should be considered when looking at adaptations from an intervention. Variables associated with the CMJ are also appropriate, however, RSImod along with most COD variables and the force produced at different time points during the IMTP were not acceptably reliable and should not be used with this cohort without further familiarisation.

Commentary 7

Following the identification of reliable performance assessments and variables, we were then able to proceed with a lower body strength training intervention. The plan was to have a cross-over design for this intervention to account for some of the variability associated within team sports, such as general scheduling and fixtures which meant that we were able to agree two six-week training blocks to complete the interventions prior to a short winter break that occurs within academy football, as well as accounting for the conclusions made in Chapter 3 which were based on interventions 6-12 weeks in duration. Unfortunately, the team participating in the study had a case of COVID-19 a couple of days prior to the pre-intervention testing and the team had to isolate based on the leagues protocols which then delayed the start of the intervention and meant we then had to condense each block to 5-weeks.

9 Chapter 9: Micro-dosing strength training in academy soccer players: a randomised crossover feasibility trial.

9.1 Abstract

Background: The ability to produce force, and produce force rapidly, is integral to performance of numerous athletic tasks as well as to aid in the reduction of non-contact injury risk. The benefits of strength training in increasing force production and rapid force production have long been demonstrated. Despite this, due to the technical/tactical demands of competition, appropriate strength training in-season can often be reduced substantially. In some cases, due to dense fixture schedules, recovery between competition becomes the key focus and athletes can go through prolonged periods without appropriate or consistent strength training. As a result of such periods, detraining can often occur, allowing performance to decrease and the propensity for injury to increase. ***Objective:*** The aim of this study was to determine the effect of dividing a traditional in-season strength training programme into volume-equated, micro-dosed sessions over a 5-week period in academy soccer players. ***Methods:*** Twenty male soccer players were assigned into two groups, resistance training volume was programmed over two session for the traditional group, with the micro-dosing group prescribed the same volume but performed over 4 sessions per week over 5 weeks. Countermovement jumps (CMJ), isometric mid-thigh pull (IMTP), Nordic hamstring exercise (NHE), 20 m sprint and 505 change of direction tests were completed pre- and post-intervention before a washout period, crossover of the groups, and a repeat of the 5-week intervention. Null hypothesis significance testing determined using permutation tests using 5000 bootstrap samples, and Hedge's *g* effect sizes were used to assess magnitude of differences between groups. ***Results:*** Small to moderate differences (g = -0.65 – 0.35) in percentage change between the two groups were demonstrated for all CMJ variables. Moderately greater improvements in force production for both the IMTP (g = 0.62) and NHE (g = 0.64) were observed in the micro-dosing group. Small to moderate differences in percentage change, between the groups, were also observed in the sprint and change of direction variables (g = 0.31-0.58), apart from the left change of direction time which was large (g = 1.25), all in favour of the micro-dosing group. Compliance was also moderately greater (g = 0.72) in the micro-dosing group. ***Conclusions:*** The traditional training did not appear to be meaningfully detrimental to performance in the measures tested, however, the micro-dosing group demonstrated a greater positive change in comparison, this could have been due to moderately greater compliance to the prescribed training volume. Micro-dosing can therefore provide a programming strategy to help improve compliance rates which then has the potential for greater improvements in performance.

9.2 Introduction

Multidirectional team sports include numerous athletic tasks such as sprinting, jumping, change of direction, tackling, and kicking, all of which are underpinned by lower limb force production (i.e., muscular strength) [3]. Evidence of these associations have been demonstrated through correlations between muscular strength (evaluated using a one repetition maximum back squat) and athletic tasks, including 10 m sprint times (r = 0.94), 30 m sprint times (r = 0.71) and vertical jump height (r = 0.78) in senior and youth soccer players [306, 307]. These associations can be explained using Newtons 2nd law, whereby when mass stays constant the only way to increase acceleration, within the same time frame, is through producing greater force which results in a greater impulse (force x time) and therefore increased velocity. There may be an argument in some team sports, particularly those involving collisions, whereby deliberate increases in body mass can be of benefit in combination with increasing relative strength in order to increase the potential for higher momentum [105]. For non-collision sports, however, there is less of a requirement for increasing momentum to overcome the opposition and therefore increases in force production (and rapid force production) through resistance training becomes paramount as the net impulse, relative to body mass, has been identified as the key determinant to both jump height [308] and short sprint performance [309].

Resistance training is typically structured around the periods associated with each sport, such as pre-season, in-season competition schedules, post-season and off-season, whereby planned (and occasionally reactive, based on changes in fixtures) fluctuations occur in the training objectives, strategies utilised, and training variables employed [145]. Depending upon the sport, the length of the off/pre-season, competition season (in-season) and post-season (play offs) can be vastly different. For several team sports around the world, particularly professional soccer, the competition season constitutes a large portion of the sporting calendar. Due to this prolonged period of competition (e.g., ~40 weeks in professional European soccer), there is a lack of time for developing physical qualities (general preparation). The demand on performance, compared to a focus on development, is also exacerbated by periods of fixture congestion (e.g., up to 3 games in 7 days), which are often experienced at numerous points throughout the competition season. In addition to periods of fixture congestion, youth athletes may move between age groups or levels of competition. This may be to provide further technical/tactical development, but alternatively it could be to account for injuries, absences, or poor performances within the group they move to, allowing priority teams within a club to train and compete as required. There are also several sports where some players will be selected to train and play with their national teams, which can occur in-season or directly following the in-season period, which further increases the training and competition demands placed upon the athlete. The increased training demand from a technical/tactical perspective typically reduces overall compliance in resistance training due to the perceived requirement to manage fatigue [273].

As described previously, there is an understandably large technical and tactical focus which constitutes the majority of training time, at the expense of other aspects of training. If players are perceived to require a reduction in training load, for example during periods of dense fixture schedules when recovery is prioritised, it is often the technical/tactical work that remains, while resistance training is sacrificed to some degree if not completely. Depending on the total volume completed and the training status of the players the sporadic and infrequent application of resistance training, at best, may only allow for the maintenance of strength and power qualities, but eventually the residual effects associated with training are lost and detraining begins [142]. The transition of training residuals to a detraining effect is particularly noticeable if the prior period of accumulation (e.g., pre-season) contained insufficient volume or duration [153]. Short pre-season periods are common in sports with long competition seasons, particularly in teams that make it to a play-off type series, or for players representing their countries in international competitions. Maintenance of physical qualities during competition periods or ‘performance peaks’ is a well-known objective in some of the early periodisation paradigms. These early paradigms were, however, focussed on Olympic sports and therefore not always appropriate for team sports due to the duration of the competition phase as performance peaks cannot be maintained for long periods [149]. Subsequent alternatives to the traditional periodisation model have been proposed, including the conjugated successive system of training [310], block periodisation models (uni-directional or multi-targeted) [143], and emphasis periodisation [153, 188]. Due to team sports requiring the application of many athletic abilities, emphasis periodisation models are perhaps more appropriate as numerous aspects of training (e.g., strength, power, and endurance) can be included in each block, with the emphasis changing in each mesocycle [153, 188].

Traditionally, in-season resistance training sessions follow a similar structure to the guidance set out by the National Strength and Conditioning Association, typically occurring 1-3 time per week and lasting ~45-90 minutes [82]. One possible solution for programming during the competition season for team sports is the implementation of programming strategies that employ micro-dosing. Recently, micro-dosing has been proposed as a method to reduce session volume by increasing the frequency of sessions, so the same volume that would be completed in an hour-long traditional session might perhaps be divided across 2 sessions, or more, in order to achieve the same total stimulus with a potential reduction in fatigue experienced following each bout of training (Chapter 3). Although different training frequencies using volume-matched programmes have been investigated within numerous studies, results from Chapter 3 identified no meaningful differences in changes in performance occurs between frequencies. Additionally, the authors highlight that very few of these studies included athletic populations and of those, none were completed during the competitive season (chapter 3). One of the early studies to use terminology like micro-dosing was research carried out by Kilen et al. [112] whereby a military population were divided into a “classic training” group and a “micro-training” group. Kilen et al. [112] did not assess any direct measures of strength or athletic performance and only assessed dynamic tasks which were based around time to exhaustion. Despite some of the potential methodological issues when comparing to athletic performance, the micro-training was demonstrated to have a positive effect on lower body isometric strength.

The aim of this study was to determine the effect of dividing a traditional in-season strength training programme into micro-dosed sessions (increasing the frequency but maintaining weekly volume) within academy soccer players. Although the result of previous research indicates that provided the completed volume of training is matched, there will be no difference in strength improvements between the groups (Chapter 3), it was hypothesised that greater improvements in strength and performance would occur in the micro-dosing group, due to a higher compliance to the planned training volume, and therefore a greater training volume completed. With the micro-dosing group likely to complete a greater percentage of the planned volume across the intervention due to their sessions being shorter and less fatiguing and therefore less likely to be impacted by changes in the training and competition schedule.

9.3 Methods

9.3.1 Experimental design

A randomised cross-over design was used to determine the effects of traditional and micro-dosed strength training and compare the differences in the adaptations between conditions, in youth soccer players, during the competitive season. Following baseline reliability testing (see chapter 8) the 5-week training intervention was undertaken, with the control (traditional training) group completing two resistance training sessions per week, and the experimental (micro-dosing) group completing the same volume and relative loads (based on a percentage of the participants' predicted one repetition maximum [RM]) but over 4 sessions per week (Table 9.1). In addition to the baseline testing, all assessments were repeated after the 5-week intervention during a two-week washout period, whereby resistance training ceased, but normal soccer training continued. At this time the full testing battery (countermovement jump [CMJ], isometric mid-thigh pull [IMTP], 20 m sprint, 505 change of direction test, Nordic hamstring exercise [NHE] and three RM) was completed prior to the traditional training and experimental groups being crossed-over and the alternate 5-week intervention completed (Figure 9.1). Finally, a testing session was completed following the conclusion of the intervention. Each testing session consisted of the CMJ, IMTP, 20 m sprint (5-, 10- and 20 m splits), 5-0-5 change of direction test and NHE, in that order.

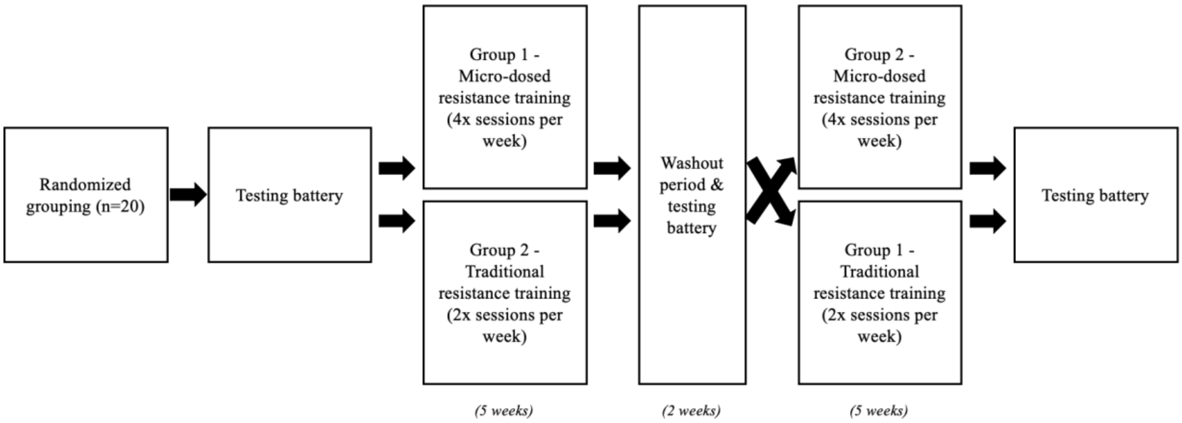


Figure 9.1. An outline of the randomised crossover design.

9.3.2 Participants

A squad of twenty male soccer players playing within a Category 2 English Football League Academy volunteered to participate in this study and were randomly divided into two groups using an a random computer-generated assignment tool. However due various dropouts including injuries and COVID-19 infections, only nine players (age: 18.1 ± 0.77 years; height: 1.81 ± 0.82 cm; body mass: 71.1 ± 6.8 kg) completed the assessments at each of the three timepoints. The two groups consisted of a traditional training group (resistance training two days per week) and an experimental / micro-dosing group (who completed the same resistance training volume load as the traditional training group but divided across four sessions per week). Resistance training volume and loads (relative intensity) were equated, with conditioning and sport specific training standardised across both groups following their normal routine. There was no minimum compliance rate used for participants inclusion in further analyses in order to observe the effect compliance may have had.

An *a priori* power calculation was performed to determine the minimum number of participants (n = 28; *14 per group*) for a statistical power ≥ 0.80, at an alpha level of $p \leq 0.05$ with a moderate Cohen's d effect size ($d = 0.48$), based on results from a previous 8-week training intervention using similar assessment methods [311]. Only participants who completed all testing occasions and therefore the cross-over were included for subsequent analysis, with compliance rates reported and compared between groups. Organisational consent was acquired prior to approaching the participants and all participants provided written informed consent, or parental/guardian assent where required, to participate in the study. Ethical approval (HSR1819-089) was granted by the institutional ethics committee in accordance with the declaration of Helsinki.

9.3.3 Procedures

9.3.3.1 Countermovement jumps

The CMJs were calculated using a forward dynamics approach, completed in accordance with McMahon et al. [278] and as described in section 8.3.3.1. Participants were required to stand still on the force platforms with hands on hips for a 1 second weighing period to allow for an onset of movement threshold to be determined. The instructions were given to jump as high and as fast as possible whilst hands remained on hips throughout the movement, with three trials executed.

9.3.3.2 Isometric mid-thigh pull

The IMTP was completed in accordance with Comfort et al. [297] and as described in section 8.3.3.2. Participants were again required to complete a 1 second period of quiet standing, their hands fixed to the bar, with minimal pre-tension (< 50 N). Two warm up trials were completed at 50% and 75% before the execution of three maximal trials, providing that their was no countermovement present and each trial was within 250 N of each other, failure to meet these conditions resulted in a repeated trial.

9.3.3.3 Nordic hamstring exercise

The NHE was completed in accordance with Opar et al. [255] and as described in section 8.3.3.3. Participants were instructed to kneel on the padded board of the NordBord (Vald Performance, Brisbane, QLD, AUS) and hook their ankles into the attachments before completing three trials with one minute rest between each.

9.3.3.4 20 m Sprint

20 m sprints were completed as described in section 8.3.3.4. Two warm up trials were performed at 50% and 75% before three maximal attempts were made with one minutes rest in between each trial.

9.3.3.5 505 Change of direction test

The 505 COD test was completed as outlined in section 8.3.3.5. Three trials were performed on each leg following two warm up attempts. Participants were instructed to place their turning foot on the line to change direction (see Figure 8.1), trials were repeated they fell short of that line.

9.3.3.6 Three repetition maximum

As a method of providing intensity prescription during the subsequent intervention rather than a strength assessment due to the exercises being involved within the program, participants performed a 3RM assessment based on the clubs standard practices for familiarity, this included the trap bar deadlift and hip thrust, using the protocol recommended by the NSCA [312]. Briefly, three warm-up sets of increasing submaximal loads (10 repetitions at 50% estimated 1RM, 5 repetitions at 75% 1RM, 3 repetitions at 85% 1RM) were completed with 2 minutes rest between each set, following that the participants then attempt their 3RM. After a successful attempt the participant rested for 3 minutes followed by a subsequent attempt with a 2-5% increase in load, a maximum of 5 attempts were permitted. Following completion of the 3RM testing, the players 1RM was predicted using the Brzycki equation [313] in line with current practices at the club.

9.3.3.7 Training intervention

A 5-week strength training intervention, focused on lower body strength development was carried out following the initial testing sessions, Table 9.1 outlines session content and prescription for both the traditional and micro-dosing groups, respectively, based on the normal training practices within the team and what had already been prescribed to them as part of their in-season programming. All planned conditioning and sport specific (field-based) training was standardised across groups, as they were of the same squad, although some athletes did compete across different age groups which resulted in no meaningful differences in total distance covered (traditional = 137km ± 16 km; micro-dosing = 138km ± 27km; $g = 0.04$). Following the 5-week intervention and a washout period, the groups were then crossed-over, and the opposite programme was completed for both groups, with loads modified based on re-evaluation of the 3-RM performance (Figure 9.1).

Table 9.1. An outline of the strength training programme used for both traditional and micro-dosing groups.

Type	**Traditional** ***(Session 1)***	**Traditional** ***(Session 2)***	**Micro-dosing** ***(Sessions 1 & 2)***	**Micro-dosing** ***(Sessions 3 & 4)***
Lower anterior (squat)	Hex bar deadlift OR back squat 4x5 @ 85-90% 1RM	Hex bar deadlift OR back squat 4x5 @ 85-90% 1RM	Hex bar deadlift OR back squat 2x5 @ 85-90% 1RM	Hex bar deadlift OR back squat 2x5 @ 85-90% 1RM
Lower posterior (hinge)	Hip thrust 4x5 @ 85-90% 1RM	Hip thrust 4x5 @ 85-90% 1RM	Hip thrust 2x5 @ 85-90% 1RM	Hip thrust 2x5 @ 85-90% 1RM
Lower frontal plane (single leg)	Cossack squat 3x4 (each side) @ 1-2 RIR	Cossack squat 3x4 (each side) @ 1-2 RIR	Cossack squat 2x4 (each side) @ 1-2 RIR (session 1)	Cossack squat 1x4 (each side) @ 1-2 RIR
Additional	NHE 2x5 Copenhagens 2x10	NHE 2x5 Copenhagens 2x10	NHE 1x5 Copenhagens 1x10	NHE 1x5 Copenhagens 1x10

RM – repetition maximum; RIR – repetitions in reserve; NHE – Nordic hamstring exercise; Hex bar = Hexagonal barbell. Load prescription was progressed throughout the 5-weeks within the thresholds outlined in the table.

