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Periodisation of Eccentrically-Integrated Resistance Training during a National Rugby League Pre-Season

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ABSTRACT

Successful performances in rugby league require the ability to engage in repeated contact efforts with minimal recovery while maintaining a high running intensity. The capacity to express high levels of time-limited force appears to underlie many important physical attributes required to meet the repeated-effort demands of rugby league play. If appropriately periodised and integrated into the training plan, resistance exercise that sufficiently loads the eccentric phase of movement may provide a beneficial stimulus to improve players' force-generating capacity. Comprehensive reviews relating to the adaptive effects of eccentric training and the methods most commonly prescribed in practical environments are available and may provide context for applying these strategies. However, no literature to date has specifically discussed the planning and programming of eccentric resistance exercise to enhance force production characteristics in elite athletes. Therefore, this narrative review focuses on the periodisation of eccentrically-integrated resistance training during a 17-week National Rugby League pre-season phase. To help guide programming during the pre-season period, the 17-week timeline is divided into several phases (i.e., general preparation, special preparation, active rest, and pre-competition). Within the periodised model, eccentric exercise parameters (i.e., volume, load [% 1RM]) are manipulated to progressively increase the rate of muscle lengthening velocity over the pre-season phase and sequentially elicit changes in muscle-tendon properties and neural function that culminate in improving muscular strength expression.

Keywords: eccentric training, neuromuscular adaptation, periodisation, rugby league

INTRODUCTION

Well-developed physical capacities (e.g., muscular strength and power, maximal running speed, change of direction, aerobic power) are required to meet the high-intensity activity demands of rugby league competition (Johnston, Gabbett, & Jenkins, 2014). Players generally travel ~85-100 m per minute and total distances of ~5,000-8,500 m, with 250-750 m of this at high-speed (≥ 5.5 m.s−1) and completing 1.1 ± 0.56 accelerations·min-1 (≥ 2.78 m.s−2) while involved in an average of 0.67 collisions per minute during match-play (Austin & Kelly, 2013; Gabbett, 2015; Gabbett, Jenkins, & Abernethy, 2012; Varley, Gabbett, & Aughey, 2014). Additionally, repeated high-intensity effort bouts (3 maximal accelerations, high-speed or contact efforts with 21 seconds of recovery between efforts) involving an average recovery period of 5.9-7.0 sec between bouts over a duration of 49-64 sec are common (4.8-9.1 min) during peak periods of match-play (Austin, Gabbett, & Jenkins, 2011; Gabbett, 2011; Gabbett et al., 2012; Gabbett, Jenkins, & Abernethy, 2011a; Johnston et al., 2014). As such, training that improves players' ability to engage in repeated contact efforts with minimal recovery while maintaining a high running intensity during competition has important implications for performance (Johnston & Gabbett, 2011; Johnston et al., 2014).

The capacity to express high levels of strength (i.e., the ability to produce force [Stone, Moir, Glaister, & Sanders, 2002]) is particularly important for success in rugby league (Hulin, Gabbett, Kearney, & Corvo, 2015; Johnston et al., 2014; McMaster, Gill, Cronin, & McGuigan, 2013). Considerable evidence highlights the association between greater muscular strength and many physical and performance attributes (Johnston et al., 2014; McMaster et al., 2013); improved technical and tactical skills (Gabbett et al., 2011a; Redman, Wade, Kelly, Connick, & Beckman, 2022; Redman, Wade, Whitley, et al., 2021); a lower chance of injury (Gabbett, Jenkins, & Abernethy, 2011b); and a higher standard of play (Baker & Newton, 2008). Considering that most activities in rugby league require players to repeatedly produce large amounts of force within a limited time period (Redman, Wade, Kelly, et al., 2021; Redman, Wade, Whitley, et al., 2021) and understanding that strength gains through resistance exercise positively influence the force-time characteristics of an individual (Andersen & Aagaard, 2006; Andersen, Andersen, Zebis, & Aagaard, 2010), training strategies that improve muscular strength will likely result in improved play.

Eccentric muscle actions can produce greater peak force (10-35%) than concentric muscle actions of equivalent velocity (Aagaard et al., 2000; Babault, Pousson, Ballay, & Van Hoecke, 2001; Beltman, Sargeant, Van Mechelen, & De Haan, 2004; Seger & Thorstensson, 2000; Westing, Cresswell, & Thorstensson, 1991). As such, traditional resistance exercise involving the prescription of loads constrained by concentric force may not sufficiently load the eccentric phase of movement (Douglas, Pearson, Ross, & McGuigan, 2017a) and therefore may limit the potential for strength development (Vogt & Hoppeler, 2014; Roig et al., 2009). In contrast, resistance training that sufficiently loads the eccentric phase of movement can induce novel stimuli to elicit morphological and neural changes that improve players' capacity to generate high levels of time-limited force (Cormie, McGuigan, & Newton, 2011a; Douglas et al., 2017a). The magnitude of mechanical tension induced by eccentric training, particularly involving loads near (≥ 85% 1 repetition maximum [RM]) or above maximal concentric strength (e.g., ≥ 1RM), has been shown to increase muscle cross-sectional area (CSA) and architecture (English, Loehr, Lee, & Smith, 2014; Potier, Alexander, & Seynnes, 2009), induce preferential recruitment of type II muscle fibres (Nardone, Romano, & Schieppati, 1989), reduce neural inhibition (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002), increase muscle activation (Tallent, Goodall, Gibbon, Hortobagyi, & Howatson, 2017), enhance task-specific gains in eccentric strength (Paddon-Jones, Leveritt, Lonergan, & Abernethy, 2001), and produce changes in tendon structure and function (Malliaras et al., 2013). Collectively, these adaptive responses can raise the potential for muscular strength development (Harden, Wolf, Haff, Hicks, & Howatson, 2019; Suchomel et al., 2019a) and therefore also improve rugby league performance (Baker & Newton, 2008; Johnston et al., 2014).

A systematic approach to training is generally applied in most sporting environments to elicit the physiological adaptations underlying the expression of muscular strength (Baker, Wilson, & Carlyon, 1994; Suchomel, Nimphius, Bellon, & Stone, 2018). If appropriately periodised and integrated into the resistance training plan, eccentric exercise may be particularly beneficial in enhancing maximal and time-limited force expression (Suchomel et al., 2019a). Comprehensive reviews relating to the adaptive effects of eccentric training (Douglas et al., 2019a,b; Handford et al., 2022) and the methods most commonly prescribed in practical environments (Suchomel et al., 2019a,b) are available and may provide context for applying these strategies. However, no literature to date has specifically discussed the planning and programming of eccentric training methods to enhance force production characteristics in elite athletes. Therefore, this narrative review focuses on the periodisation of eccentrically-integrated resistance training during a National Rugby League (NRL) pre-season phase.

PERIODISED MODEL FOR ECCENTRIC TRAINING DURING AN NRL PRE-SEASON

Periodisation strategies in rugby league often involve dividing the annual training plan into three primary macrocycles (i.e., pre-season, competition, and off-season phases) (Kelly & Coutts, 2007). Pre-season rugby league training typically spans 17 weeks (November-February) and generally involves frequent bouts of resistance exercise that aim to develop the muscular strength required to meet the physical demands of competitive match-play (Baker et al., 1994; de Lacey et al., 2014; McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). To help guide programming during the pre-season period, the 17-week timeline is divided into several phases (i.e., general preparation, special preparation, active rest, and pre-competition). Within the periodised model, eccentric exercise parameters (i.e., volume, load [%1RM]) (Table 1) are manipulated to progressively increase the rate of muscle lengthening velocity over the pre-season phase and sequentially elicit changes in muscle-tendon properties and neural function that culminate in improving muscular strength expression (Figure 1). The following sections discuss the implementation of eccentric resistance training within an NRL pre-season based on the available evidence.

GENERAL PREPARATION PHASE

The primary aim of the 4-week general preparation phase (GPP) is to increase muscle hypertrophy and raise work capacity (i.e., force production capacity [O'Bryant, Byrd, & Stone, 1988]) in order to improve the potential for players to repeatedly express large amounts of time-limited force (Stone, Sands, & Stone, 2007). Exercise parameters (e.g., 70-75% 1RM) are manipulated to slow (5 sec [Krzysztofik, Wilk, Wojdala, & Golas, 2019]) the eccentric phase of movement and therefore augment time under tension (i.e., the time a muscle is held under tension or strain during an exercise set [Handford et al., 2022]) and elicit high resistance training volumes.

Metabolic stress within a muscle through a resistance exercise stimulus of sufficient magnitude results in the upregulation of muscle protein synthesis and, subsequently, protein accretion and changes in muscle size (Schoenfeld et al., 2021). Increases in muscle protein synthesis rates within the day following lower-body resistance exercise involving submaximal intensities performed with a 6-sec lowering phase until volitional fatigue have been reported (Burd et al., 2012). This suggests that maximal fibre activation may not exclusively drive muscle protein synthesis rates (Burd et al., 2012). Increasing exercise volume, through increasing time under tension during the eccentric phase of movement, may also stimulate protein accretion and lead to muscle growth despite lower resistance exercise loads (Burd et al., 2010; Schoenfeld, 2010; Terzis et al., 2010). Greater time under tension during muscle lengthening actions with moderate loads can result in larger accumulations of blood lactate, growth hormone, and testosterone when compared to volume-matched eccentric exercise involving faster tempos (Kraemer & Castracane, 2015). With repeated exercise bouts, these acute hormonal responses can produce increases in muscle size (Godfrey, Whyte, Buckley, & Quinlivan, 2009; Kraemer & Castracane, 2015). This may explain the increases in muscle hypertrophy following 12 weeks of resistance exercise involving a 4-sec eccentric phase of movement with moderate loads (~81% CON 1RM) in resistance-trained males (Pereira et al., 2016). The improvements in muscle size were attributed to the prolonged eccentric phase of movement and therefore a heightened time under tension (Schoenfeld, 2010) that may have elicited substantial metabolic stress (Lieber & Friden, 1988; Stauber, 1988) and subsequent increases in muscle size following the training intervention (Schoenfeld et al., 2021).