9.3.3.8 Statistical analyses

Null hypothesis significance testing was carried out using a series of permutation tests for each comparison pre- to post-intervention as well as for the percentage change between groups. Five thousand bootstrap samples were taken for each group as part of the permutation tests with the *p* value reported as the likelihood of observing the effect size reported if the null hypothesis of zero difference was true [261]. An *a priori* alpha level was set at < 0.05. Effect sizes were calculated using Hedge's *g* with the 95% confidence interval (CI) bias-corrected and accelerated to determine the magnitude of change pre- to post-intervention or difference between the traditional and micro-dosing groups. Effect sizes were interpreted according to recommendations by Cohen [263]: (≤ 0.19, trivial; 0.20-0.49, small; 0.50-0.79, moderate; ≥ 0.80, large). As mentioned, effect sizes have been used in order to present the magnitude of effect as a standardised metric, this is important as it provides understanding regardless of the scale used, which can allow conclusions to be drawn compared to findings from previous literature and used to plan future studies [314]. The minimal detectable change (MDC) for this population (outlined in Chapter 8) will also be used to aid understanding of any meaningful changes.

9.4 Results

9.4.1 Countermovement jump performance

Group changes pre- to post-intervention for CMJ metrics are outlined in Table 9.2 with individual data plots presented in Figure 9.2. Both the micro-dosing and traditional groups demonstrated trivial to small changes ($g \leq 0.27$) in jump height pre- to post intervention. The time to take-off for the traditional group also demonstrated small changes ($g = 0.23$), whereas the micro-dosing group showed a moderate increase in time to take-off ($g = 0.68$). Countermovement depth, mean propulsive force and propulsive phase duration showed trivial to small change ($g \leq 0.23$). In addition, there were small to moderate differences ($g = -0.65 – 0.35$) in the changes in CMJ variables between groups (Table 9.2 and Figure 9.3).

Table 9.2. Pre- to post-intervention changes in countermovement jump force-time variables and between-group differences.

n = 8	Micro-dosing		Traditional		Difference (%)	
Jump Height (m)	Pre	Post	Pre	Post	Micro-dosing	Traditional
Mean	0.35	0.36	0.35	0.36	5.00	3.26
SD	0.07	0.05	0.05	0.06	7.97	13.63
p	0.16		0.65		0.76	
g [95% CI]	0.27 [-0.14, 0.83].		0.14 [-0.56, 0.72]		-0.14 [-1.33, 0.86]	
Time to take-off (s)						
Mean	0.65	0.72	0.70	0.71	11.71	2.95
SD	0.11	0.07	0.06	0.09	11.78	13.46
p	0.05*		0.61		0.19	
g [95% CI]	0.68 [-0.01, 1.73]		0.23 [-0.73, 1.11]		-0.65 [-1.76, 0.35]	
Countermovement depth (cm)						
Mean	-0.26	-0.27	-0.26	-0.27	3.55	5.33
SD	0.06	0.09	0.08	0.07	18.13	11.80
p	0.49		0.28		0.83	
g [95% CI]	-0.15 [-0.59, 0.42]		-0.16 [-0.49, 0.17]		0.11 [-0.93, 1.10]	
Mean propulsive force (N)						
Mean	1582.77	1565.55	1571.84	1592.37	-1.28	1.11
SD	238.01	287.48	255.03	290.98	6.78	6.31
p	0.72		0.57		0.48	
g [95% CI]	0.06 [-0.38, 0.31]		0.07 [-0.17, 0.40]		0.35 [-0.69, 1.36]	
Propulsive phase duration (s)						
Mean	0.22	0.23	0.22	0.22	5.74	2.62
SD	0.04	0.05	0.04	0.04	14.26	8.91
p	0.28		0.51		0.63	
g [95% CI]	0.23 [-0.21, 0.74]		0.15 [-0.25, 0.43]		-0.25 [-1.21, 0.77]	

*SD = Standard deviation; CI = Confidence interval; *denotes a statistically significant difference ($p \leq 0.05$)*

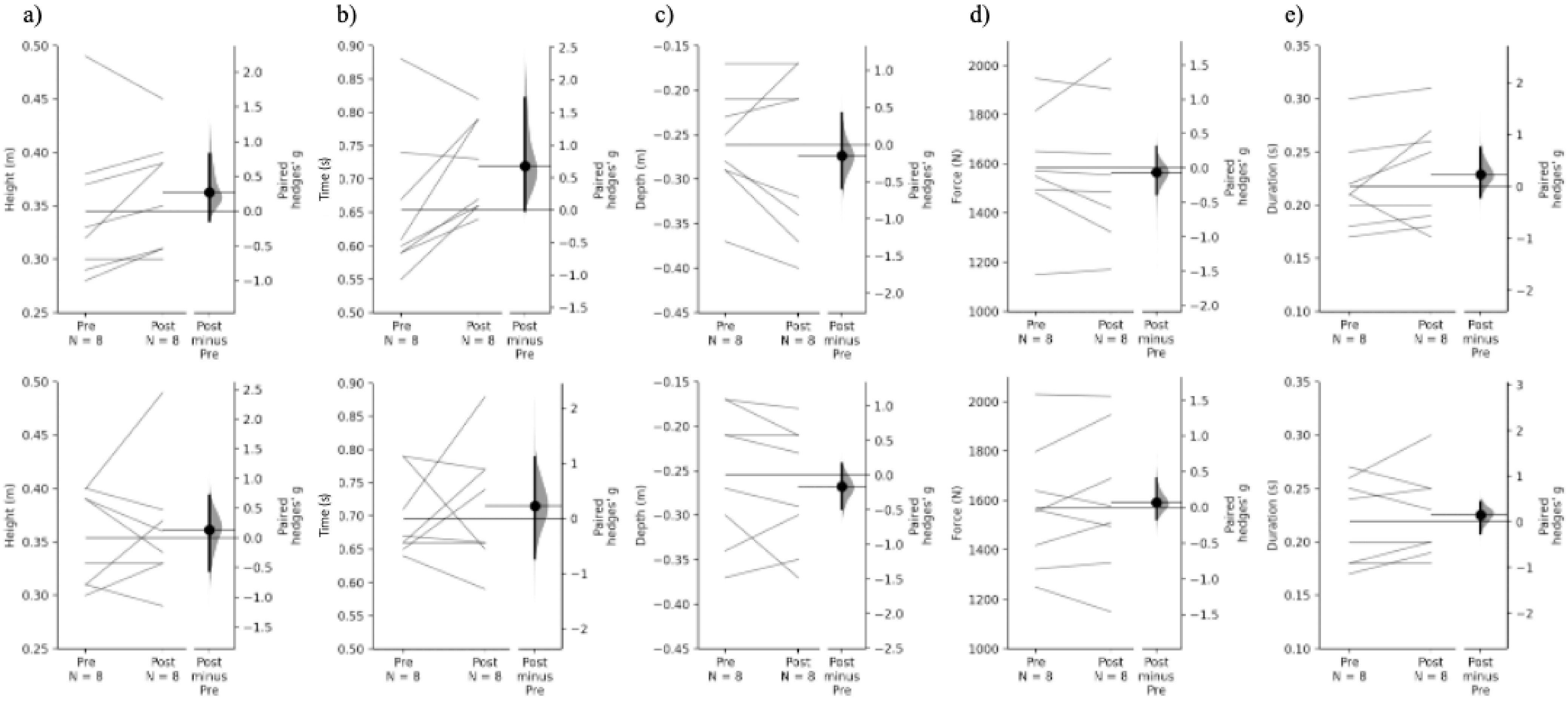


Figure 9.2. Individual pre- to post-intervention changes in countermovement jump variables. (a) jump height, (b) time to take-off, (c) countermovement depth, (d) mean propulsive force, (e) propulsive phase duration. Top row illustrates the individual pre-to post-intervention changes for the micro-dosing group, the bottom row illustrates those for the traditional group. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between testing occasions.

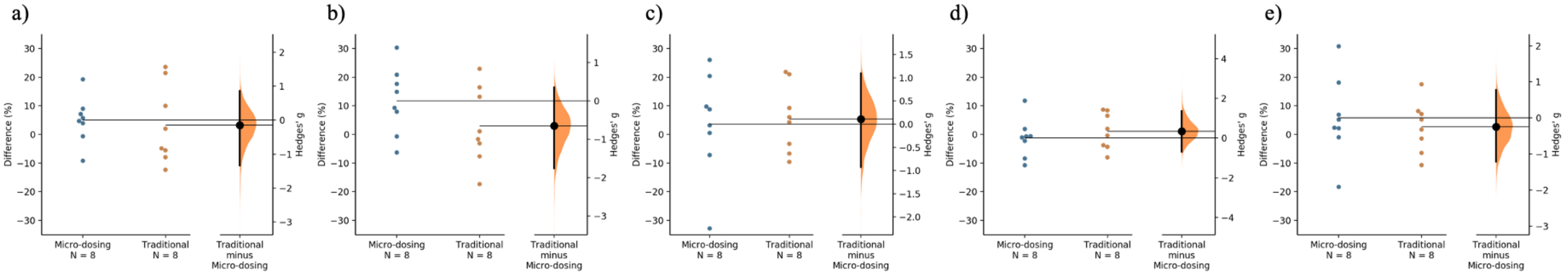


Figure 9.3. Differences between groups for countermovement jump metrics. (a) jump height, (b) time to take-off, (c) countermovement depth, (d) mean propulsive force, (e) propulsive phase duration. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between groups.

9.4.2 Force production characteristics

The traditional groups demonstrated no meaningful change in IMTP relative peak force, in contrast the micro-dosing group demonstrated moderate improvements (*g* = 0.55), resulting in a moderately greater percentage increase in the micro-dosing group (*g* = 0.62) (Table 9.3 and Figures 9.4 and 9.5). The same pattern was demonstrated by both groups pre- to post-intervention relative eccentric knee flexor strength during the NHE and in the differences between groups (*g* = 0.64) (Table 9.3 and Figures 9.4 and 9.5).

Table 9.3. Pre- to post-intervention changes in force production variables and between-group differences.

n = 9	Micro-dosing		Traditional		Difference (%)	
IMTP relative peak force (N/kg)	Pre	Post	Pre	Post	Micro-dosing	Traditional
Mean	32.13	34.54	34.16	34.12	8.28	0.35
SD	4.06	4.33	3.07	3.15	13.64	10.57
p	0.15		0.97		0.19	
g [95% CI]	0.55 [-0.16, 1.14]		-0.01 [-0.79, 0.77]		-0.62 [0.31, 1.51].	
NHE relative peak force (N/kg)						
Mean	9.24	9.81	9.65	9.42	9.64	-1.18
SD	1.26	1.09	1.31	1.30	15.97	16.23
p	0.10		0.57		0.18	
g [95% CI]	0.61 [-0.16, 1.43]		-0.17 [-0.87, 0.52]		-0.64 [-1.65, 0.39]	

IMTP = Isometric mid-thigh pull; NHE = Nordic hamstring exercise N/kg = Newtons per kilogram; SD = Standard Deviation; CI = Confidence interval

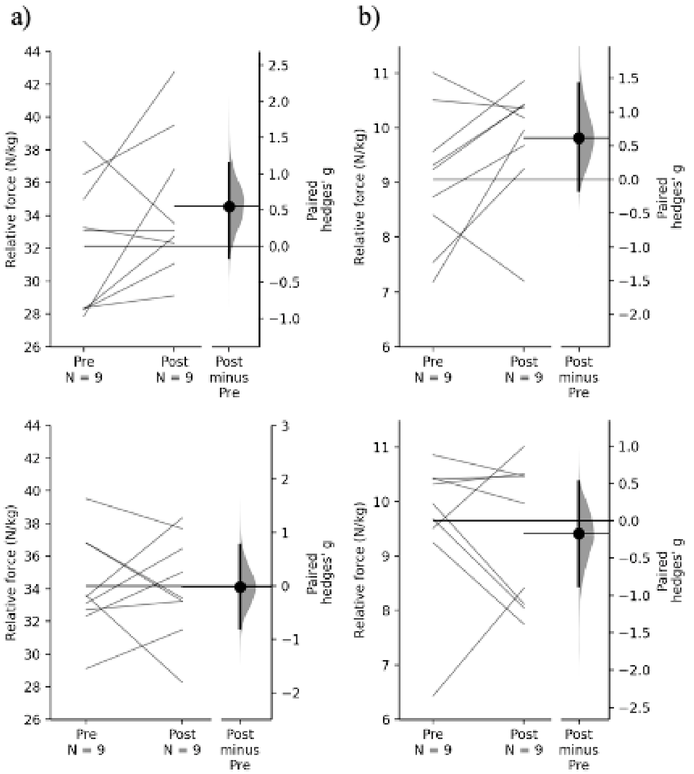


Figure 9.4. Individual pre- to post-intervention changes in force production variables. (a) isometric mid-thigh pull, (b) Nordic hamstring exercise. Top row illustrates the individual pre-to post-intervention changes for the micro-dosing group, the bottom row illustrates those for the traditional group. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between testing occasions.

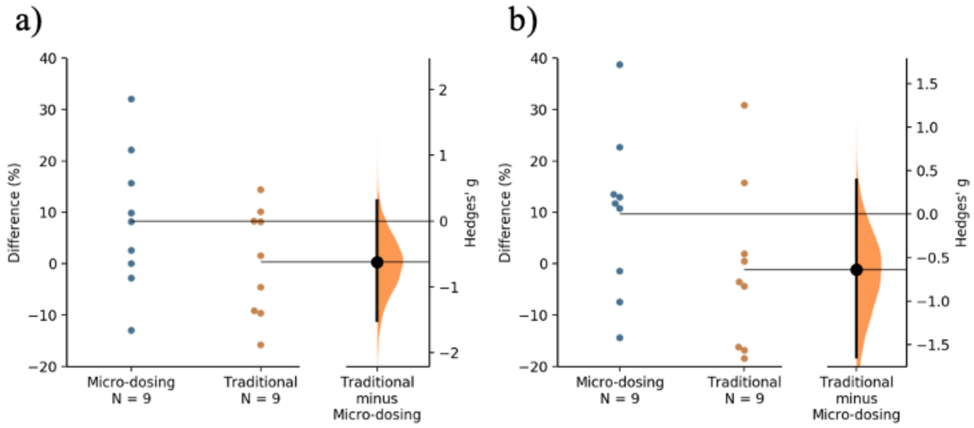


Figure 9.5. Differences between groups for force production variables. (a) isometric mid-thigh pull, (b) Nordic hamstring exercise. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between groups.

9.4.3 Sprint and change of direction performance

Changes in sprint and COD times pre- to post-intervention for the micro-dosing and traditional groups can be seen in Table 9.4, with individual plots observed in Figure 9.6. The micro-dosing group demonstrated decreases in their sprint times across all split distances, as well as decreases in left and right COD times, however, these differences were small (*g* = 0.20-0.49). In contrast, the traditional group demonstrated small to moderated (*g* = 0.11-0.74) increases in times for all split distances and COD times. There was also a small to moderate difference (*g* = 0.31-0.58) in the percentage change in sprint and COD times between groups, other than the left COD times which demonstrated a large difference (*g* = 1.25) favouring the micro-dosing groups whose times reduced (Table 9.4, Figure 9.7).

Table 9.4. Pre- to post-intervention changes in sprint and change of direction performance.

n = 9	Micro-dosing		Traditional		Difference (%)	
5 m (s)	Pre	Post	Pre	Post	Micro-dosing	Traditional
Mean	1.06	1.04	1.04	1.05	-1.58	1.91
SD	0.04	0.04	0.05	0.05	4.83	6.60
p	0.35		0.45		0.23	
g [95% CI]	-0.46 [-1.34, 0.34]		0.39 [-0.85, 1.13]		0.58 [-0.54, 1.49]	
10 m (s)						
Mean	1.88	1.79	1.78	1.79	-0.68	0.96
SD	0.05	0.05	0.06	0.05	3.98	4.09
p	0.63		0.65		0.42	
g [95% CI]	-0.20 [-1.20, 0.63]		0.24 [-0.56, 1.09]		0.39 [-0.59, 1.24]	
20 m (s)						
Mean	3.09	3.07	3.05	3.06	-0.60	0.45
SD	0.08	0.07	0.10	0.07	3.31	3.13
p	0.66		0.80		0.52	
g [95% CI]	-0.23 [-1.28, 0.50]		0.11 [-0.82, 0.87]		0.31 [-0.67, 1.18]	
COD Left (s)						
Mean	4.12	4.06	4.05	4.15	-1.45	2.45
SD	0.11	0.12	4.04	4.08	2.41	3.45
p	0.11		0.06		0.01*	
g [95% CI]	-0.49 [-1.18, 0.07]		0.74 [0.14, 1.70]		1.25 [0.36, 1.99]	
COD Right (s)						
Mean	4.08	4.05	4.04	4.08	-0.56	1.15
SD	0.12	0.09	0.05	0.11	3.36	2.26
p	0.59		0.16		0.22	
g [95% CI]	-0.23 [-1.16, 0.84]		0.50 [-0.20, 1.47]		0.57 [-0.54, 1.65].	