Evidence suggests that sarcoplasmic hypertrophy (i.e., an increase in sarcoplasmic volume and its constituents [e.g., fluid, enzymes, organelles] [Roberts, Haun, Vann, Osburn, & Young, 2020]) contributes to increases in muscle size following higher volume resistance training (Haun et al., 2019a) and that these changes support subsequent myofibril hypertrophy (Roberts et al., 2020). Data show that increasing the time under tension during the eccentric phase of movement (~6 sec) increases the amplitude of sarcoplasmic protein synthesis within 6 h of the exercise bout and results in a delayed simulation of myofibril accretion 24-30 h post-training (Burd et al., 2012). Myofibrillar protein synthetic rate was also shown to be associated with p70S6K phosphorylation within this time frame following the training session (Burd et al., 2012). Previous findings have demonstrated that the increase in p70S6K 6 h following resistance exercise involving high-resistance muscle lengthening actions is almost perfectly correlated to the percent change in muscle mass after 6 weeks of training (Baar & Esser, 1999). As such, transient increases in sarcoplasmic protein synthesis rates following slow eccentric resistance exercise with relatively higher exercise volumes and submaximal loads may support subsequent increases in myofibril hypertrophy (Haun et al., 2019b; Roberts et al., 2020) and thus long-term increases in muscle size (Baar & Esser, 1999),

Table 1. Eccentric resistance exercise parameters during the 17-week pre-season period.

Eccentric Resistance Exercise Parameters				
		GPP 1		
	Week 1	Week 2	Week 3	Week 4
Back Squat	50%/60%/5, (70%/5[5sec])3	50%/60%/5, (70%/5[5sec])2, (75%/5[5sec])2	50%/60%/5, (75%/5[5sec])4	50%/60%/5, 70%/5[5sec], (75%/5[5sec])2
Bench Press	50%/60%/5, (70%/5[5sec])3	55%/65%/5, 65%[5sec]/5, (75%/5[5sec])2	55%/65%/5, 70%/5[5sec], (75%/5[5sec])2	55%/65%/5, (75%/5[5sec])2
		GPP 2		
	Week 5	Week 6	Week 7	
Back Squat	60%/75%/5, (85%/4[3sec])2*, 90%/3[3sec]*	60%/75%/5, (85%/4[3sec])2*, 90%/3[3sec]*, 95%/3[3sec]*	60%/75%/5, 85%/3[3sec]*, 95%/3[3sec]*, 100%/2[3sec]*, 105%/2[3sec]*	
Bench Press	50%/60%/5, (85%/4[3sec])2*, 90%/3[3sec]*	60%/70%/75%/5, 85%/4[3sec]*, 90%/3[3sec]*, 95%/3[3sec]*	60%/70%/5, 80%/3, 90%/3[3sec], 95%/3[3sec]*, 100%/3[3sec]*	
		Active Rest		
	Week 8		Week 9	
		SPP		
	Week 10	Week 11	Week 12	Week 13
Back Squat	60%/5, 75%/3, 85%/1 (90%/3[<1sec])3*	60%/5, 75%/3, 85%/1 90%/3[<1sec]*, 95%/3[<1sec]*, 100%/3[<1sec]*	60%/5, 75%/3, 85%/1 95%/3[<1sec]*, 100%/2[<1sec]*, 105%/2[<1sec]*	60%/5, 75%/3, 85%/1 (95%/2[<1sec])3*
Bench Press	60%/70%/5, 80%/3, (90%/4[<1sec])3*	60%/70%/5, 80%/3, (90%/3[<1sec])2*, 95%/3[<1sec]*, 100%/3[<1sec]*	60%/5, 70%/3, 80%/3, 90%/2[<1sec]*, 95%/2[<1sec]*, 100%/2[<1sec]*, 105%/2[<1sec]*	60%/5, 70%/3, 80%/3, 90%/3[<1sec]*, 95%/3[<1sec]*, 100%/2[<1sec]*

	PCP			
	Week 14	Week 15	Week 16	Week 17
Back Squat	60%/70%5, 80%/3, 85%/2[<1sec]*, 90%/2[<1sec]*, 95%/1[<1sec]*	60%/70%5, 80%/3, 85%/2[<1sec]*, 90%/2[<1sec]*, 95%/1[<1sec]*, 100%/1[<1sec]*	60%/70%5, 80%/3, 90%/2[<1sec], 95%/1[<1sec]*	60%/70%5, 80%/3, 90%/2[<1sec], 95%/1[<1sec]*
DJ	(X/3)3	(X/3)4	(X/3)2	(X/3)2
Bench Press	60%/70%5, 80%/3, (85%/2[<1sec])2*, 90%/2[<1sec]*	60%/70%5, 80%/3, 85%/2[<1sec]*, 90%/2[<1sec]*	60%/70%5, 80%/3, (85%/2[<1sec])2*	60%/70%5, 80%/3, (85%/2[<1sec])2*
Lying MB Rebound Chest Pass	(X/5)3	(X/5)2	X/5	X/5

Notes: Italics = eccentric exercise working sets; [] = duration of the eccentric phase of movement; *partner assisted during the concentric phase of movement; postactivation potentiation enhancement complexes are performed with ≥ 3 min rest between the conditioning stimulus and plyometric exercise (Seitz & Haff, 2016); exercise loads are based on concentric 1 repetition maximum; drop jump height is based on the vertical height that maximised a player's power output during pre-testing
DJ drop jump; *GPP* general physical preparation; *MB* medicine ball; *PCP* pre-competition phase; *SPP* special physical preparation

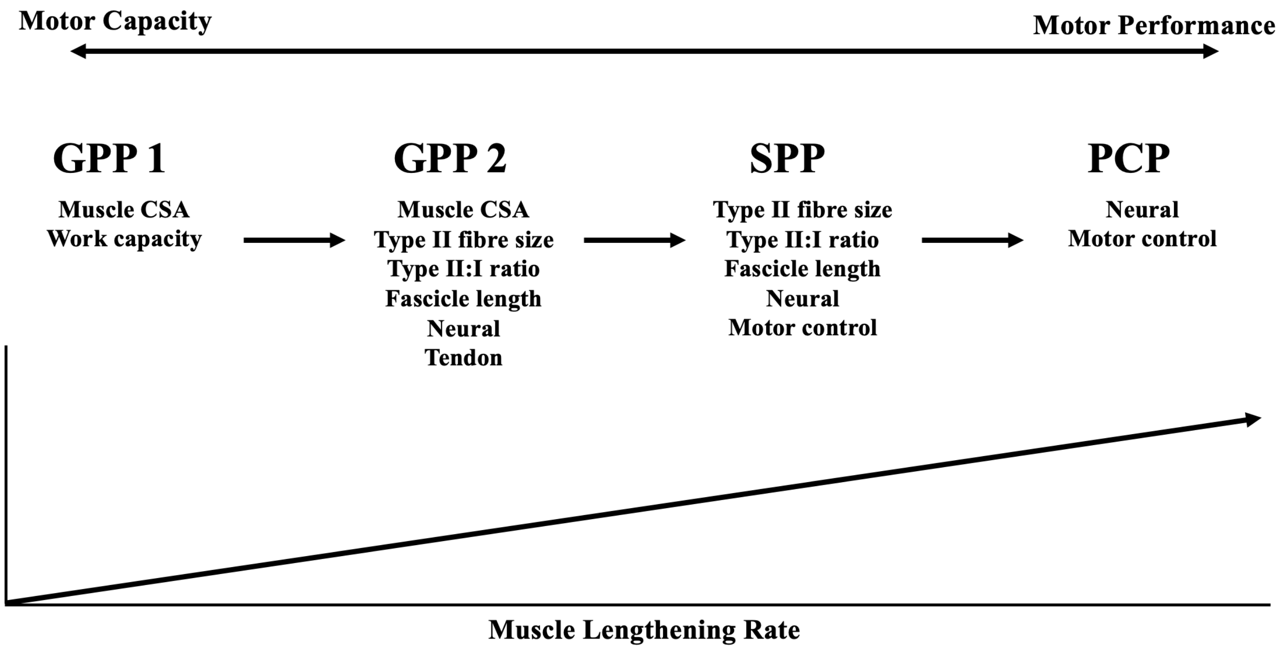

Figure 1. Periodisation of eccentrically-integrated resistance training during a pre-season phase. Adapted from Stone et al., 2007; Suchomel et al., 2018 *CSA* cross-sectional area, *GPP* general preparation phase, *SPP* special preparation phase

which should result in improved force output (Taber, Vigotsky, Nuckols, & Haun, 2019). Accordingly, increases in muscle size and strength were found after 12 weeks of moderate-load resistance exercise involving slow lengthening actions (Pereira et al., 2016), which may support prolonging the eccentric phase of movement to induce morphological changes and improvements in force production.

Exercise-induced increases in the protein expression of sarcoplasmic enzymes responsible for generating ATP (Haun et al., 2019a,b; Roberts et al., 2020) also have implications for improving work capacity. Greater time under tension elicited by a 6-sec eccentric movement phase performed to volitional fatigue has been shown to increase sarcoplasmic and mitochondrial protein synthesis rates following a bout of resistance exercise completed on the same day in resistance-trained individuals (Burd et al., 2012). Same-day increases in peroxisome proliferator-activated receptor-gamma coactivator (PGC-1α) expression were also observed following the training session (Burd et al., 2012). Given its central role in the regulation of cellular energy metabolism and the remodelling of muscle tissue that is metabolically more oxidative (Liang & Ward, 2006), increases in PGC-1α together with the heightened protein expression of sarcoplasmic enzymes responsible for generating ATP could result in enhanced work capacity (Haun et al., 2019a,b; Roberts et al., 2020). These responses to eccentric exercise involving a longer time under tension and subsequently higher volumes may occur early in the training process to prepare muscle cells spatially and energetically for subsequent myofibril hypertrophy (Roberts et al., 2020). This may have implications for professional rugby league athletes as there is evidence to suggest that sarcoplasmic hypertrophy may result from a myofibrillar protein accretion threshold being reached in individuals with years of resistance training experience (Roberts et al., 2020). To accumulate more myofibril proteins, increases in intracellular space generated by sarcoplasmic hypertrophy may be required (Roberts et al., 2020). The subsequent replacement of sarcoplasmic space with contractile components (Roberts et al., 2020) should result in increased force output (Taber et al., 2019) and improved play (Gabbett et al., 2011a; Johnston et al., 2014; McMaster et al., 2013; Redman et al., 2022; Redman, Wade, Whitley, et al., 2021).