COD = Change of direction; SD = Standard deviation; CI = Confidence Interval

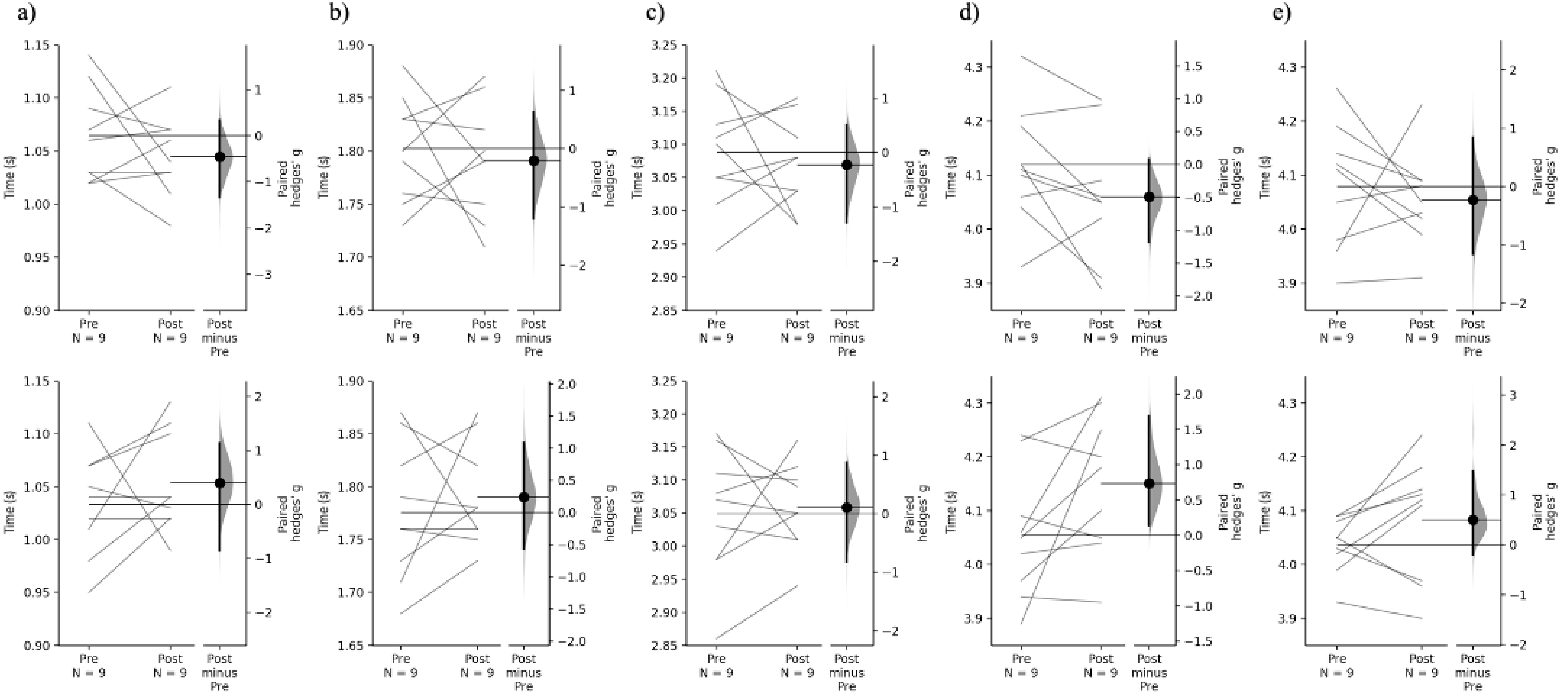


Figure 9.6. Differences between groups for sprint and change of direction performance. (a) 5 m, (b) 10 m, (c) 20 m (d) left change of direction, (e) right change of direction. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between groups.

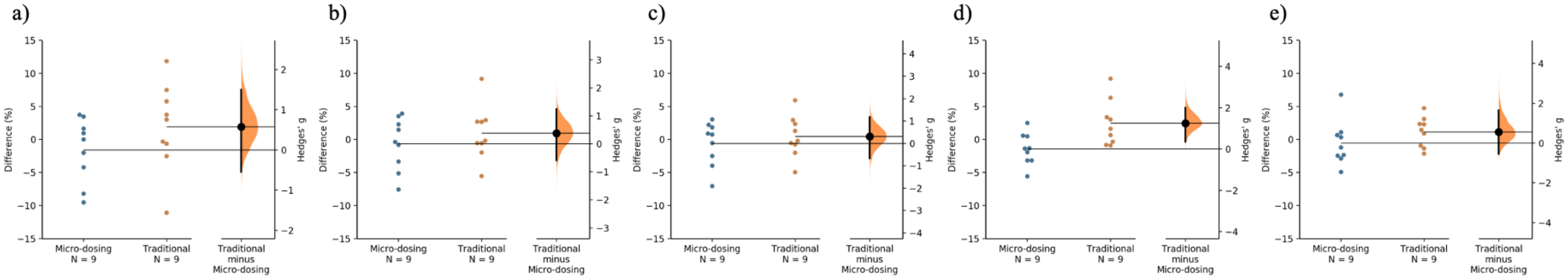


Figure 9.7. Individual pre- to post-intervention changes in force production variables. (a) 5 m, (b) 10 m, (c) 20 m (d) left change of direction, (e) right change of direction. Top row illustrates the individual pre-to post-intervention changes for the micro-dosing group, the bottom row illustrates those for the traditional group. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between testing occasions.

9.4.4 Compliance

Individual plots comparing compliance rate (expressed as a percentage) for both groups are presented in Figure 9.8. The compliance for the micro-dosing group was moderately (g = 0.722) higher (61 ± 21%) compared to the traditional group (48 ± 13%).

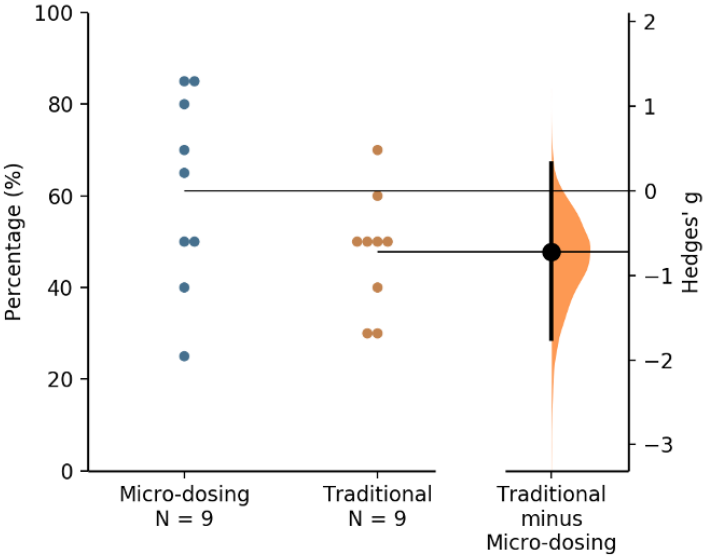


Figure 9.8. Difference in percentage compliance between groups. Hedge's g effect sizes and 95% confidence intervals illustrate mean differences between groups.

9.5 Discussion

The aim of this investigation was to determine the effect of dividing a traditional in-season strength training programme into multiple micro-dosed sessions and to compare the changes in performance between the two groups. Pre- to post intervention, trivial to small changes were observed in CMJ performance, but small to moderate increases were demonstrated in force production characteristics (during the IMTP and NHE), and sprint and COD performance. However, when comparing the percentage change between the two groups there was no meaningful difference in CMJ height but small to large differences in both measures of force production as well as sprint and COD performance in favour of the micro-dosing group. These results were in line with the hypothesis and as hypothesised, there was a (moderate) difference in compliance between the two groups in favour of micro-dosing.

9.5.1 Countermovement jump performance

Although there were trivial differences in the outcome measure of the CMJ (i.e., jump height) between the two groups, it is important to understand how jump height was achieved by each group through inspecting some of the contributing variables (Table 9.2) to understand if these changes were a result of increased capability or just a change in strategy. There was no meaningful change or difference between groups in countermovement depth, meaning that neither group changed that component of their strategy (e.g., to go through a greater range of motion). Despite no change in countermovement depth, there was a moderate difference in time to take-off between the groups whereby the micro-dosing group were performing the CMJ over a longer duration which is reflective of a change in strategy. This increase was not beyond the MDC highlighted in Chapter 8 although based on the large SD it will have exceeded the MDC for some individuals. A moderate increase in TTT paired with a small increase in propulsion phase duration demonstrates that increases occurred in both unweighting and/or braking phases as well as the propulsion phase. In contrast, the traditional group demonstrated a small increase in time to take-off but no meaningful change in propulsion phase duration, suggesting the increase only came during the unweighting and/or braking phases. The importance of the changes in phase duration needs to be considered in conjunction with the force being produced to understand why there was a small increase in jump height for the micro-dosing group and no meaningful change for the traditional group. It may seem contradictory that there was a small difference between the mean propulsive force produced in favour of the traditional group, when it was the micro-dosing group that improved their jump height to a greater extent, however, the micro-dosing group applied the force over a moderately longer duration which would have increased the impulse produced and explains the difference in jump height pre- to post-intervention. There was no meaningful difference (g = 0.11) in body mass pre- to post-intervention for either group which means that this did not have any influence over the change in strategy observed.

Similar findings have been reported by Rønnestad et al. [28] who observed no differences in CMJ height in either training frequency groups during 12-weeks of their in-season soccer period. Although the study by Rønnestad [28] was described as investigating the frequency of training required to maintain jump and sprint performance, as well as maximum strength, the groups were not volume matched and the study was really investigating minimum effective dose. Despite this, there is a suggestion that the strength stimulus applied within the current study was enough to maintain jump performance despite the compliance being relatively low in both groups. Hoffman et al. [113] also investigated the effect of four different strength training frequencies on division I collegiate American football players during their off-season and also found no differences in vertical jump height for any group pre- to post-intervention. Jump strategy was not investigated for either of those studies, however, and therefore not compared between groups [28, 113].

9.5.2 Force production characteristics

The differences in relative lower body force production characteristics showed a similar pattern across both the IMTP and NHE, with moderately greater increases observed in the micro-dosing group. Considering this was a strength-based intervention, only the micro-dosing intervention resulted in a meaningful increase for both variables pre- to post-intervention, whereas the traditional group maintained their IMTP peak force but demonstrated decreases in NHE peak force, despite this being trivial. The cause of these moderate differences between the two groups is likely a result of the traditional group performing < 50% of the prescribed training volume, which was already conservative due to being an in-season program, whereas the micro-dosing group had a moderately greater compliance (~61%) in comparison. The importance of maintaining hamstring force production has been highlighted previously as hamstring strength is identified as an injury risk factor [48] and the NHE has also been shown to reduce injury occurrence although the evidence is equivocal [191, 315].

As mentioned, Hoffman et al. [113] previously investigated four different resistance training frequencies, whereby 4-6 days per week resulted in significant lower body strength improvements pre- to post-intervention compared to the lower frequency of 3 days per week. These observed increases in strength were evaluated via a 1RM squat, rather than an isometric mid-thigh pull, the issue with using this measurement within the study by Hoffman et al. [113] is that the squat was a core exercise within the training intervention and therefore specific to the task being tested, whereas the current study did not include any isometric elements and was therefore independent of any potential additional learning effect. When comparing the current study to one of similar frequencies (2 vs 4 times per week), a small difference in relative 1RM squat performance has been observed by Yue et al. [117] in favour of the lower frequency group, however after inspection of the training intervention, the lower body exercises were only performed on 1 or 2 occasions rather than 2 or 4. There was also an increase in body mass for the higher frequency group which may have altered the magnitude of difference considering there was a trivial difference between the changes in absolute 1RM performance pre- to post-intervention [117].

9.5.3 Sprint and change of direction performance

Trivial to small changes occurred in sprint performance across all split distances in both groups pre- to post-intervention, however, the trivial to small effects observed were in opposite directions with the micro-dosing group improving their performance and the traditional group getting slower. The effect this has on the difference between the two groups meant that there was a moderately greater improvement in 5 metre sprint times for the micro-dosing group. This observation may have been related to the point made surrounding little to no change in jump height, whereby the focus of the intervention was strength training and the increase of force production, which has previously been observed to have a good inverse relationship ($r = -0.52$) with 5 metre sprint times when investigated using a back squat 1RM in youth soccer players [307]. Styles et al. [248] also demonstrated that 5 metre times improved to the greatest magnitude in soccer players compared to 10 and 20 metres following a strength training programme, supporting the findings observed in the micro-dosing group. A similar pattern was observed in the total time to complete the 505 change of direction test, only with greater differences between the two groups (moderate to large). Considering the requirement to accelerate over a short distance within the 505 test, this is understandable based on the findings of the moderate improvement in 5 m sprint times in the micro-dosing group.

9.5.4 Compliance

Although both groups demonstrated a relatively low level of compliance, it is clear by the moderate difference between the two groups and the improvements made in force production, sprint, and change of direction in the micro-dosing group, that the < 48% volume completed by the traditional was not enough to improve in strength or performance in-season. One reason for the poor compliance overall, as highlighted in the introduction, is likely to be due to fixture congestion. Prior to the intervention, four games were scheduled for the under-18 group, however most of the players were involved the club's under-23 squad throughout the intervention period where a further 7 games were scheduled. Following the conclusion of the intervention period, 13 games had been played across 10 weeks with 6 of those games happening with a three-day turnaround. In addition, one player received their senior debut, and another player went represented their country in a fixture camp during the international window. One other observation was that several intervention sessions were completed prior to pitch-based training, the requirements for goalkeepers in that time is typically to complete a pitch-based session specific to their technical needs before being involved with the whole squad, which reduced compliance dramatically. Compliance has not commonly been reported in resistance training interventions which was demonstrated within Chapter 3, where only one study reported compliance [117]. The importance of compliance has been outlined by Ripley et al. [288] who has reported that > 50% compliance demonstrates a positive effect on the reduction of hamstring strain injury, but > 75.1% resulted in a much greater result.

There are several limitations associated with the current study, the most prevalent would be the small homogenous sample size, although this provides insight into the effect of micros-dosing in season training within a squad of athletes, these findings would be more transferable with a larger sample size. Secondly, the duration of the intervention was 5 weeks and as highlighted previously, the 'in-season' period is usually much more prolonged, particularly in soccer whereby the competitive season can last up to 10 months. Although some practitioners may look to extrapolate the current findings over a season, an area of future research would be to complete this empirically. Another limitation was the use if the Brzycki equation for the estimation of 1RM as highlighted by Whisenant et al. [313], however, this was the method of programming utilised by the club. A further avenue for future research would include the use of female athletes, and different sporting populations which would therefore include a range of different fixture schedules. Due to the intervention within the current study being heavily strength biased and considering some of the arguments around training residuals, and the potential for increased intensity through micro-dosing, it would also be useful to investigate the micro-dosing of a power-biased intervention, whilst also investigating some of the potential acute effects of the approach (Chapter 4). Finally, although the prescribed training volume was equated between the two groups, we did not control the number of warm-up sets meaning there could have been slight differences in total work done. Due to the time constraints of the micro-dosing sessions and the strength levels of the athletes, however, the slight differences are likely to have had minimal effect.

9.6 Conclusion

Whilst the traditional group did not prove to be meaningfully detrimental to overall performance in the measures tested, the micro-dosing group proved to have induced small to large positive changes in comparison over the 5-week intervention. Moderately greater compliance from the micro-dosing group suggests that at the very least, micro-dosing can be a useful method of increasing the total volume completed by individuals during a season which will help incur greater adaptations. Allowing greater flexibility in programming can allow practitioners to decide when micro-dosing of volume is appropriate so that their athletes are able to develop or, if required, simply maintain physical capabilities over the course of a tournament or season.

10 Chapter 10: Overall Discussion.

The overall aim of this thesis was to investigate possible programming solutions for appropriate resistance training prescription to be applied during the competitive soccer season. The research within this thesis has centred around one programming solution in particular, micro-dosing. Although within the review of literature it was highlighted that, theoretically, micro-dosing is not a new concept and is simply derived from numerous other training strategies (e.g., phase potentiation, planned overreaching, and tapering) and models (e.g., multi-targeted block periodisation, emphasis periodisation), until now it has never been clearly (or formally) defined from a resistance training perspective. As a result, it was important to lay the foundations of the concept empirically, taking it down to its first principles and investigating the manipulation of training frequency in-season, to understand if there were any differences between traditional and micro-dosing approaches over a period of training.

10.1 Summary of findings

Whilst the results of the review of literature (in particular, Chapters 2 and 3) clearly pointed towards there being no clear or meaningful differences between a number of varied training frequency groups, particularly when training was volume-matched, it was important to understand if the same pattern occurs in-season for an athletic (rather than just 'well-trained') population. Between the single micro-cycle (Chapter 6) and the 9-week training studies (Chapter 7), the 'proof of concept' of micro-dosing strength training, completed within a single muscle group, (i.e., the hamstrings), demonstrated further that no meaningful differences were present with variations in frequency with small differences in compliance. A further conclusion could also be made that loading muscle groups eccentrically can be applied in-season, even on consecutive days providing that the volume is prescribed appropriately. Appropriate volume prescription was discussed in relation to the NHE in Chapter 2 and subsequently applied in Chapters 6 and 7. The principles discussed, however, remain similar for other eccentric exercises whereby low volumes are required due to eccentric exercises usually being high intensity. The introduction of a new exercise or stimulus, which is not necessarily just eccentric focussed can cause DOMS, and if the severity is too great, especially in-season this could potentially effect performance or buy-in of the athletes. If micro-dosing allows for the reduction of DOMS in the first instance, but is still a sufficient stimulus to induce a RBE, this would be further rationale to use micro-dosing as a method of introducing new exercises in-season. Despite providing further evidence that there were no meaningful differences between frequencies, it is also important to understand that soccer is chaotic in nature. This chaos is not necessarily restricted to the field of play, but also with fixture congestion, ever changing schedules, team selection, and injuries etc. As a result, there are several moving parts that could impact the compliance of resistance training. The 'proof of concept' (Chapter 7) allowed us to begin to understand how micro-dosing may work in-season, but being restricted to one muscle group, and one exercise, meant that in theory the application was much easier than micro-dosing a full lower body strength training programme. Even then, full compliance was not achieved, although critically there was only a small difference (6.56 ± 8.17%; $g = 0.47$) between the groups, meaning volume was closely matched.