Despite these potential benefits, there may be disadvantages to prolonging the eccentric phase of movement (Suchomel et al., 2019a). Increasing the time under tension has been shown to limit the contribution of the stretch-shortening cycle (SSC) during resistance exercise repetitions, resulting in decreased average (e.g., ~18%) and peak (e.g., ~20%) concentric power output during training bouts (Wilk, Goals, Krzysztofik, Nawrocka, & Zajac, 2019). Additionally, slow eccentric muscle actions may result in higher acute fatigue and perceived exertion during resistance training sessions (Diniz, Martins-Costa, Machado, Lima, & Chagas, 2014; Martins-Costa et al., 2016). Chronic fatigue with higher volume training may activate the AMP-activated protein kinase pathway to reduce protein turnover for type II muscle fibre growth and subsequently decrease the II:I fibre CSA ratio (Kristensen et al., 2015), which can result in decreases in the rate of force development (RFD) (Mike, 2015; Stasinaki, Zaras, Methenitis, & Bogdanis, 2019). Training strategies that have the potential to decrease time-limited force expression in rugby league players may be untenable. However, increasing muscle size and work capacity initially may improve the ability to maximise muscular strength development in later phases of training (Minetti, 2002; Stone et al., 2007; Zamparo et al., 2002).

GENERAL PREPARATION PHASE 2

The subsequent 3-week GPP aims to elicit changes in muscle-tendon properties and neural function through slow (3 sec [Krzysztofik et al., 2019]) eccentric tempos and high-load (85-105% 1RM) muscle lengthening actions.

Increases in resistance exercise volume and load have been shown to influence muscle growth and changes in fascicle length (Duclay, Martin, Duclay, Cometti, & Pousson, 2009; Franchi et al., 2014; Pereira et al., 2016). The potential for high levels of mechanical tension with eccentric resistance exercise may be particularly beneficial for increasing muscle size (Eliasson et al., 2006). Eccentric exercise involving high loads induces large amounts of mechanical tension per motor unit (Hollander et al., 2007) and may influence the magnitude of muscle damage post-exercise (Chen et al., 2019). This may upregulate anabolic and cellular activity within muscle fibres to elicit a potent signal for protein synthesis (Eliasson et al., 2006). These observations may explain the increases in muscle hypertrophy following 6-weeks of heavy (90% CON 1RM) eccentric training involving a squatting movement performed with a slow lengthening phase (Stasinaki et al., 2019). High-load eccentric training appears to promote increases in muscle CSA by adding sarcomeres in series, as inferred from changes in fascicle length (Blazevich, Cannavan, Coleman, & Horne, 2007; Douglas et al., 2017a; Franchi et al., 2014). Notably, most studies investigating changes in fascicle length following eccentric training have involved untrained participants (Baroni et al., 2013; Blazevich et al., 2007; Duclay et al., 2009; Franchi et al., 2014; Potier et al., 2009; Seynnes, de Boer, & Narici, 2007; Stasinaki et al., 2019). As such, how the findings may translate to highly-trained athletes is unclear, although it has been suggested that adaptive processes may be similar but of a lesser magnitude (Vogt & Hoppeler, 2014). Nevertheless, greater fascicle length may affect muscle power by allowing fibres to produce forces at more optimal lengths and shortening velocities (Azizi & Brainerd, 2007; Kaufman, An, & Chao, 1989; Wickiewicz, Roy, Powell, Perrine, & Edgerton, 1984), which may increase the potential for improvements in physical capacities (e.g., maximal running speed [Abe, Fukashiro, Harada, & Kawamoto, 2001]) required for successful performances in rugby league (Johnston & Gabbett, 2011; Johnson et al., 2014).

High-load eccentric training may uniquely influence fibre type composition (Raue, Terpstra, Williamson, Gallagher, & Trappe, 2005). The predisposition for type II fibre growth may be associated with the tension-generating capacity and subsequent damage of these fibres due to increased recruitment with heavy eccentric exercise (Friedmann-Bette et al., 2010). Accordingly, increases in type II fibre size and a shift towards a faster phenotype have been shown following an 8-week training intervention involving slow muscle lengthening actions and maximal resistive loads in untrained participants (Shepstone et al., 2005). In resistance-trained males, an increase in the relative CSA occupied by type II fibres was similarly found after slow eccentric exercise with progressively heavier loads (~94% ECC 1RM) over a 12-week training intervention (Vikne et al., 2006). Type II fibre type area is associated with percent fibre type area (Fry, Allemeier, & Staron, 1994) and most likely represents an important contractile variable for repeatedly expressing large amounts of time-limited force (Fry, Schilling, et al., 2003; Tesch & Karlsson, 1985). However, type II fibre composition increases may be evident only after several weeks of eccentric training (Hortobagyi et al., 2000; Seynnes et al., 2007). Performance outcomes may similarly reflect muscle fibre alterations only after adequate recovery (~6-8 weeks) (Leong, McDermott, Elmer, & Martin, 2014; Shepstone et al., 2005). As such, these time frames should be considered when planning pre-season training.