As a result of the subsequent lower body strength intervention, the chaotic nature previously mentioned was highlighted, and the hypothesised benefits of micro-dosing were demonstrated, particularly when regarding compliance rates. Micro-dosing demonstrated moderately greater compliance (61.11 ± 21.18%; $g = 0.72$) compared to the traditional group (47.78 ± 13.02%), alongside small to large differences ($g = 0.31$-1.25) in percentage change for force production, sprint, and change of direction performance in favour of the micro-dosing group. Considering the intervention was very strength-biased the findings begin to highlight the possible benefits of micro-dosing as a programming strategy in-season. Although a 5-week block is not strictly a 'chronic' period of training, if these differences are present across this training block, then consistency across a season should allow for development throughout, so that physical capability does not become a limiting factor for the success of a team.

Particularly in initial stages of the thesis, there was a theme of 'no meaningful difference'. Whilst current/traditional practices in scientific writing do not allow for a hypothesis of no difference, due to null hypothesis significance testing being the default statistical approach for many journals, the 'meaningful' descriptions associated with magnitude-based inferences allows a bandwidth of findings that you could in theory hypothesise [316]. Regardless of the hypothesis, no meaningful differences can often be considered negative, implying perhaps that nothing new or novel has been identified. In this thesis, however, no meaningful difference has the potential to allow practitioners to have much greater flexibility with their programming. As Chapter 4 discusses, although the division of total volume is described within our formal definition of micro-dosing (Chapter 3) the division does not necessarily have to be equal. The strength training intervention (Chapter 9) was equally split in terms of volume as the 2 traditional sessions were divided into 4 micro-dosed sessions, but had this not been the case, there could have been an even greater compliance by the micro-dosing group. At the same time, the opposite could have been observed and there may have been no meaningful difference in compliance and therefore no difference in completed volume between the two. In addition to distributing the volume micro-dosed across a training week unequally, there would also be rationale to investigate the way in which the training bias is divided across a training week, for example front loading the week with a strength-speed focus and moving onto speed-strength closer to competition, or vice versa.

10.2 The process

The outlined process of the thesis was included as a list of studies in the introduction. As with most plans, particularly when working in professional sport, there is usually a requirement to evolve and adapt based on certain outcomes or scenarios. This project was no different, of course, and the completed process outlined was different to that which was initially planned, as highlighted in the commentaries throughout. Figure 10.1 provides a visualisation of the whole process whereby the originally planned study to investigate the repeated bout effect of the Nordic hamstring exercise was not carried out due to the field-based hamstring tests not demonstrating a low enough minimum detectable change (MDC) to realistically detect day to day changes in hamstring force production. Chapter 6 effectively replaced the investigation into the repeated bout effect, as the study was still able demonstrate some of the acute differences (or lack of) between the traditional and micro-dosing approaches. Chapter 6 was also adapted as a result of the SARS-Cov-2 (COVID-19) pandemic, whereby data collection to increase the sample size for the 9-week hamstring intervention (Chapter 7) was halted due to a national lockdown. While the various lockdowns that happened subsequently stopped data collection, it did allow for Chapter 4 which also had not been originally planned. The hierarchical model presented in Figure 4.2 (Chapter 4) in particular has highlighted the divergent nature of this project and although it was not originally planned, it has allowed an overview of micro-dosing as a concept and highlighted a wide range of research areas in which micro-dosing could apply to resistance training in particular in team sports, as well as potentially individual, military, or first-response populations.

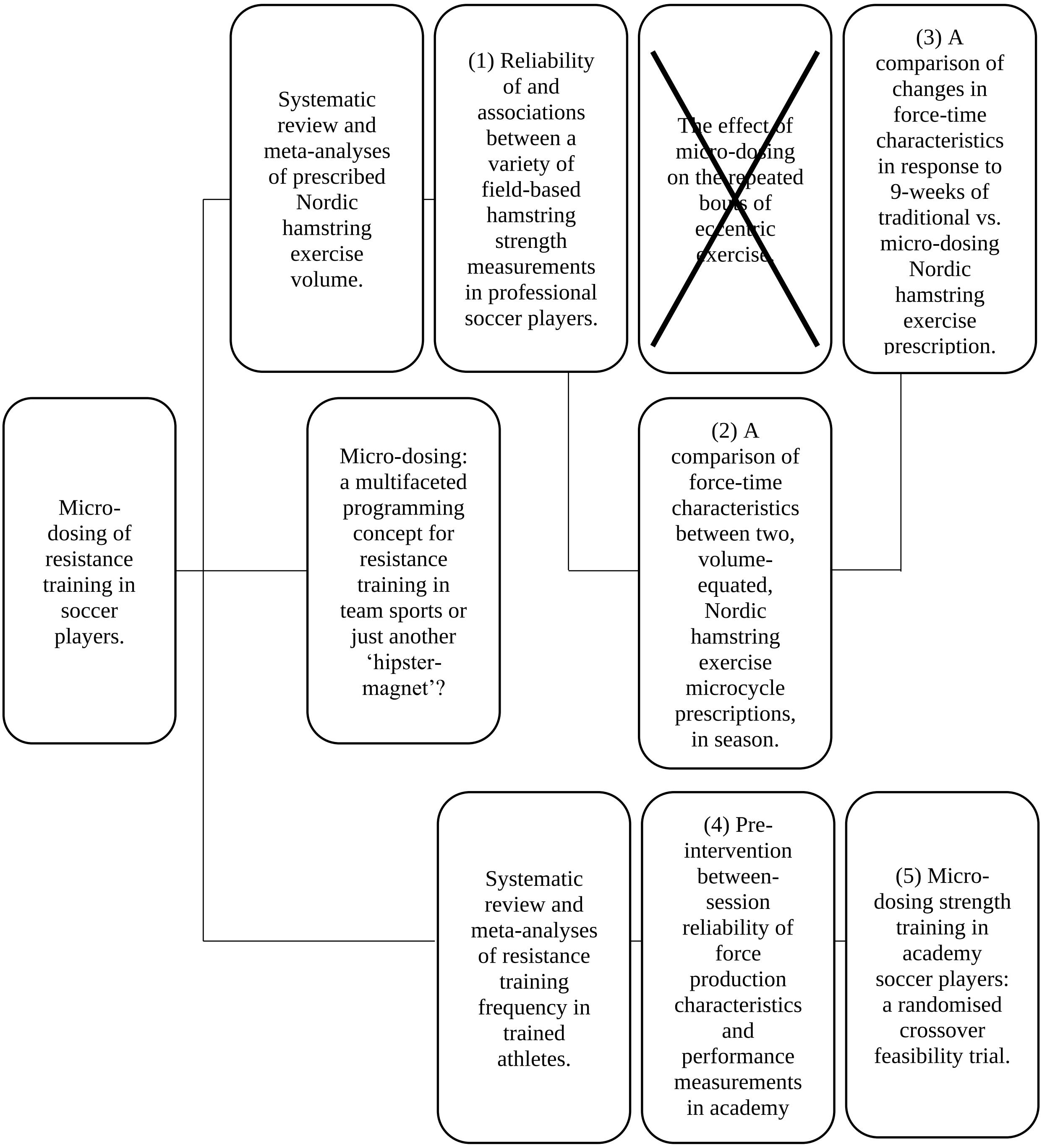


Figure 10.1. A flow diagram depicting the planned and completed study process included in this thesis.

10.3 Limitations

A clear limitation for both intervention studies (Chapters 7 and 9) was the small sample size, a common issue when investigating professional sporting populations [317]. Working with team sports, there are often some constraints or limits on sample size particularly if the population being investigated encompasses one squad of athletes. Using multiple squads in this instance may increase the error, or variability, due to different training and fixture schedules being used by the different teams. In addition, due to the complex nature of team sports, injuries are often unavoidable at times resulting in players being unable to continue their involvement in applied research. We attempted numerous strategies to try and combat this issue and increase the sample sizes as much as possible, particularly for the interventions. As mentioned previously, additional data collection for Chapter 7 was under way, when the first lockdown occurred as a result of the global pandemic and that was halted. In conjunction with the supervisory team, a grant was successfully applied for with the National Strength and Conditioning Association, which was aimed to facilitate the strength training intervention within a collegiate program in the United States, whereby much greater squad numbers would be present. Due to travel restrictions again imposed by the pandemic this intervention has yet to be carried out. Despite unsuccessfully attempting to collect a greater sample, our attention turned to making our statistical approach as robust as possible whilst accounting for the small sample size, which lead us to the use of Hedge's *g* effect size and having a greater emphasis on magnitude based inferences [314, 317, 318]. Null hypothesis significance testing is still a requirement in many journals, however, so the use of permutation tests was employed as an appropriate method of significance testing when studies are under powered. Another limitation was the lack of additional familiarisation sessions for the reliability studies (Chapters 5 and 8). Similar to issues with sample size the ability to access squads of athletes for applied research has its constraints particularly when the players and organisations are taking part in external applied research, as the time allocated to testing needs to be as minimally invasive as possible, particularly in-season. Although this should not be at the expense of scientific rigour, we were unable to gain access to the athletes for more than the between-session testing completed prior to the interventions, and with the cohort involved in Chapter 5. Had the focus shifted more towards the effect on familiarisation, it may not have been possible to complete the interventions, which were agreed with the funding organisation when the project was initiated. The knock on effect to a lack of familiarisation

A further limitation of this thesis was the variation in sampled population, although all investigation occurred within soccer players, the hamstring studies (Chapters 5, 6 and 7) were taken from a female population whereas the strength training intervention studies (Chapters 8 and 9) were conducted with males. Fortunately, there was no further mixing between studies and due to the Chapters 5, 6 and 7 being part of the proposed 'proof of concept' we were not making direct comparisons between the two interventions (Chapters 7 and 9). As mentioned in Chapter 4, strength and neuromuscular adaptations are broadly similar between male and females provided that training status is comparable [234].

10.4 Areas of future research

Whilst a range of potential future research directions based on the application of micro-dosing were explored in Chapter 4, this thesis was only ever going to begin to lay the foundations of the concept empirically. Now that we understand that micro-dosing over a 5- to 9-week period is not detrimental to strength, future directions should include investigation into the possible acute benefits (≤ 72 hours) as well more prolonged longitudinal investigations e.g., over a whole season to determine a more comprehensive understanding of the chronic effects of micro-dosing in soccer players. Considering how micro-dosing is still only developing as a standalone concept, future investigations should also be applied to many different team sports, as well as individual athletes and within tactical strength and conditioning populations to gain further understanding of the application in different environments where demands are still high but varied in comparison to soccer. As mentioned, Chapter 4 highlights how divergent micro-dosing as a programming strategy could become, Figure 10.2 has been adapted to show how all the sections outlined could crossover/interlink. It is now a great opportunity to open this concept up to allow experts in a whole range of topic areas, highlighted within Figure 10.2, to investigate the potential benefits and pitfalls of micro-dosing as an approach to the programming of resistance training now that we have begun to lay the foundations of the concept.

The mean compliance rates observed within Chapters 7 (69-75%) and 9 (48-61%) highlights that even when using micro-dosing the group means are still only just reaching the thresholds outlined by Ripley et al. [288]. The distribution of completed sessions also needs to be accounted for as Ripley et al. [288] outlined further, in relation to hamstrings strength interventions, a consistency of < 3 weeks between exposures having a positive influence on hamstring injury incidence. Compliance is unlikely to ever be 100% for a whole squad of athletes, considering individual responses to match-play and training, injuries, illness, and other absences etc., however, further research needs to be conducted to understand how best to improve overall compliance as much as possible, especially in soccer. The solutions may be more than the programming strategy used, for example micro-dosing may only get a practitioner so far with improving compliance before other issues need to be addressed such as coaches/players buying into the process.

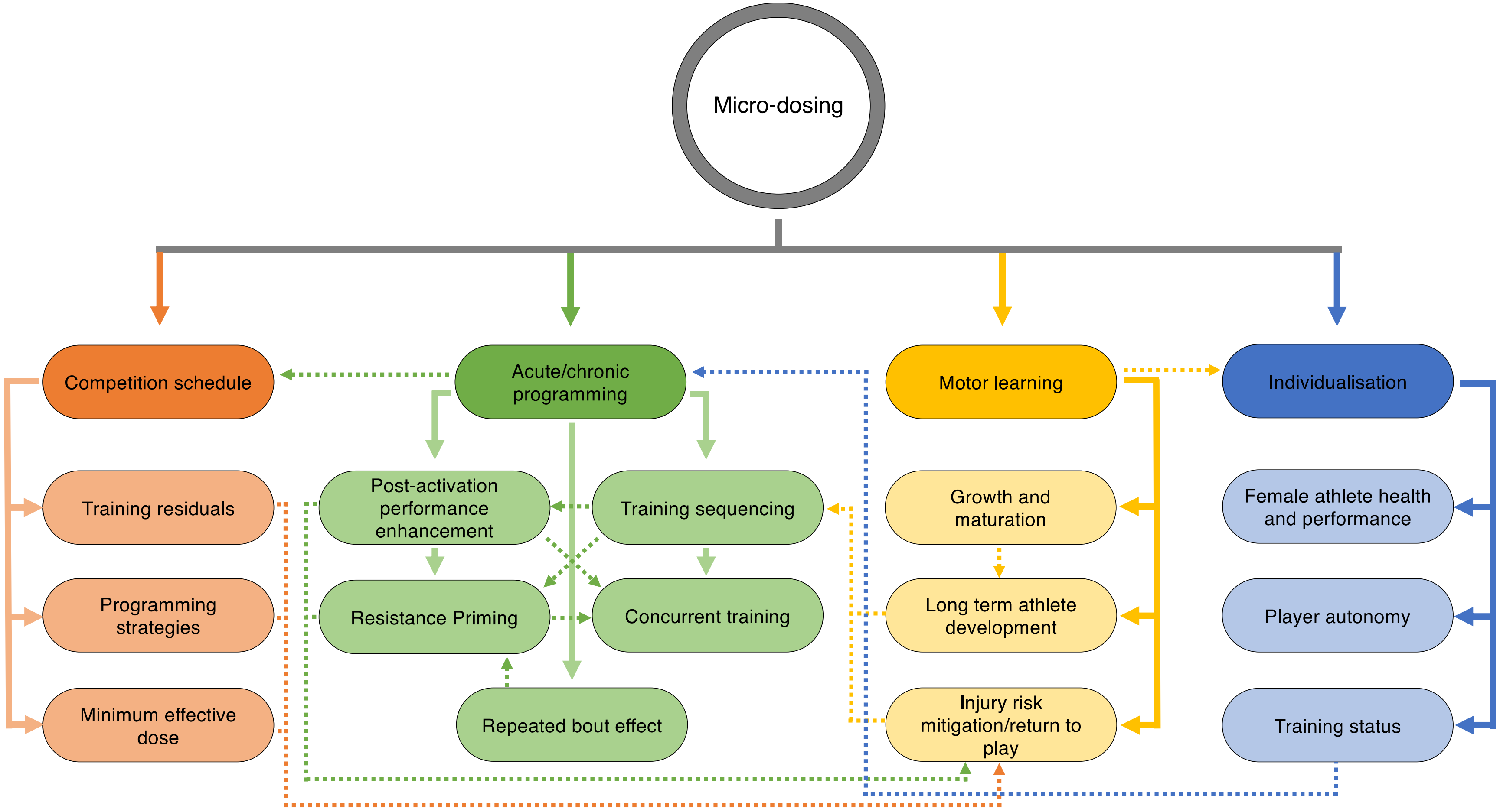
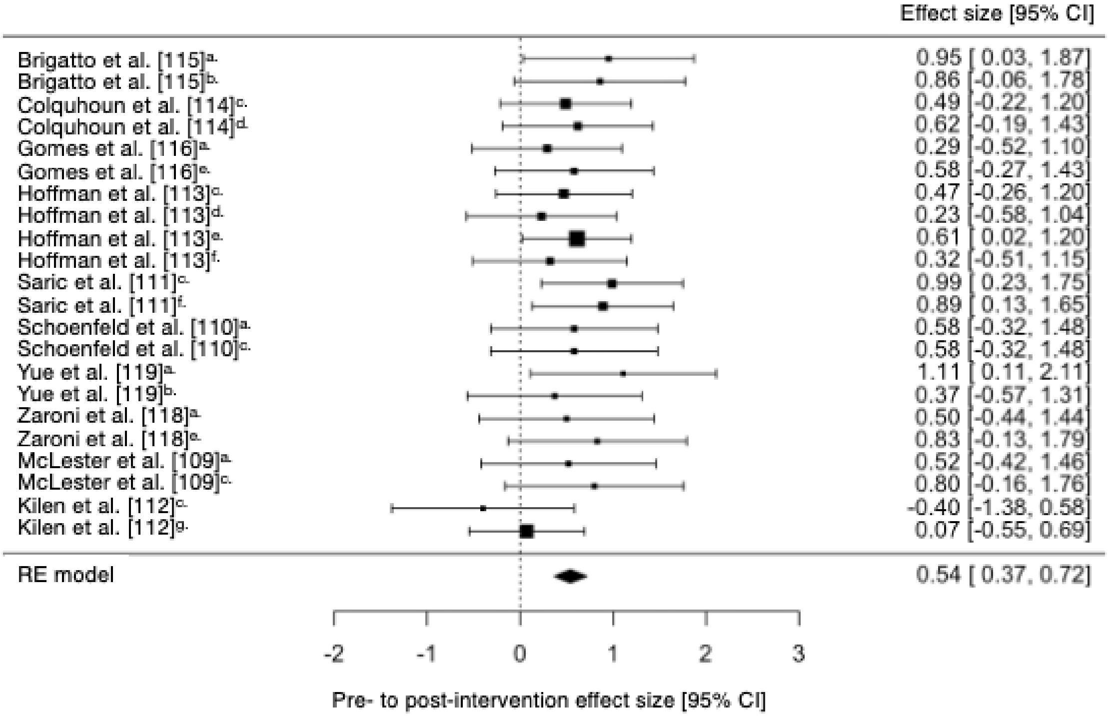


Figure 10.2. An adapted illustration of key areas where micro-dosing resistance training may be advantageous and the potential links/cross-over in approach.