Heavy eccentric training may take advantage of unique neural activation strategies to raise volitional muscle activation (Aagaard, 2003; Vangsgaard, Taylor, Hansen, & Madeleine, 2014) through increases in motor unit firing rates (Higbie, Cureton, Warren, & Prior, 1996), downregulation of inhibitory pathways (Aagaard et al., 2002), and greater central descending motor drive (Fang, Siemionow, Sahgal, Xiong, & Yue, 2004, 2001). Motor unit firing rates appear to be the primary inhibitory mechanism limiting voluntary activation (Duchateau & Baudry, 2014). As such, it may play a significant role in increasing force production characteristics after high-load eccentric training (Aagaard, 2003; Douglas et al., 2017a). Decreased neural inhibition has been shown following slow eccentric training with progressively higher loads (~90% CON 1RM) in previously untrained males (Aagaard et al., 2002). This was paralleled by substantial increases in neuromuscular activation and maximal strength following the 14-week training intervention (Aagaard et al., 2002). Supraspinal and spinal adaptation mechanisms (i.e., greater central descending motor drive, increased motoneuron excitability, decreased presynaptic inhibition) were similarly shown following heavy (120% CON 1RM) eccentric training involving slow lengthening actions in recreationally-trained participants (Duclay et al., 2009). Neural mechanisms have been shown to underpin training-induced increases in strength in novice trainees (Aagaard, 2003; Seynnes et al., 2007). Although it is less clear whether a similar magnitude of improvement occurs in highly-trained individuals, evidence suggests that neural plasticity exists in participants with highly augmented neural function (Aagaard, 2003). As such, slow, heavy eccentric training may provide a beneficial stimulus to elicit neural changes that improve players' force output. Nevertheless, considerable fatigue can occur with heavy eccentric exercise (particularly involving slower movement speeds) and this may attenuate force-time characteristics (Mike, 2015; Stasinaki et al., 2019) and affect motor control for several weeks following the cessation of training (Leong et al., 2014). Thus, improvements in neural function and therefore heightened maximal and time-limited force expression may be a delayed response to high-load eccentric training involving prolonged lengthening actions (Baroni et al., 2013). Performance outcomes may parallel this delayed neuromuscular response and should, therefore, be taken into consideration.

Changes in tendon structure and function have been reported following slow, heavy eccentric training, possibly due to the large magnitude of mechanical tension induced (Farup et al., 2014; Malliaras et al., 2013). Maximal eccentric exercise was found to elicit large amounts of tendon force and stress and produce improvements in tendon CSA and stiffness following 12 weeks of high-load (80% ECC 1RM) training involving slow muscle lengthening actions (Malliaras et al., 2013). Increases in maximal voluntary contraction and RFD were also observed following the training intervention (Malliaras et al., 2013). Findings suggest that changes in tendon properties after high-load eccentric training with longer time under tension increase the use of elastic energy during SSC actions (Bojsen-Moller, Magnusson, Rasmussen, Kjaer, and Aagaard, 2005), which may raise the potential for improvements in motor control and time-limited force expression (Cormie, McGuigan, & Newton, 2010; Elmer, Hahn, McAllister, Leong, & Martin, 2012; Liu et al., 2013; Papadopoulos et al., 2014). Decreases in ankle, knee, and hip joint angles during the eccentric phase of a drop jump assessment were observed following 8 weeks of slow eccentric training involving progressively heavier loads (90% ECC 1RM) (Papadopoulos et al., 2014). This was associated with large improvements in maximal eccentric and concentric force output and RFD and drop jump performance (Papadopoulos et al., 2014). Variables associated with SSC performance are associated with many important physical attributes and technical and tactical skills required for successful performance in rugby league (Gabbett et al., 2011a ; Johnston et al., 2014; McMaster et al., 2013; Redman, Wade, Kelly et al., 2022; Redman, Wade, Whitley, et al., 2021).

Prolonging the lowering phase during eccentric resistance exercise can decrease the number of repetitions completed and reduce the potential for muscle growth (Nobrega et al., 2018; Pryor, Sforzo, & King, 2011). Yet, if overall time under tension is emphasised, lengthening the eccentric phase of movement during the early pre-season period may provide a beneficial stimulus to improve muscle-tendon structure and function (Pereira et al., 2016; Stasinaki et al., 2019) and, subsequently, force output (Liu et al., 2013). Increasing eccentric time under tension can also induce considerable fatigue and attenuate performance (Baroni et al., 2013; Leong et al., 2014; Mike, 2015; Shepstone et al., 2005; Stasinaki et al., 2019). Nevertheless, training that elicits improvements in muscle-tendon properties and neural function while raising work capacity during the early pre-season period may maximise force production characteristics with later training (Minetti, 2002; Stone et al., 2007; Zamparo et al., 2002). This may have important implications for rugby league play in which competition is characterised by many repeated high-intensity effort bouts (Gabbert & Wheeler, 2015; Johnston et al., 2014).

ACTIVE REST

The 2-week active rest period occurs over the holiday season and aims to promote recovery following previously strenuous training through substantially lower resistance training volume-loads compared to the other pre-season phases (Bompa & Haff, 2009). Eccentric training is not programmed during this period so that neuromuscular fatigue is minimised. A supercompensatory effect whereby improvements in psychophysiological state and performance occur has been reported following active rest periods (Bompa & Haff, 2009; Brannstrom & Rova, 2013), which may have positive implications for subsequent training.

SPECIAL PREPARATION PHASE

The primary aim of the 4-week special preparation phase (SPP) is to elicit the physiological adaptations underlying improvements in neuromuscular function. Compared to previous training phases, the SPP involves reduced exercise volumes, high-loads (≥ 90% 1RM), and fast (< 2 sec [Krzysztofik et al., 2019]) muscle lengthening actions.