10.5 Conclusions/Practical applications

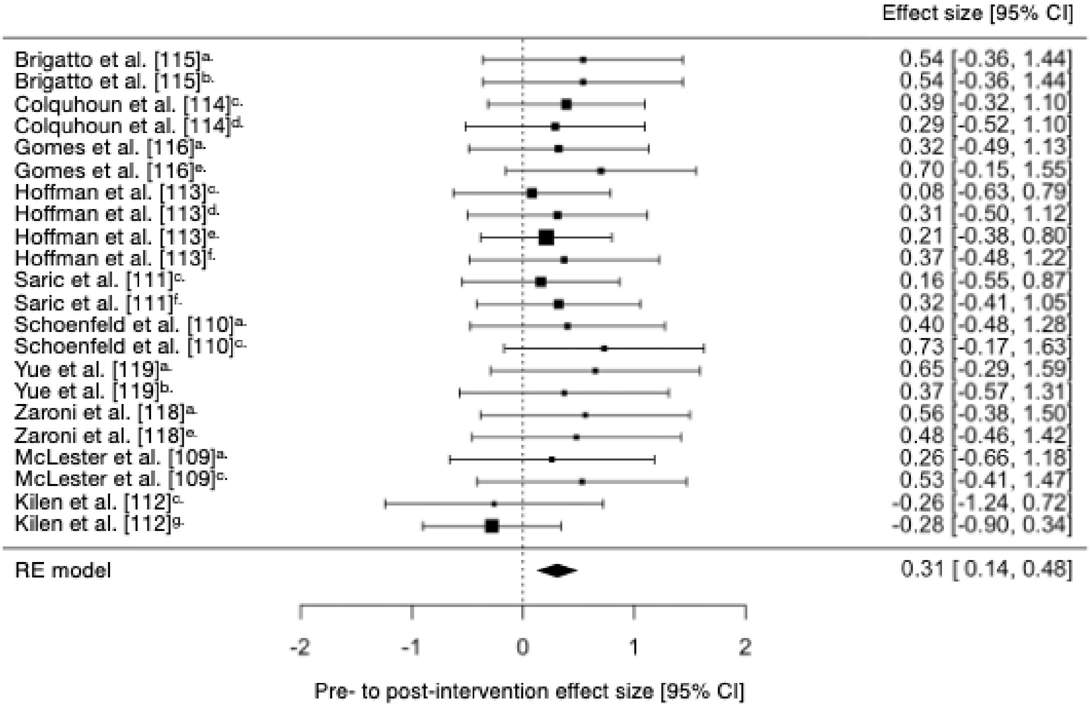
Anecdotally, numerous people following the Ph.D. process claim to know a lot about very little. Typically, having dedicated their time to investigating a specific area for a number of years and concluding with a lot more questions then answer. That does not appear to be the case in this instance, which is not to say that following this process we know very little about a lot, but we have broadened the shape of how micro-dosing could fit into practice whilst applying the basic concept to understand whether it is a viable method of resistance training. Not only do we suggest micro-dosing as a viable method from a ‘minimal effective dose’ perspective, but also as a method of increasing resistance training volume and applying the concept across the full dose-response ‘training zone’ highlighted in Figure 4.1 (Chapter 4). The fact that this thesis was initiated through applied practice, whereby specific questions of programming during periods of dense fixture schedules was highlighted in international soccer. The findings of this thesis have applications far wider than just international soccer and could have positive implications on the way programming is conducted in the wider soccer community but also across other team sports and potentially individual and tactical populations. As a result of this thesis, micro-dosing can provide moderately greater improvements in force production compared to a traditional approach across a 5-week period in soccer players. There is, however, no black or white in programming resistance training, whilst there were moderate differences in force production there was no meaningful difference between the groups for CMJ, meaning that there is definitely a time and a place for micro-dosing, but it should be used as another tool in the coaching toolbox.

11 Appendices



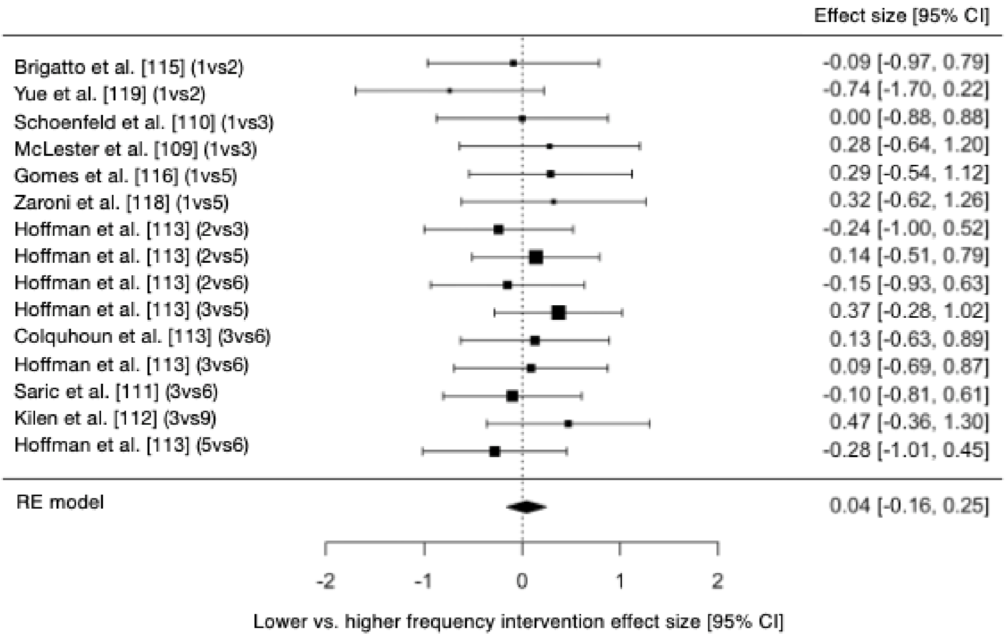
Appendix 2. An outline of effect sizes pre- and post-intervention for lower body strength.

^{a} once-weekly, ^{b} twice-weekly, ^{c} 3 x/week, ^{d} 4 x/week, ^{e} 5 x/week, ^{f} 6 x/week, ^{g} 9 x/week. RE = random effects, CI = confidence interval



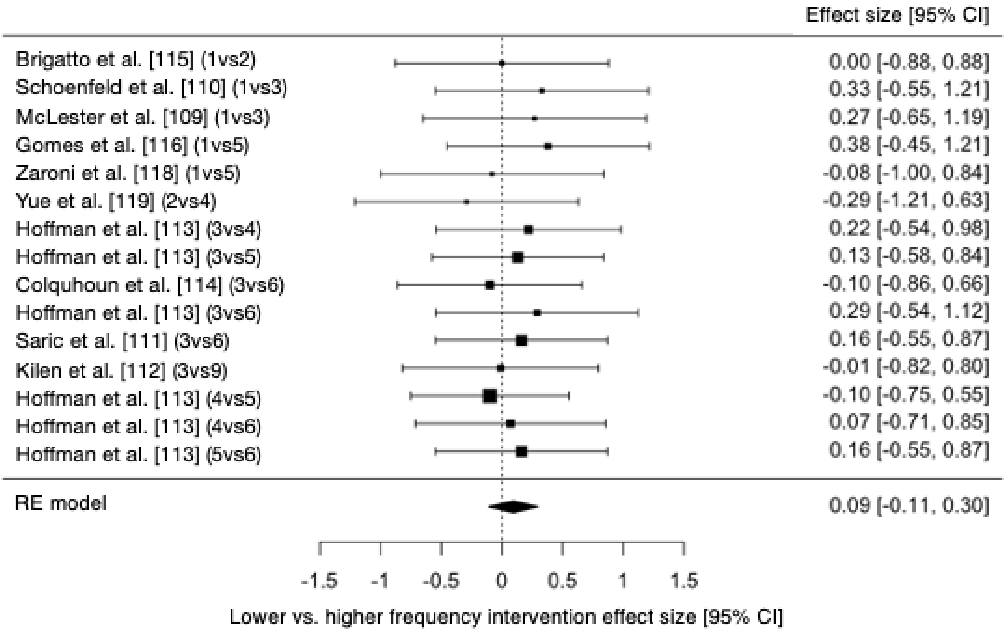
Appendix 1. An outline of effect sizes pre- and post-intervention for upper body strength.

^{a} once-weekly, ^{b} twice-weekly, ^{c} 3 x/week, ^{d} 4 x/week, ^{e} 5 x/week, ^{f} 6 x/week, ^{g} 9 x/week. RE = random effects, CI = confidence interval



Appendix 4. Differences in effect size between lower frequency and higher frequency groups on lower body strength (positive values favour the higher frequency groups and negative values favour the lower frequency groups).

(1vs2) = once-weekly vs twice-weekly, (1vs3) = once-weekly vs 3 x/week, (1vs5) = once-weekly vs 5 x/week, (2vs3) = twice-weekly vs 3 x/week, (2vs5) = twice-weekly vs 5 x/week, (2vs6) = twice-weekly vs 6 x/week, (3vs6) = 3 x/week vs 6 x/week, (3vs9) = 3 x/week vs 9 x/week, (5vs6) = 5 x/week vs 6 x/week. RE = random effects, CI = confidence interval.



Appendix 3. Differences in effect size between lower frequency and higher frequency groups on upper body strength (positive values favour the higher frequency groups and negative values favour the lower frequency groups).

(1vs2) = once-weekly vs twice-weekly, (1vs3) = once-weekly vs 3 x/week, (1vs5) = once-weekly vs 5 x/week, (2vs4) = twice-weekly vs 4 x/week, (3vs4) = 3 x/week vs 4 x/week, (3vs5) = 3 x/week vs 5 x/week, (3vs6) = 3 x/week vs 6 x/week, (3vs9) = 3 x/week vs 9 x/week, (4vs5) = 4 x/week vs 5 x/week, (4vs6) = 4 x/week vs 6 x/week, (5vs6) = 5 x/week vs 6 x/week. RE = random effects, CI = confidence interval.

12 References

1. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English Premier League. Int J Sports Med. 2014 Dec;35(13):1095-100.
2. Hoff J, Helgerud J. Endurance and strength training for soccer players: physiological considerations. Sports Med. 2004;34(3):165-80.
3. Bangsbo J. The physiology of soccer--with special reference to intense intermittent exercise. Acta Physiol Scand Suppl. 1994;619:1-155.
4. Stølen T, Chamari K, Castagna C, Wisløff U. Physiology of soccer: an update. Sports Med. 2005;35(6):501-36.
5. Morgans R, Orme P, Anderson L, Drust B. Principles and practices of training for soccer. Journal of Sport and Health Science. 2014 2014/12/01/;3(4):251-7.
6. Hennessy L, Jeffreys I. The Current Use of GPS, Its Potential, and Limitations in Soccer. Strength Cond J. 2018;40(3).
7. Di Salvo V, Gregson W, Atkinson G, Tordoff P, Drust B. Analysis of high intensity activity in Premier League soccer. Int J Sports Med. 2009 Mar;30(3):205-12.
8. Bradley PS, Carling C, Gomez Diaz A, Hood P, Barnes C, Ade J, et al. Match performance and physical capacity of players in the top three competitive standards of English professional soccer. Human Mov Sci. 2013 2013/08/01/;32(4):808-21.
9. Johnston RD, Gabbett TJ, Jenkins DG, Hulin BT. Influence of physical qualities on post-match fatigue in rugby league players. J Sci Med Sport. 2015 Mar;18(2):209-13.
10. Akenhead R, Hayes PR, Thompson KG, French D. Diminutions of acceleration and deceleration output during professional football match play. J Sci Med Sport. 2013 Nov;16(6):556-61.
11. Osgnach C, Poser S, Bernardini R, Rinaldo R, di Prampero PE. Energy cost and metabolic power in elite soccer: a new match analysis approach. Med Sci Sports Exerc. 2010 Jan;42(1):170-8.
12. McBurnie AJ, Harper DJ, Jones PA, Dos'Santos T. Deceleration Training in Team Sports: Another Potential 'Vaccine' for Sports-Related Injury? Sports Med. 2022 Jan;52(1):1-12.
13. Edwards WB. Modeling Overuse Injuries in Sport as a Mechanical Fatigue Phenomenon. Exerc Sport Sci Rev. 2018 Oct;46(4):224-31.
14. Byrne C, Twist C, Eston R. Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications. Sports Med. 2004;34(1):49-69.
15. Owen A, Dunlop G, Rouissi M, Chtara M, Paul D, Zouhal H, et al. The relationship between lower-limb strength and match-related muscle damage in elite level professional European soccer players. J Sports Sci. 2015;33(20):2100-5.
16. Malone S, Hughes B, Doran DA, Collins K, Gabbett TJ. Can the workload-injury relationship be moderated by improved strength, speed and repeated-sprint qualities? J Sci Med Sport. 2019 Jan;22(1):29-34.
17. Ekstrand J, Hägglund M, Waldén M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med. 2011 Jun;45(7):553-8.
18. Ekstrand J, Waldén M, Hägglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study. Br J Sports Med. 2016;50(12):731-7.
19. Ekstrand J, Hägglund M, Waldén M. Epidemiology of muscle injuries in professional football (soccer). Am J Sports Med. 2011 Jun;39(6):1226-32.
20. Dai B, Mao D, Garrett WE, Yu B. Anterior cruciate ligament injuries in soccer: Loading mechanisms, risk factors, and prevention programs. J Sport Health Sci. 2014 2014/12/01/;3(4):299-306.
21. Beato M, Maroto-Izquierdo S, Turner AN, Bishop C. Implementing Strength Training Strategies for Injury Prevention in Soccer: Scientific Rationale and Methodological Recommendations. Int J Sports Physiol Perform. 2021 Mar 1;16(3):456-61.
22. Springham M, Williams S, Waldron M, Burgess D, Newton RU. Large Reductions in Match Play Physical Performance Variables Across a Professional Football Season With Control for Situational and Contextual Variables. Front Sports Active Living. 2020 2020-October-15;2.
23. Morgans R, Adams D, Mullen R, McLellan C, Williams MD. Technical and Physical Performance over an English Championship League Season. Int J Sports Sci Coaching. 2014 2014/10/01;9(5):1033-42.
24. Silva JR, Rumpf MC, Hertzog M, Nassis GP. Does the FIFA World Cup s Congested Fixture Program Affect Playerì Performance? Asian J Sports Med. 2017;8.
25. Anderson L, Orme P, Di Michele R, Close GL, Milsom J, Morgans R, et al. Quantification of Seasonal-Long Physical Load in Soccer Players With Different Starting Status From the English Premier League: Implications for Maintaining Squad Physical Fitness. Int J Sports Physiol Perform. 2016 Nov;11(8):1038-46.

26. Casajús JA. Seasonal variation in fitness variables in professional soccer players. J Sports Med Phys Fitness. 2001 Dec;41(4):463-9.
27. Kalapotharakos VI, Ziogas G, Tokmakidis SP. Seasonal aerobic performance variations in elite soccer players. J Strength Cond Res. 2011 Jun;25(6):1502-7.
28. Rønnestad BR, Nymark BS, Raastad T. Effects of in-season strength maintenance training frequency in professional soccer players. J Strength Cond Res. 2011 Oct;25(10):2653-60.
29. Elliott MCCW, Zarins B, Powell JW, Kenyon CD. Hamstring Muscle Strains in Professional Football Players: A 10-Year Review. Am J Sports Med. 2011 2011/04/01;39(4):843-50.
30. Liu H, Garrett WE, Moorman CT, Yu B. Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature. J Sport Health Sci. 2012 2012/09/01/;1(2):92-101.
31. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. Br J Sports Med. 2005 Oct;39(10):757-66.
32. Verrall GM, Slavotinek JP, Barnes PG. The effect of sports specific training on reducing the incidence of hamstring injuries in professional Australian Rules football players. Br J Sports Med. 2005 Jun;39(6):363-8.
33. Gabbett TJ. The training-injury prevention paradox: should athletes be training smarter and harder? Br J Sports Med. 2016 Mar;50(5):273-80.
34. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. Br J Sports Med. 2004 Feb;38(1):36-41.
35. Petersen J, Thorborg K, Nielsen MB, Hölmich P. Acute hamstring injuries in Danish elite football: a 12-month prospective registration study among 374 players. Scandi J Med Sci Sports. 2010;20(4):588-92.
36. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. Am J Sports Med. 2006 Aug;34(8):1297-306.
37. Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. Am J Sports Med. 2015;43(11):2663-70.
38. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high speed running. Med Sci Sports Exerc. 2011;43(3):525.
39. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. J Biomech. 2007;40(16):3555-62.
40. Higashihara A, Nagano Y, Takahashi K, Fukubayashi T. Relationship between hamstring muscle kinematics and hip rotation during the terminal swing of the sprinting gait cycle. J Sci Med Sport. 2012;15:S63.
41. Schache AG, Dorn TW, Blanch PD, Brown N, Pandy MG. Mechanics of the human hamstring muscles during sprinting. Med Sci Sports Exerc. 2012;44(4):647-58.
42. Schache AG, Dorn TW, Wrigley TV, Brown NAT, Pandy MG. Stretch and activation of the human biarticular hamstrings across a range of running speeds. Eur J Appl Physiol. 2013 2013/11/01;113(11):2813-28.
43. Thelen DG, Chumanov ES, Best TM, Swanson SC, Heiderscheit BC. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. Med Sci Sports Exerc. 2005;37(11):1931-8.
44. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. J Biomech. 2008 Nov 14;41(15):3121-6.
45. Fiorentino NM, Rehorn MR, Chumanov ES, Thelen DG, Blemker SS. Computational models predict larger muscle tissue strains at faster sprinting speeds. Med Sci Sports Exerc. 2014 Apr;46(4):776-86.
46. Turner AN, Cree J, Comfort P, Jones L, Chavda S, Bishop C, et al. Hamstring strain prevention in elite soccer players. Strength Cond J. 2014;36(5):10-20.
47. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Med Sci Sports Exerc. 2015 Apr;47(4):857-65.
48. Opar DA, Williams MD, Shield AJ. Hamstring Strain Injuries. Sports Med. 2012 2012/03/01;42(3):209-26.
49. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. British Journal of Sports Med. 2016;50(24):1524-35.
50. Lieber RL, Fridén J. Functional and clinical significance of skeletal muscle architecture. Muscle Nerve. 2000 Nov;23(11):1647-66.
51. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. Med Sci Sports Exerc. 2004;36(3):379-87.
52. Thelen DG, Chumanov ES, Hoerth DM, Best TM, Swanson SC, Li L, et al. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exerc. 2005;37(1):108-14.
53. Franchi MV, Reeves ND, Narici MV. Skeletal muscle remodeling in response to eccentric vs. concentric loading: morphological, molecular, and metabolic adaptations. Front physiol. 2017;8:447.
54. Brockett CL, Morgan DL, Proske U. Human hamstring muscles adapt to eccentric exercise by changing optimum length. Med Sci Sports Exerc. 2001;33(5):783-90.