High force outputs may be achieved with fast lengthening actions given that muscle force production is not constrained by lengthening velocity during the eccentric phase of movement (Edman, 1988). As such, muscle size and strength gains, which are generally proportional to the degree of overload (Martino, Perestrelo, Vinarsky, Pagliari, & Forte, 2018), may be elicited through heavy resistance exercise involving fast eccentric actions (Douglas et al., 2017a). Greater muscle growth has been reported following maximal eccentric exercise involving a fast compared to a slow lengthening speed (English et al., 2014; Farthing & Chilibeck, 2003; Shepstone et al., 2005). This may be due to the larger magnitude of muscle damage and subsequent anabolic response produced with fast eccentric training when compared to load-matched slow eccentric training (Chapman, Newton, Sacco, & Nosaka, 2006; Proske & Morgan, 2001). Studies have also largely found greater improvements in muscle strength following eccentric training involving a faster versus slower eccentric phase of movement (Handford et al., 2022), which may not be surprising given the relationship between muscle size and strength (Taber et al., 2019). Nevertheless, research suggests that force production characteristics may be decreased for longer periods following fast, heavy eccentric training (Shepstone et al., 2005). Shepstone et al. (2005) showed decreases in weekly peak torque production that only exceeded pre-training measures in the last week of the 8-week eccentric training intervention involving maximal resistive loads and following 4 days of complete rest. Given that heavy eccentric exercise with faster speeds can induce large amounts of muscle damage and heightened neuromuscular fatigue (Chapman et al., 2006; English et al., 2014; Farthing & Chilibeck, 2003; Mike, 2015; Shepstone et al., 2005), moderate- and high-load eccentric training involving a slow eccentric phase of movement are programmed in prior phases to elicit a progressive overload over the pre-season period.

Stretch-induced strain from fast lengthening actions under high loads can increase the number of sarcomeres in series (Goldspink & Harridge, 2003; Sharifnezhad, Marzilger, & Arampatzis, 2014). This may explain the reported changes in fascicle length and subsequent increases in muscle CSA, force production, and shortening velocity following similar eccentric training protocols (Potier et al., 2009; Seynnes et al., 2007; Sharifnezhad et al., 2014). Following 10 and 12 weeks of fast eccentric training involving maximal loads, fascicle length was shown to be increased by 10% and 14%, respectively (Baroni et al., 2013; Sharifnezhad et al., 2014). In the latter study, significant improvements in fascicle length were only observed in the condition involving the leg that was exercised using a higher lengthening velocity (240 deg·s-1 versus 90 deg·s-1) through a larger range of motion (25° to 100° versus 25° to 65°) (Sharifnezhad et al., 2014). The increases in fascicle length may be attributed to the rapid lengthening of the muscle fibres in the descending part of the force-length relationship that can induce a high magnitude of strain, resulting in sarcomerogenesis (Butterfield & Herzog, 2005) and subsequent improvements in time-limited force expression (Baroni et al., 2013; Blazevich et al., 2007; Sharifnezhad et al., 2014). This may support previous findings suggesting that exercise range of motion is the strongest influencing factor for fascicle length adaptations (Blazevich et al., 2007) and provide a rationale for including fast, heavy squats performed to full depth in the mid-pre-season period.

A shift in fibre type composition towards a more fatigue-resistant phenotype generally occurs with resistance training (Fry, Webber, et al., 2003). However, eccentric training may uniquely influence fibre type composition to maintain or increase type IIx fibre composition (Colliander & Tesch, 1990; Hortobagyi et al., 1996; Paddon-Jones et al., 2001; Vikne et al., 2006). Following a 10-week training intervention involving fast eccentric exercise with high loads, type I and IIx composition were decreased and increased by ~14% and ~7%, respectively (Paddon-Jones et al., 2001). This study also reported substantial increases in eccentric, concentric, and isometric force production characteristics post-training (Paddon-Jones et al., 2001). In contrast, muscle fibre composition and maximal force expression (irrespective of contraction type) were generally unchanged with the same protocol involving slow lengthening actions (Paddon-Jones et al., 2001). Shepstone et al. (2005) also showed greater increases in force generation following similar eccentric training interventions over 8 weeks. Type I and type IIx fibre composition, however, were reportedly increased and decreased, respectively, following both the slow and fast eccentric training protocols (Shepstone et al., 2005). Nevertheless, the total area occupied by type IIa fibres was increased following the fast but not slow eccentric protocol (Shepstone et al., 2005). Previous findings have shown increases in type IIa fibre CSA and percent following resistance training (Fry, Webber, et al., 2003). Although type IIa fibres have a lower peak force-generating capacity compared to type IIx fibres, type IIa fibres have a greater oxidative capacity and are generally more resistant to fatigue than type IIx fibres (Schiaffino et al., 2019). As such, type IIa fibres may have a greater capacity to incur muscle damage, which can elicit larger increases in muscle CSA (Friedmann-Bette et al., 2010; Schiaffino et al., 2019). This may explain the greater increases in muscle hypertrophy and force production following fast versus slow eccentric training despite the shift in fibre composition from type IIx to type IIa reported by Shepstone et al. (2005). Furthermore, the shift toward a more fatigue-resistant phenotype generally occurs with greater volume-loads (Andersen & Aagaard, 2000). As such, the differences in average weekly (3.14 rad.s-1 x 24 repetitions versus 3.66 rad.s-1 x 32.5 repetitions) and total volume-load between the studies of Paddon-Jones et al. (2001) and Shepstone et al. (2005) may explain the conflicting findings related to changes in type IIx fibre composition. Findings suggest that there may be a pattern of decreased force production due to fibre remodelling that subsequently improves the type II:I fibre ratio and increases muscle hypertrophy following fast, heavy eccentric training (Shepstone et al., 2005). This may provide an explanation of the delayed training effects often observed following similar training protocols (Baroni et al., 2013; Leong et al., 2014) and support for high-load exercise prescription involving a faster eccentric phase of movement in the mid-pre-season period.