55. Arnason A, Andersen T, Holme I, Engebretsen L, Bahr R. Prevention of hamstring strains in elite soccer: an intervention study. Scandi J Med Sci Sports. 2008;18(1):40-8.
56. Bourne MN, Williams MD, Opar DA, Al Najjar A, Kerr GK, Shield AJ. Impact of exercise selection on hamstring muscle activation. Br J Sports Med. 2017;51(13):1021-8.
57. Mjølsnes R, Arnason A, Østhagen T, Raastad T, Bahr R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. Scandi J Med Sci Sports. 2004;14(5):311-7.
58. Seagrave III RA, Perez L, McQueeney S, Toby EB, Key V, Nelson JD. Preventive effects of eccentric training on acute hamstring muscle injury in professional baseball. Orthop J Sports Med. 2014;2(6):2325967114535351.
59. Ishøi L, Hölmich P, Aagaard P, Thorborg K, Bandholm T, Serner A. Effects of the Nordic Hamstring exercise on sprint capacity in male football players: a randomized controlled trial. J Sports Sci. 2018 Jul;36(14):1663-72.
60. Lieber RL, Friden J. Morphologic and mechanical basis of delayed-onset muscle soreness. J Am Acad Orthop Surg. 2002 Jan-Feb;10(1):67-73.
61. Bahr R, Thorborg K, Ekstrand J. Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. Br J Sports Med. 2015 Nov;49(22):1466-71.
62. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009 Jul 21;6(7):e1000097.
63. Kellis E, Baltzopoulos V. Isokinetic eccentric exercise. Sports Med. 1995 Mar;19(3):202-22.
64. Iossifidou AN, Baltzopoulos V. Angular velocity in eccentric isokinetic dynamometry. Isokinetics Exerc Sci. 1996;6(1):65-70.
65. Smart NA, Waldron M, Ismail H, Giallauria F, Vigorito C, Cornelissen V, et al. Validation of a new tool for the assessment of study quality and reporting in exercise training studies: TESTEX. Int J Evid Based Healthc. 2015 Mar;13(1):9-18.
66. The jamovi project. 0.9 ed. https://www.jamovi.org; 2019.
67. Alonso-Fernandez D, Docampo-Blanco P, Martinez-Fernandez J. Changes in muscle architecture of biceps femoris induced by eccentric strength training with nordic hamstring exercise. Scandi J Med Sci Sports. 2018;28(1):88-94.
68. Alt T, Nodler Y, Severin J, Knicker A, Strüder H. Velocity-specific and time-dependent adaptations following a standardized Nordic Hamstring exercise training. Scandi J Med Sci Sports. 2018;28(1):65-76.
69. Anastasi SM, Hamzeh MA. Does the eccentric Nordic Hamstring exercise have an effect on isokinetic muscle strength imbalance and dynamic jumping performance in female rugby union players? Isokinetics Exerc Sci. 2011;19(4):251-60.
70. Clark R, Bryant A, Culgan J-P, Hartley B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. Physical Ther Sport. 2005;6(2):67-73.
71. Delahunt E, McGroarty M, De Vito G, Ditroilo M. Nordic hamstring exercise training alters knee joint kinematics and hamstring activation patterns in young men. Eur J Appl Physiol. 2016;116(4):663-72.
72. Freeman BW, Young WB, Talpey SW, Smyth AM, Pane CL, Carlon TA. The effects of sprint training and the Nordic hamstring exercise on eccentric hamstring strength and sprint performance in adolescent athletes. J Sports Med Phys Fitness. 2019 Jul;59(7):1119-25.
73. Iga J, Fruer C, Deighan M, Croix M, James D. ‘Nordic’hamstrings exercise–engagement characteristics and training responses. Int J Sports Med. 2012;33(12):1000-4.
74. Presland JD, Timmins RG, Bourne MN, Williams MD, Opar DA. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. Scandi J Med Sci Sports. 2018;28(7):1775-83.
75. Ribeiro-Alvares JB, Marques VB, Vaz MA, Baroni BM. Four weeks of Nordic hamstring exercise reduce muscle injury risk factors in young adults. J Strength Cond Res. 2018;32(5):1254-62.
76. Seymore KD, Domire ZJ, DeVita P, Rider PM, Kulas AS. The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. Eur J Appl Physiol. 2017;117(5):943-53.
77. Tansel RB, Salci Y, Yildirim A, Kocak S, Korkusuz F. Effects of eccentric hamstring strength training on lower extremity strength of 10–12 year old male basketball players. Isokinetics Exerc Sci. 2008;16(2):81-5.
78. Thomas JR, French KE. The use of meta-analysis in exercise and sport: A tutorial. Res Quarterly Exerc Sport. 1986;57(3):196-204.
79. Hedges LV, Olkin I. Statistical methods for meta-analysis: Academic press; 2014.
80. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. Sportscience. 2010;14:49-59.

81. Higgins JPT, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. BMJ. 2003;327(7414):557-60.
82. Sheppard JM, Triplett NT. Program design for resistance training. Essentials of Strength Training and Conditioning. 2016:439-70.
83. van Dyk N, Witvrouw E, Bahr R. Interseason variability in isokinetic strength and poor correlation with Nordic hamstring eccentric strength in football players. Scandi J Med Sci Sports. 2018;28(8):1878-87.
84. Cuthbert M, Ripley N, McMahon JJ, Evans M, Haff GG, Comfort P. The Effect of Nordic Hamstring Exercise Intervention Volume on Eccentric Strength and Muscle Architecture Adaptations: A Systematic Review and Meta-analyses. Sports Med. 2020;50(1):83-99.
85. Cuthbert M, Ripley N, McMahon JJ, Evans M, Haff GG, Comfort P. Corrections to: The Effect of Nordic Hamstring Exercise Intervention Volume on Eccentric Strength and Muscle Architecture Adaptations: A Systematic Review and Meta-analyses. Sports Med. 2020 2020/01/01;50(1):101-2.
86. Alt T, Nodler YT, Severin J, Knicker AJ, Strüder HK. Comment On: “The Effect of Nordic Hamstring Exercise Intervention Volume on Eccentric Strength and Muscle Architecture Adaptations: A Systematic Review and Meta-Analyses”. Sports Med. 2020 2020/01/01;50(1):219-21.
87. Cuthbert M, Ripley N, McMahon JJ, Evans M, Haff GG, Comfort P. Reply to: “Comment on: The Effect of Nordic Hamstring Exercise Intervention Volume on Eccentric Strength and Muscle Architecture Adaptations: A Systematic Review and Meta-analyses”. Sports Med. 2020 2020/01/01;50(1):223-5.
88. Suchomel TJ, Nimphius S, Stone MH. The Importance of Muscular Strength in Athletic Performance. Sports Med. 2016 Oct;46(10):1419-49.
89. Cormie P, McGuigan MR, Newton RU. Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. Sports Med. 2011 Feb 1;41(2):125-46.
90. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The Importance of Muscular Strength: Training Considerations. Sports Med. 2018 Apr;48(4):765-85.
91. Fleck SJ, Falkel JE. Value of resistance training for the reduction of sports injuries. Sports Med. 1986 Jan-Feb;3(1):61-8.
92. Lehnhard RA, Lehnhard HR, Young R, Butterfield SA. Monitoring injuries on a college soccer team: the effect of strength training. J Strength Cond Res. 1996;10:115-9.
93. Lauersen JB, Bertelsen DM, Andersen LB. The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. Br J Sports Med. 2014 Jun;48(11):871-7.
94. Cormie P, McGuigan MR, Newton RU. Adaptations in athletic performance after ballistic power versus strength training. Med Sci Sports Exerc. 2010 Aug;42(8):1582-98.
95. Stowers T, McMillan J, Scala D, Davis V, Wilson D, Stone M. The short-term effects of three different strength-power training methods. Strength Cond J. 1983;5(3):24-7.
96. Wilson GJ, Newton RU, Murphy AJ, Humphries BJ. The optimal training load for the development of dynamic athletic performance. Med Sci Sports Exerc. 1993 Nov;25(11):1279-86.
97. Bompa T, Haff GG. Periodization: theory and methodology of training; 2009.
98. Medicine ACoS. ACSM Guidelines for exercise testing and prescription 10th edition: Lippincott Williams & Wilkins; 2018.
99. Matveyev LP. Fundamentals of sports training; 1981.
100. UEFA. Regulations of the UEFA European Under-17 Championship 2019/20. 2019 [cited 2020 28th May]
101. Lundberg TR, Weckström K. Fixture congestion modulates post-match recovery kinetics in professional soccer players. Res Sports Med. 2017 Oct-Dec;25(4):408-20.
102. Tofari PJ, Kemp JG, Cormack SJ. Measuring the response to simulated fixture congestion in soccer. Sci Med Football. 2020;4(4):293-304.
103. Johnston RD, Gabbett TJ, Jenkins DG. Influence of playing standard and physical fitness on activity profiles and post-match fatigue during intensified junior rugby league competition. Sports Med Open. 2015;1(1):18.
104. Platonov V. Periodization concepts of sports training. Theor Pract Phys Cult. 1998;8:23-6.
105. Baker DG. 10-year changes in upper body strength and power in elite professional rugby league players--the effect of training age, stage, and content. J Strength Cond Res. 2013 Feb;27(2):285-92.
106. Grgic J, Schoenfeld BJ, Davies TB, Lazinica B, Krieger JW, Pedisic Z. Effect of Resistance Training Frequency on Gains in Muscular Strength: A Systematic Review and Meta-Analysis. Sports Med. 2018 May;48(5):1207-20.
107. Ralston GW, Kilgore L, Wyatt FB, Buchan D, Baker JS. Weekly Training Frequency Effects on Strength Gain: A Meta-Analysis. Sports Med Open. 2018 Aug 3;4(1):36.

108. Mangine GT, Hoffman JR, Gonzalez AM, Townsend JR, Wells AJ, Jajtner AR, et al. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. Physiol Rep. 2015 Aug;3(8).
109. McLester JR, Bishop E, Guilliams M. Comparison of 1 day and 3 days per week of equal-volume resistance training in experienced subjects. J Strength Cond Res. 2000;14(3):273-81.
110. Schoenfeld BJ, Ratamess NA, Peterson MD, Contreras B, Tiryaki-Sonmez G. Influence of Resistance Training Frequency on Muscular Adaptations in Well-Trained Men. J Strength Cond Res. 2015 Jul;29(7):1821-9.
111. Saric J, Lisica D, Orlic I, Grgic J, Krieger JW, Vuk S, et al. Resistance training frequencies of 3 and 6 times per week produce similar muscular adaptations in resistance-trained men. J Strength Cond Res. 2019;33:S122-S9.
112. Kilen A, Hjelvang LB, Dall N, Kruse NL, Nordsborg NB. Adaptations to Short, Frequent Sessions of Endurance and Strength Training Are Similar to Longer, Less Frequent Exercise Sessions When the Total Volume Is the Same. J Strength Cond Res. 2015 Nov;29 Suppl 11:S46-51.
113. Hoffman JR, Kraemer WJ, Fry AC, Deschenes M, Kemp M. The effects of self-selection for frequency of training in a winter conditioning program for football. J Strength Cond Res. 1990;4(3):76-82.
114. Colquhoun RJ, Gai CM, Aguilar D, Bove D, Dolan J, Vargas A, et al. Training Volume, Not Frequency, Indicative of Maximal Strength Adaptations to Resistance Training. J Strength Cond Res. 2018 May;32(5):1207-13.
115. Brigatto FA, Braz TV, Zanini T, Germano MD, Aoki MS, Schoenfeld BJ, et al. Effect of Resistance Training Frequency on Neuromuscular Performance and Muscle Morphology After 8 Weeks in Trained Men. J Strength Cond Res. 2019 Aug;33(8):2104-16.
116. Gomes GK, Franco CM, Nunes PRP, Orsatti FL. High-Frequency Resistance Training Is Not More Effective Than Low-Frequency Resistance Training in Increasing Muscle Mass and Strength in Well-Trained Men. J Strength Cond Res. 2019 Jul;33 Suppl 1:S130-s9.
117. Yue FL, Karsten B, Larumbe-Zabala E, Seijo M, Naclerio F. Comparison of 2 weekly-equalized volume resistance-training routines using different frequencies on body composition and performance in trained males. Appl Physiol Nutr Metab. 2018 May;43(5):475-81.
118. Zaroni RS, Brigatto FA, Schoenfeld BJ, Braz TV, Benvenutti JC, Germano MD, et al. High Resistance-Training Frequency Enhances Muscle Thickness in Resistance-Trained Men. J Strength Cond Res. 2019 Jul;33 Suppl 1:S140-s51.
119. Chen TC, Yang TJ, Huang MJ, Wang HS, Tseng KW, Chen HL, et al. Damage and the repeated bout effect of arm, leg, and trunk muscles induced by eccentric resistance exercises. Scand J Med Sci Sports. 2019 May;29(5):725-35.
120. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Architectural adaptations of muscle to training and injury: a narrative review outlining the contributions by fascicle length, pennation angle and muscle thickness. Br J Sports Med. 2016 Dec;50(23):1467-72.
121. Sale DG. Neural adaptation to resistance training. Med Sci Sports Exerc. 1988 Oct;20(5 Suppl):S135-45.
122. Schoenfeld BJ, Ratamess NA, Peterson MD, Contreras B, Sonmez GT, Alvar BA. Effects of different volume-equated resistance training loading strategies on muscular adaptations in well-trained men. J Strength Cond Res. 2014 Oct;28(10):2909-18.
123. Steele J. Intensity; in-ten-si-ty; noun. 1. Often used ambiguously within resistance training. 2. Is it time to drop the term altogether? Br J Sports Med. 2014 Dec;48(22):1586-8.
124. Arent SM, Landers DM, Matt KS, Etnier JL. Dose-Response and Mechanistic Issues in the Resistance Training and Affect Relationship. J Sport Exerc Psychol. 2005 01 Mar. 2005;27(1):92-110.
125. Carroll KM, Bernards JR, Bazyler CD, Taber CB, Stuart CA, DeWeese BH, et al. Divergent performance outcomes following resistance training using repetition maximums or relative intensity. Int J Sports Physiol Perform. 2019;14(1):46-54.
126. Carroll KM, Bazyler CD, Bernards JR, Taber CB, Stuart CA, DeWeese BH, et al. Skeletal Muscle Fiber Adaptations Following Resistance Training Using Repetition Maximums or Relative Intensity. Sports (Basel). 2019 Jul 11;7(7).
127. Ahtiainen JP, Pakarinen A, Alen M, Kraemer WJ, Häkkinen K. Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. Eur J Appl Physiol. 2003 Aug;89(6):555-63.
128. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. J Strength Cond Res. 2010 Oct;24(10):2857-72.
129. Wilson JM, Marin PJ, Rhea MR, Wilson SM, Loenneke JP, Anderson JC. Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises. J Strength Cond Res. 2012 Aug;26(8):2293-307.

130. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. J Strength Cond Res. 2004 Nov;18(4):918-20.
131. Willoughby DS. The effects of mesocycle-length weight training programs involving periodization and partially equated volumes on upper and lower body strength. J Strength Cond Res. 1993;7(1):2-8.
132. Hansen DM. Micro-dosing with speed and tempo sessions for performance gains and injury prevention. https://www.strengthpowerspeed.com/micro-dosing-speed-tempo/; 2015.
133. Cuthbert M, Haff GG, Arent SM, Ripley N, McMahon JJ, Evans M, et al. Effects of Variations in Resistance Training Frequency on Strength Development in Well-Trained Populations and Implications for In-Season Athlete Training: A Systematic Review and Meta-analysis. Sports Med. 2021 2021/09/01;51(9):1967-82.
134. Lappin G, Noveck R, Burt T. Microdosing and drug development: past, present and future. Expert Opin Drug Metab Toxicol. 2013 Jul;9(7):817-34.
135. Lappin G, Garner RC. Big physics, small doses: the use of AMS and PET in human microdosing of development drugs. Nature Rev Drug Discov. 2003 2003/03/01;2(3):233-40.
136. Polito V, Stevenson RJ. A systematic study of microdosing psychedelics. PLoS One. 2019;14(2):e0211023.
137. Fadiman J. The psychedelic explorer's guide: safe, therapeutic, and sacred journeys. 2011.
138. Sabag A, Lovell R, Walsh NP, Grantham N, Lacome M, Buchheit M. Upper-Body Resistance Training Following Soccer Match Play: Compatible, Complementary, or Contraindicated? Int J Sports Physiol Perform. 2021 Jan 13;16(2):165-75.
139. Hansen DM. Let’s make a case for boring. https://sprintcoach.com/wp-content/uploads/2018/08/Lets-Make-a-Case-for-Boring-Derek-M-Hansen.pdf; 2018.
140. Stone MH, Hornsby WG, Haff GG, Fry AC, Suarez DG, Liu J, et al. Periodization and block periodization in sports: emphasis on strength-power training— a provocative and challenging narrative. The J Strength Cond Res. 2021;35(8):2351-71.
141. Counsilman B, Counsilman J. The residual effects of training. J Swimming Res. 1991;7(1):5-12.
142. Issurin VB. Generalized training effects induced by athletic preparation. A review. J Sports Med Phys Fitness. 2009 Dec;49(4):333-45.
143. Issurin VB. New horizons for the methodology and physiology of training periodization. Sports Med. 2010 Mar 1;40(3):189-206.
144. Issurin VB. Block periodization versus traditional training theory: a review. J Sports Med Phys Fitness. 2008 Mar;48(1):65-75.
145. Cunanan AJ, DeWeese BH, Wagle JP, Carroll KM, Sausaman R, Hornsby WG, 3rd, et al. The General Adaptation Syndrome: A Foundation for the Concept of Periodization. Sports Med. 2018 Apr;48(4):787-97.
146. DeWeese BH, Hornsby G, Stone M, Stone MH. The training process: Planning for strength–power training in track and field. Part 2: Practical and applied aspects. J Sport Health Sci. 2015 2015/12/01/;4(4):318-24.
147. Fry AC, Kraemer WJ. Resistance exercise overtraining and overreaching. Neuroendocrine responses. Sports Med. 1997 Feb;23(2):106-29.
148. Turner A. The Science and Practice of Periodization: A Brief Review. Strength Cond J. 2011;33(1).
149. Stone MH, Stone M, Sands WA, Sands B. Principles and Practice of Resistance Training: Human Kinetics; 2007.
150. DeWeese BH, Hornsby G, Stone M, Stone MH. The training process: Planning for strength–power training in track and field. Part 1: Theoretical aspects. J Sport Health Sci. 2015 2015/12/01/;4(4):308-17.
151. Issurin V, Yessis M. Block Periodization: Breakthrough in Sports Training: Ultimate Athlete Concepts; 2008.
152. Issurin V, Thome M. Building the Modern Athlete: Scientific Advancements & Training Innovations: Ultimate Athlete Concepts; 2015.
153. Zatsiorsky VM, Kraemer WJ. Timing in Strength Training, in: *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics; 2006.
154. Zatsiorsky VM. Timing in Strength Training, in: *Science and Practice of Strength Training*. Champaign, IL: Human Kinetics; 1995.
155. Issurin VB. Benefits and Limitations of Block Periodized Training Approaches to Athletes' Preparation: A Review. Sports Med. 2016 Mar;46(3):329-38.
156. D’Emanuele S, Maffiuletti NA, Tarperi C, Rainoldi A, Schena F, Boccia G. Rate of Force Development as an Indicator of Neuromuscular Fatigue: A Scoping Review. Front Human Neurosci. 2021 2021-July-09;15.
157. Bickel CS, Cross JM, Bamman MM. Exercise dosing to retain resistance training adaptations in young and older adults. Med Sci Sports Exerc. 2011 Jul;43(7):1177-87.

158. Androulakis-Korakakis P, Fisher JP, Steele J. The Minimum Effective Training Dose Required to Increase 1RM Strength in Resistance-Trained Men: A Systematic Review and Meta-Analysis. Sports Med. 2020 Apr;50(4):751-65.
159. Iversen VM, Norum M, Schoenfeld BJ, Fimland MS. No Time to Lift? Designing Time-Efficient Training Programs for Strength and Hypertrophy: A Narrative Review. Sports Med. 2021 2021/10/01;51(10):2079-95.
160. Izquierdo M, Ibañez J, González-Badillo JJ, Häkkinen K, Ratamess NA, Kraemer WJ, et al. Differential effects of strength training leading to failure versus not to failure on hormonal responses, strength, and muscle power gains. J Appl Physiol (1985). 2006 May;100(5):1647-56.
161. Martorelli S, Cadore EL, Izquierdo M, Celes R, Martorelli A, Cleto VA, et al. Strength Training with Repetitions to Failure does not Provide Additional Strength and Muscle Hypertrophy Gains in Young Women. Eur J Transl Myol. 2017;27(2):6339-.
162. Spiering BA, Mujika I, Sharp MA, Foulis SA. Maintaining Physical Performance: The Minimal Dose of Exercise Needed to Preserve Endurance and Strength Over Time. J Strength Cond Res. 2021;35(5):1449-58.
163. Afonso J, Nakamura FY, Baptista I, Rendeiro-Pinho G, Brito J, Figueiredo P. Microdosing: Old Wine in a New Bottle? Current State of Affairs and Future Avenues. Int J Sports Physiol Perform. 2022 Oct 6:1-4.
164. Blazevich AJ, Babault N. Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. Front Physiol. 2019 2019-November-01;10(1359).
165. Prieske O, Behrens M, Chaabene H, Granacher U, Maffiuletti NA. Time to Differentiate Postactivation "Potentiation" from "Performance Enhancement" in the Strength and Conditioning Community. Sports Med. 2020 2020/09/01;50(9):1559-65.
166. Ng CY, Chen SE, Lum D. Inducing Postactivation Potentiation With Different Modes of Exercise. Strength Cond J. 2020;42(2).
167. Low D, Harsley P, Shaw M, Peart D. The effect of heavy resistance exercise on repeated sprint performance in youth athletes. J Sports Sci. 2015;33(10):1028-34.
168. Bullock N, Comfort P. An investigation into the acute effects of depth jumps on maximal strength performance. J Strength Cond Res. 2011 Nov;25(11):3137-41.
169. Wilson JM, Duncan NM, Marin PJ, Brown LE, Loenneke JP, Wilson SM, et al. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. J Strength Cond Res. 2013 Mar;27(3):854-9.
170. Stone MH, Sands WA, Pierce KC, Ramsey MW, Haff GG. Power and Power Potentiation Among Strength–Power Athletes: Preliminary Study. Int J Sports Physiol Perf. 2008 01 Mar. 2008;3(1):55-67.
171. Marshall J, Bishop C, Turner A, Haff GG. Optimal Training Sequences to Develop Lower Body Force, Velocity, Power, and Jump Height: A Systematic Review with Meta-Analysis. Sports Med. 2021 Jun;51(6):1245-71.
172. Rhea MR, Alvar BA, Burkett LN, Ball SD. A meta-analysis to determine the dose response for strength development. Med Sci Sports Exerc. 2003 Mar;35(3):456-64.
173. Suchomel TJ, Lamont HS, Moir GL. Understanding Vertical Jump Potentiation: A Deterministic Model. Sports Med. 2016 Jun;46(6):809-28.
174. Seitz LB, de Villarreal ES, Haff GG. The temporal profile of postactivation potentiation is related to strength level. J Strength Cond Res. 2014 Mar;28(3):706-15.
175. Okuno NM, Tricoli V, Silva SB, Bertuzzi R, Moreira A, Kiss MA. Postactivation potentiation on repeated-sprint ability in elite handball players. J Strength Cond Res. 2013 Mar;27(3):662-8.
176. Harrison PW, James LP, McGuigan MR, Jenkins DG, Kelly VG. Resistance Priming to Enhance Neuromuscular Performance in Sport: Evidence, Potential Mechanisms and Directions for Future Research. Sports Med. 2019 Oct;49(10):1499-514.
177. Van Hooren B, Bosch F. Is there really an eccentric action of the hamstrings during the swing phase of high-speed running? part I: A critical review of the literature. J Sports Sci. 2017 2017/12/02;35(23):2313-21.
178. Dick TJM, Wakeling JM. Shifting gears: dynamic muscle shape changes and force-velocity behavior in the medial gastrocnemius. J Appl Physiol (1985). 2017 Dec 1;123(6):1433-42.
179. Harrison PW, James LP, McGuigan MR, Jenkins DG, Kelly VG. Prevalence and application of priming exercise in high performance sport. J Sci Med Sport. 2020 2020/03/01/;23(3):297-303.
180. Russell M, King A, Bracken RM, Cook CJ, Giroud T, Kilduff LP. A Comparison of Different Modes of Morning Priming Exercise on Afternoon Performance. Int J Sports Physiol Perform. 2016 Sep;11(6):763-7.
181. McHugh MP, Connolly DA, Eston RG, Gleim GW. Exercise-induced muscle damage and potential mechanisms for the repeated bout effect. Sports Med. 1999 Mar;27(3):157-70.
182. Nosaka K, Clarkson PM. Muscle damage following repeated bouts of high force eccentric exercise. Med Sci Sports Exerc. 1995;27(9):1263-9.

183. Peñailillo L, Blazevich A, Numazawa H, Nosaka K. Rate of force development as a measure of muscle damage. Scand J Med Sci Sports. 2015 Jun;25(3):417-27.
184. Hody S, Croisier J-L, Bury T, Rogister B, Leprince P. Eccentric Muscle Contractions: Risks and Benefits. Front Physiol. 2019;10:536-.
185. Francis C. Structure of Training for Speed. CharlieFrancis.com; 2008.
186. Nosaka K, Sakamoto K, Newton M, Sacco P. The repeated bout effect of reduced-load eccentric exercise on elbow flexor muscle damage. Eur J Appl Physiol. 2001 Jul;85(1-2):34-40.
187. Bondarchuk AP, Yessis M. Transfer of Training in Sports: Ultimate Athlete Concepts; 2007.
188. Haff GG. Periodization and Power Integration. In: McGuigan M, editor. Developing Power. Champaign, IL: Human Kinetics; 2017. p. 33-62.
189. Tee JC, Bosch AN, Lambert MI. Metabolic consequences of exercise-induced muscle damage. Sports Med. 2007;37(10):827-36.
190. Eston RG, Finney S, Baker S, Baltzopoulos V. Muscle tenderness and peak torque changes after downhill running following a prior bout of isokinetic eccentric exercise. J Sports Sci. 1996 Aug;14(4):291-9.
191. Impellizzeri FM, McCall A, van Smeden M. Why methods matter in a meta-analysis: a reappraisal showed inconclusive injury preventive effect of Nordic hamstring exercise. J Clin Epidemiol. 2021 2021/12/01/;140:111-24.
192. Howatson G, Van Someren K, Hortobágyi T. Repeated bout effect after maximal eccentric exercise. Int J Sports Med. 2007 Jul;28(7):557-63.
193. Haff GG, Whitley A, McCoy LB, O'Bryant HS, Kilgore JL, Haff EE, et al. Effects of Different Set Configurations on Barbell Velocity and Displacement During a Clean Pull. J Strength Cond Res. 2003;17(1).
194. Sánchez-Medina L, González-Badillo JJ. Velocity loss as an indicator of neuromuscular fatigue during resistance training. Med Sci Sports Exerc. 2011 Sep;43(9):1725-34.
195. Hardee JP, Triplett NT, Utter AC, Zwetsloot KA, McBride JM. Effect of interrepetition rest on power output in the power clean. J Strength Cond Res. 2012 Apr;26(4):883-9.
196. Tufano JJ, Conlon JA, Nimphius S, Brown LE, Seitz LB, Williamson BD, et al. Maintenance of Velocity and Power With Cluster Sets During High-Volume Back Squats. Int J Sports Physiol Perform. 2016 Oct;11(7):885-92.
197. Häkkinen K, Kallinen M. Distribution of strength training volume into one or two daily sessions and neuromuscular adaptations in female athletes. Electromyogr Clin Neurophysiol. 1994 Mar;34(2):117-24.
198. Bartolomei S, Malagoli Lanzoni I, Di Michele R. Two vs. One Resistance Exercise Sessions in One Day: Acute Effects on Recovery and Performance. Res Q Exerc Sport. 2022 Jan 4:1-6.
199. Docherty D, Sporer B. A proposed model for examining the interference phenomenon between concurrent aerobic and strength training. Sports Med. 2000 Dec;30(6):385-94.
200. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. Eur J Appl Physiol Occup Physiol. 1980;45(2):255-63.
201. Sabag A, Najafi A, Michael S, Esgin T, Halaki M, Hackett D. The compatibility of concurrent high intensity interval training and resistance training for muscular strength and hypertrophy: a systematic review and meta-analysis. J Sports Sci. 2018 Nov;36(21):2472-83.
202. Vechin FC, Conceição MS, Telles GD, Libardi CA, Ugrinowitsch C. Interference Phenomenon with Concurrent Strength and High-Intensity Interval Training-Based Aerobic Training: An Updated Model. Sports Med. 2021 Apr;51(4):599-605.
203. Petré H, Löfving P, Psilander N. The Effect of Two Different Concurrent Training Programs on Strength and Power Gains in Highly-Trained Individuals. J Sports Sci Med. 2018;17(2):167-73.
204. Buchheit M, Laursen PB. High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. Sports Med. 2013 May;43(5):313-38.
205. Robineau J, Babault N, Piscione J, Lacome M, Bigard AX. Specific Training Effects of Concurrent Aerobic and Strength Exercises Depend on Recovery Duration. J Strength Cond Res. 2016 Mar;30(3):672-83.
206. Schumann M, Feuerbacher JF, Sünkeler M, Freitag N, Rønnestad BR, Doma K, et al. Compatibility of Concurrent Aerobic and Strength Training for Skeletal Muscle Size and Function: An Updated Systematic Review and Meta-Analysis. Sports Med. 2021 2021/11/10.
207. Smith CD, Scarf D. Spacing Repetitions Over Long Timescales: A Review and a Reconsolidation Explanation. Front Psychol. 2017 2017-June-20;8(962).
208. Moody JA, Naclerio F, Green P, Lloyd RS. Motor skill development in youths. In: Lloyd RS, Oliver JL, editors. Strength and conditioning for young athletes: science and application: Routledge; 2014.
209. Lloyd RS, Oliver JL, Faigenbaum AD, Myer GD, De Ste Croix MBA. Chronological Age vs. Biological Maturation: Implications for Exercise Programming in Youth. J Strength Cond Res. 2014;28(5).
210. Winstein CJ. Knowledge of results and motor learning--implications for physical therapy. Phys Ther. 1991 Feb;71(2):140-9.

211. Lloyd RS, Dobbs IJ, Wong MA, Moore IS, Oliver JL. Effects of Training Frequency During a 6-Month Neuromuscular Training Intervention on Movement Competency, Strength and Power in Male Youth. Sports Health. 2021:19417381211050005.
212. Lloyd RS, Cronin JB, Faigenbaum AD, Haff GG, Howard R, Kraemer WJ, et al. National Strength and Conditioning Association Position Statement on Long-Term Athletic Development. J Strength Cond Res. 2016;30(6).
213. Stratton G, Oliver JL. The impact of growth and maturation on physical performance. In: Lloyd RS, Oliver JL, editors. Strength and conditioning for young athletes: science and application: Routledge; 2014.
214. Philippaerts RM, Vaeyens R, Janssens M, Van Renterghem B, Matthys D, Craen R, et al. The relationship between peak height velocity and physical performance in youth soccer players. J Sports Sci. 2006 2006/03/01;24(3):221-30.
215. Ramsay JA, Blimkie CJ, Smith K, Garner S, MacDougall JD, Sale DG. Strength training effects in prepubescent boys. Med Sci Sports Exerc. 1990 Oct;22(5):605-14.
216. Myer GD, Kushner AM, Faigenbaum AD, Kiefer A, Kashikar-Zuck S, Clark JF. Training the developing brain, part I: cognitive developmental considerations for training youth. Curr Sports Med Rep. 2013 Sep-Oct;12(5):304-10.
217. Behringer M, Vom Heede A, Matthews M, Mester J. Effects of strength training on motor performance skills in children and adolescents: a meta-analysis. Pediatr Exerc Sci. 2011 May;23(2):186-206.
218. Gentil P, Bottaro M. Influence of supervision ratio on muscle adaptations to resistance training in nontrained subjects. J Strength Cond Res. 2010 Mar;24(3):639-43.
219. Lloyd RS, Faigenbaum AD, Stone MH, Oliver JL, Jeffreys I, Moody JA, et al. Position statement on youth resistance training: the 2014 International Consensus. Br J Sports Med. 2014 Apr;48(7):498-505.
220. Viru A, Loko J, Harro M, Volver A, Laaneots L, Viru M. Critical Periods in the Development of Performance Capacity During Childhood and Adolescence. Eur J Physical Educ. 1999 1999/01/01;4(1):75-119.
221. Lloyd RS, Oliver JL. The Youth Physical Development Model: A New Approach to Long-Term Athletic Development. Strength Cond J. 2012;34(3).
222. Radnor JM, Moeskops S, Morris SJ, Mathews TA, Kumar NTA, Pullen BJ, et al. Developing Athletic Motor Skill Competencies in Youth. Strength Cond J. 2020;42(6).
223. Gogtay N, Giedd JN, Lusk L, Hayashi KM, Greenstein D, Vaituzis AC, et al. Dynamic mapping of human cortical development during childhood through early adulthood. Proc Natl Acad Sci U S A. 2004 May 25;101(21):8174-9.
224. Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, et al. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. Neurosci Biobehav Rev. 2010 Apr;34(5):721-33.
225. Shaw I, Shaw B, Brown G, Shariat A. Review of the role of resistance training and musculoskeletal injury prevention and rehabilitation. J Orthop Res Ther. 2016;2016:1-5.
226. Herrington L. The Effects of 4 Weeks of Jump Training on Landing Knee Valgus and Crossover Hop Performance in Female Basketball Players. J Strength Cond Res. 2010;24(12).
227. Taberner M, Allen T, Cohen DD. Progressing rehabilitation after injury: consider the 'control-chaos continuum'. British Journal of Sports Med. 2019;53(18):1132.
228. Dos'Santos T, Thomas C, McBurnie A, Comfort P, Jones PA. Biomechanical Determinants of Performance and Injury Risk During Cutting: A Performance-Injury Conflict? Sports Med. 2021 2021/09/01;51(9):1983-98.
229. Emmonds S, Heyward O, Jones B. The challenge of applying and undertaking research in female sport. Sports Med Open. 2019;5(1):1-4.
230. Findlay RJ, Macrae EHR, Whyte IY, Easton C, Forrest LJ. How the menstrual cycle and menstruation affect sporting performance: experiences and perceptions of elite female rugby players. Br J Sports Med. 2020;54(18):1108.
231. McNulty KL, Elliott-Sale KJ, Dolan E, Swinton PA, Ansdell P, Goodall S, et al. The Effects of Menstrual Cycle Phase on Exercise Performance in Eumenorrheic Women: A Systematic Review and Meta-Analysis. Sports Med. 2020 Oct;50(10):1813-27.
232. Brown N, Knight CJ, Forrest LJ. Elite female athletes' experiences and perceptions of the menstrual cycle on training and sport performance. Scand J Med Sci Sports. 2021;31(1):52-69.
233. Nimphius S. Exercise and Sport Science Failing by Design in Understanding Female Athletes. Int J Sports Physiol Perform. 2019 Sep 25:1-2.
234. Staron RS, Karapondo DL, Kraemer WJ, Fry AC, Gordon SE, Falkel JE, et al. Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. J Appl Physiol. 1994 1994/03/01;76(3):1247-55
235. Cook CJ, Kilduff LP, Crewther BT, Beaven M, West DJ. Morning based strength training improves afternoon physical performance in rugby union players. J Sci Med Sport. 2014 2014/05/01/;17(3):317-21.

236. Gould D, Dieffenbach K, Moffett A. Psychological Characteristics and Their Development in Olympic Champions. J Appl Sport Psychol. 2002 2002/01/01;14(3):172-204.
237. Vallerand RJ. Intrinsic and extrinsic motivation in sport and physical activity: A review and a look at the future. 2007.
238. Deci EL. Effects of externally mediated rewards on intrinsic motivation. J Personal Social Psychol. 1971;18(1):105.
239. Mageau GA, Vallerand RJ. The coach–athlete relationship: a motivational model. J Sports Sci. 2003 2003/11/01;21(11):883-904.
240. Conroy DE, Coatsworth JD. Assessing Autonomy-Supportive Coaching Strategies in Youth Sport. Psychol Sport Exerc. 2007;8(5):671-84.
241. Haff GG, Nimphius S. Training Principles for Power. Strength Cond J. 2012;34(6):2-12.
242. Peterson MD, Rhea MR, Alvar BA. Applications of the dose-response for muscular strength development: a review of meta-analytic efficacy and reliability for designing training prescription. J Strength Cond Res. 2005 Nov;19(4):950-8.
243. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. Scand J Med Sci Sports. 2019 Aug;29(8):1083-91.
244. Chumanov ES, Schache AG, Heiderscheit BC, Thelen DG. Hamstrings are most susceptible to injury during the late swing phase of sprinting. Br J Sports Med. 2012;46(2):90.
245. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. Am J Sports Med. 2006 Feb;34(2):299-311.
246. Morin JB, Gimenez P, Edouard P, Arnal P, Jiménez-Reyes P, Samozino P, et al. Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. Front Physiol. 2015;6:404.
247. Bourne MN, Timmins RG, Opar DA, Pizzari T, Ruddy JD, Sims C, et al. An Evidence-Based Framework for Strengthening Exercises to Prevent Hamstring Injury. Sports Med. 2018 Feb;48(2):251-67.
248. Styles WJ, Matthews MJ, Comfort P. Effects of strength training on squat and sprint performance in soccer players. J Strength Cond Res. 2016;30(6):1534-9.
249. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. Pm r. 2011 May;3(5):472-9.
250. Baltzopoulos V, Brodie DA. Isokinetic Dynamometry. Sports Med. 1989 1989/08/01;8(2):101-16.
251. Aagaard P, Simonsen EB, Magnusson SP, Larsson B, Dyhre-Poulsen P. A new concept for isokinetic hamstring: quadriceps muscle strength ratio. Am J Sports Med. 1998 Mar-Apr;26(2):231-7.
252. Green B, Bourne MN, Pizzari T. Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: a systematic review and meta-analysis. Br J Sports Med. 2018 Mar;52(5):329-36.
253. Bennell K, Wajswelner H, Lew P, Schall-Riaucour A, Leslie S, Plant D, et al. Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. Br J Sports Med. 1998 Dec;32(4):309-14.
254. Fillyaw M, Bevins T, Fernandez L. Importance of correcting isokinetic peak torque for the effect of gravity when calculating knee flexor to extensor muscle ratios. Phys Ther. 1986 Jan;66(1):23-31.
255. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. J Orthop Sports Phys Ther. 2013 Sep;43(9):636-40.
256. McCall A, Nedelec M, Carling C, Le Gall F, Berthoin S, Dupont G. Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players. J Sports Sci. 2015;33(12):1298-304.
257. Matinlauri A, Alcaraz PE, Freitas TT, Mendiguchia J, Abedin-Maghanaki A, Castillo A, et al. A comparison of the isometric force fatigue-recovery profile in two posterior chain lower limb tests following simulated soccer competition. PLoS One. 2019;14(5):e0206561.
258. Madison G, Patterson SD, Read P, Howe L, Waldron M. Effects of Small-Sided Game Variation on Changes in Hamstring Strength. J Strength Cond Res. 2019 Mar;33(3):839-45.
259. Schache AG, Crossley KM, Macindoe IG, Fahrner BB, Pandy MG. Can a clinical test of hamstring strength identify football players at risk of hamstring strain? Knee Surg Sports Traumatol Arthrosc. 2011 Jan;19(1):38-41.
260. Mondin D, Owen JA, Negro M, D'Antona G. Validity and Reliability of a Non-invasive Test to Assess Quadriceps and Hamstrings Strength in Athletes. Front Physiol. 2018;9:1702.
261. Ho J, Tumkaya T, Aryal S, Choi H, Claridge-Chang A. Moving beyond P values: data analysis with estimation graphics. Nature Methods. 2019 2019/07/01;16(7):565-6.
262. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med. 2016 Jun;15(2):155-63.

263. Cohen J. Statistical power analysis for the behavioral sciences: Routledge; 2013.
264. Read PJ, Turner AN, Clarke R, Applebee S, Hughes J. Knee Angle Affects Posterior Chain Muscle Activation During an Isometric Test Used in Soccer Players. Sports (Basel). 2019 Jan 4;7(1).
265. Opar DA, Serpell BG. Is there a potential relationship between prior hamstring strain injury and increased risk for future anterior cruciate ligament injury? Arch Phys Med Rehabil. 2014 Feb;95(2):401-5.
266. Orchard J, Seward H. Epidemiology of injuries in the Australian Football League, seasons 1997-2000. Br J Sports Med. 2002 Feb;36(1):39-44.
267. Oakley AJ, Jennings J, Bishop CJ. Holistic hamstring health: not just the Nordic hamstring exercise. Br J Sports Med. 2018;52(13):816-7.
268. Sadigursky D, Braid JA, De Lira DNL, Machado BAB, Carneiro RJF, Colavolpe PO. The FIFA 11+ injury prevention program for soccer players: a systematic review. BMC Sports Sci Med Rehab. 2017 2017/11/28;9(1):18.
269. Chebbi S, Chamari K, Van Dyk N, Gabbett T, Tabben M. Hamstring Injury Prevention for Elite Soccer Players: A Real-World Prevention Program Showing the Effect of Players' Compliance on the Outcome. J Strength Cond Res. 2020.
270. van der Horst N, Hoef SV, Otterloo PV, Klein M, Brink M, Backx F. Effective But Not Adhered to: How Can We Improve Adherence to Evidence-Based Hamstring Injury Prevention in Amateur Football? Clin J Sport Med. 2021 Jan;31(1):42-8.
271. McHugh MP. Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise. Scand J Med Sci Sports. 2003;13(2):88-97.
272. Lago-Peñas C, Rey E, Lago-Ballesteros J, Casáis L, Domínguez E. The influence of a congested calendar on physical performance in elite soccer. J Strength Cond Res. 2011 Aug;25(8):2111-7.
273. Lyakh V, Mikołajec K, Bujas P, Witkowski Z, Zając T, Litkowycz R, et al. Periodization in Team Sport Games - A Review of Current Knowledge and Modern Trends in Competitive Sports. J Hum Kinet. 2016;54:173-80.
274. McMaster DT, Gill N, Cronin J, McGuigan M. The development, retention and decay rates of strength and power in elite rugby union, rugby league and American football: a systematic review. Sports Med. 2013 May;43(5):367-84.
275. Plisk SS, Stone MH. Periodization Strategies. Strength Cond J. 2003;25(6).
276. Morgans R, Di Michele R, Drust B. Soccer Match Play as an Important Component of the Power-Training Stimulus in Premier League Players. Int J Sports Physiol Perform. 2018 May 1;13(5):665-7.
277. Silva JR, Magalhães JF, Ascensão AA, Oliveira EM, Seabra AF, Rebelo AN. Individual match playing time during the season affects fitness-related parameters of male professional soccer players. J Strength Cond Res. 2011 Oct;25(10):2729-39.
278. McMahon JJ, Suchomel TJ, Lake JP, Comfort P. Understanding the Key Phases of the Countermovement Jump Force-Time Curve. Strength Cond J. 2018;40(4).
279. Cormack SJ, Newton RU, McGuigan MR, Doyle TL. Reliability of measures obtained during single and repeated countermovement jumps. Int J Sports Physiol Perform. 2008;3(2):131-44.
280. Weissgerber TL, Milic NM, Winham SJ, Garovic VD. Beyond bar and line graphs: time for a new data presentation paradigm. PLoS Biol. 2015;13(4):e1002128.
281. Medeiros TM, Ribeiro-Alvares JB, Fritsch CG, Oliveira GS, Severo-Silveira L, Pappas E, et al. Effect of weekly training frequency with the nordic hamstring exercise on muscle-strain risk factors in football players: a randomized trial. Int J Sports Physiol Perform. 2020;15(7):1026-33.
282. Drury B, Peacock D, Moran J, Cone C, Campillo RR. Different Interset Rest Intervals During the Nordic Hamstrings Exercise in Young Male Athletes. J Athl Train. 2021;56(9):952-9.
283. Cuevas-Aburto J, Jukic I, Chirosa-Ríos LJ, González-Hernández JM, Janicijevic D, Barboza-González P, et al. Effect of Traditional, Cluster, and Rest Redistribution Set Configurations on Neuromuscular and Perceptual Responses During Strength-Oriented Resistance Training. J Strength Cond Res. 2020.
284. Ekstrand J. Keeping your top players on the pitch: the key to football medicine at a professional level. Br J Sports Med. 2013;47(12):723.
285. Buckthorpe M, Gimpel M, Wright S, Sturdy T, Stride M. Hamstring muscle injuries in elite football: translating research into practice. Br J Sports Med. 2018;52(10):628.
286. Pollard CW, Opar DA, Williams MD, Bourne MN, Timmins RG. Razor hamstring curl and Nordic hamstring exercise architectural adaptations: Impact of exercise selection and intensity. Scand J Med Sci Sports. 2019;29(5):706-15.
287. Presland JD, Opar DA, Williams MD, Hickey JT, Maniar N, Lee Dow C, et al. Hamstring strength and architectural adaptations following inertial flywheel resistance training. J Sci Med Sport. 2020 2020/11/01/;23(11):1093-9.

288. Ripley NJ, Cuthbert M, Ross S, Comfort P, McMahon JJ. The Effect of Exercise Compliance on Risk Reduction for Hamstring Strain Injury: A Systematic Review and Meta-Analyses. Int J Environ Res Public Health. 2021;18(21):11260.
289. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007 May;39(2):175-91.
290. McGuigan MR, Cormack SJ, Gill ND. Strength and Power Profiling of Athletes: Selecting Tests and How to Use the Information for Program Design. Strength Cond J. 2013;35(6).
291. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Med. 1998 Oct;26(4):217-38.
292. Safrit MJWTM. Measurement concepts in physical education and exercise science. 1989.
293. Bates BT, Zhang S, Dufek JS, Chen FC. The effects of sample size and variability on the correlation coefficient. Med Sci Sports Exerc. 1996 Mar;28(3):386-91.
294. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med. 2000 Jul;30(1):1-15.
295. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res. 2005 Feb;19(1):231-40.
296. Comfort P, Dos'Santos T, Jones PA, McMahon JJ, Suchomel TJ, Bazyler C, et al. Normalization of Early Isometric Force Production as a Percentage of Peak Force During Multijoint Isometric Assessment. Int J Sports Physiol Perform. 2019 Oct 8:1-5.
297. Comfort P, Dos'Santos T, Beckham GK, Stone MH, Guppy SN, Haff GG. Standardization and Methodological Considerations for the Isometric Midthigh Pull. Strength Cond J. 2019;41(2):57-79.
298. Nimphius S, Callaghan SJ, Spiteri T, Lockie RG. Change of Direction Deficit: A More Isolated Measure of Change of Direction Performance Than Total 505 Time. J Strength Cond Res. 2016 Nov;30(11):3024-32.
299. Buchheit M, Mendez-Villanueva A. Reliability and stability of anthropometric and performance measures in highly-trained young soccer players: effect of age and maturation. J Sports Sci. 2013;31(12):1332-43.
300. Fitzpatrick JF, Hicks KM, Russell M, Hayes PR. The Reliability of Potential Fatigue-Monitoring Measures in Elite Youth Soccer Players. J Strength Cond Res. 2021 Dec 1;35(12):3448-52.
301. Mercer RAJ, Russell JL, McGuigan LC, Coutts AJ, Strack DS, McLean BD. Finding the Signal in the Noise—Interday Reliability and Seasonal Sensitivity of 84 Countermovement Jump Variables in Professional Basketball Players. J Strength Cond Res. 2021.
302. Ryan S, Pacecca E, Tebble J, Hocking J, Kempton T, Coutts AJ. Measurement Characteristics of Athlete Monitoring Tools in Professional Australian Football. Int J Sports Physiol Perform. 2019 Oct 14:1-7.
303. Thomas C, Dos'Santos T, Comfort P, Jones PA. Between-Session Reliability of Common Strength- and Power-Related Measures in Adolescent Athletes. Sports (Basel, Switzerland). 2017;5(1):15.
304. Dos’Santos T, Thomas C, Comfort P, McMahon JJ, Jones PA, Oakley NP, et al. Between-Session Reliability of Isometric Midthigh Pull Kinetics and Maximal Power Clean Performance in Male Youth Soccer Players. J Strength Cond Res. 2018 Dec;32(12):3364-72.
305. Altmann S, Ringhof S, Neumann R, Woll A, Rumpf MC. Validity and reliability of speed tests used in soccer: A systematic review. PLoS One. 2019;14(8):e0220982.
306. Wisløff U, Castagna C, Helgerud J, Jones R, Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. Br J Sports Med. 2004;38(3):285-8.
307. Comfort P, Stewart A, Bloom L, Clarkson B. Relationships between strength, sprint, and jump performance in well-trained youth soccer players. J Strength Cond Res. 2014 Jan;28(1):173-7.
308. McBride JM, Kirby TJ, Haines TL, Skinner J. Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. Int J Sports Physiol Perform. 2010 Dec;5(4):484-96.
309. Sleivert G, Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. Eur J Appl Physiol. 2004 Jan;91(1):46-52.
310. Verkhoshansky Y, Verkhoshansky N. Special strength training : manual for coaches. Rome: Verkhoshansky SSTM; 2011.
311. Comfort P, Dos'Santos T, Thomas C, McMahon JJ, Suchomel TJ. An Investigation Into the Effects of Excluding the Catch Phase of the Power Clean on Force-Time Characteristics During Isometric and Dynamic Tasks: An Intervention Study. J Strength Cond Res. 2018;32(8).
312. McGuigan M. Principles of test selection and administration. Essentials of strength training and conditioning. 2016:249-58.
313. Whisenant MJ, Panton LB, East WB, Broeder CE. Validation of submaximal prediction equations for the 1 repetition maximum bench press test on a group of collegiate football players. J Strength Cond Res. 2003 May;17(2):221-7.

314. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol. 2013 2013-November-26;4.
315. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. British Journal of Sports Med. 2019;53(21):1362-70.
316. Lakens D. Equivalence Tests: A Practical Primer for t Tests, Correlations, and Meta-Analyses. Social Psychol Personal Sci. 2017 2017/05/01;8(4):355-62.
317. Hecksteden A, Kellner R, Donath L. Dealing with small samples in football research. Sci Med Football. 2021:1-9.
318. Cumming G. The New Statistics:Why and How. Psychol Sci. 2014;25(1):7-29.