Neural adaptations may influence the reported increases in maximal and time-limited force expression following high-load eccentric training involving fast lengthening actions (Oliveira, Corvino, Caputo, Aagaard, & Denadai, 2016). Following 8 weeks of fast, maximal eccentric training, peak force production and early-phase (100 ms) RFD increased by 28% and 30%, respectively (Oliveira et al., 2016). Increases in volitional supraspinal drive and spinal reflex disinhibition have been shown to positively influence early-phase RFD (Michaut, Babault, & Pousson, 2004; Pensini, Martin, & Maffiuletti, 2002) and may explain the findings of Oliveira et al. (2016). In contrast, improvements in late-phase (> 100 ms) RFD generally occur in parallel with increases in strength and may be related to muscle CSA and mechanical stiffness (Andersen & Aagaard, 2006). Interestingly, Oliveira et al. (2016) showed no changes in late-phase RFD despite increases in maximal force production. This may further indicate that neural adaptations largely influence increases in early-phase RFD following fast, heavy eccentric training (Andersen et al., 2010; Oliveira et al., 2016). However, Oliveira et al. (2016) did not investigate changes in muscular properties (i.e., fibre composition), which are associated with early-phase RFD (Bottinelli, Pellegrino, Canepari, Rossi, & Reggiani, 1999). Additionally, the study participants were recreationally-trained. As such, the substantial improvements in force-generating capacity may be due to their training status (Aagaard, 2003; Seynnes et al., 2007). Although a similar increase may not occur in professional rugby league players, neural plasticity is evident in individuals with highly augmented neural function (Aagaard, 2003). These results suggest that increasing the speed of high-load lengthening actions may elicit improvements in neural function that subsequently increase RFD at the early phase of rising torque.

Findings suggest that improvements in force-time characteristics are more evident when the testing velocity matches that generally used in training (Roig et al., 2009). Studies have shown that high-load eccentric training with slow lengthening actions can improve sprint and jump performance (Cook, Beaven, & Kilduff, 2013; Stasinaki et al., 2019). Increases in upper- and lower-body maximal strength and countermovement jump performance were found following 3 weeks of heavy (120% CON 1RM) eccentric training in semi-professional rugby players (Cook et al., 2013). However, 40 m sprint performance was only improved when fast, unloaded eccentric exercises (i.e., assisted countermovement jumps and downhill running) were added to the protocol (Cook et al., 2013). Training that progressively exposes players to faster lengthening actions may improve motor control and time-limited force expression to a greater degree compared to training involving slower lengthening actions (Handford et al., 2022; Suchomel et al., 2018). This may elicit a large transfer of training effect (particularly after training-induced changes in muscle-tendon and neural function have occurred [Cormie et al., 2010]) that subsequently enhances many physical attributes associated with a broad range of technical and tactical skills (Gabbett et al., 2011a; Johnston et al., 2014; Liu et al., 2013; McMaster et al., 2013; Redman, Wade, Kelly, et al., 2021; Redman, Wade, Whitley, et al., 2021).

PRE-COMPETITION PHASE

The realisation of delayed training effects following eccentric training may require considerable time (Baroni et al., 2013; Coratella & Schena, 2016; Leong et al., 2014; Shepstone et al., 2005). As such, high-load eccentric training with fast lengthening actions is prescribed with lower volumes during the 4-week pre-competition phase to allow for adequate recovery while maintaining high levels of force production. Plyometric training involving high rates of muscle lengthening is performed subsequent to fast, heavy eccentric exercise during training sessions to further elicit the morphological and neural adaptations underlying improvements in time-limited force expression and enhance motor control (Golas, Maszczyk, Zajac, Mikolajec, & Stastny, 2016; Markovic & Mikulic, 2010; Suchomel et al., 2018) while maximising training economy.

The performance benefits of plyometric training are well documented (Markovic & Mikulic, 2010). Studies have demonstrated changes in muscle-tendon properties (e.g., muscle size and architecture, type II fibre CSA, type II:I ratio, tendon CSA and stiffness) (Kubo et al., 2017; Malisoux, Francaux, Nielens, & Theisen, 2006; Potteiger et al., 1999) and neural function (e.g., voluntary activation) (Behrens, Mau-Moeller, & Bruhn, 2014; Behrens et al., 2016) underpinning force-time characteristics following plyometric training (Markovic & Mikulic, 2010). Nevertheless, improvements in performance outcomes involving an SSC component may not be maximised only through increases in force production (Bobbert & Van Soest, 1994; Toumi et al., 2001). Changes in muscle activation strategies (i.e., intermuscular coordination) subsequent to plyometric training may be particularly important for enhancing motor control (Kyrolainen, Komi, & Kim, 1991; Markovic & Mikulic, 2010) and thus the expression of skilled movement (Bobbert & Van Soest, 1994; Cormie et al., 2010; Toumi et al., 2001). This may support the findings of Cook et al. (2013) who observed increases in sprint and jump performance only after sprinting and jumping activities were included in the eccentric training intervention. Thus, improvements in motor control that occur with plyometric exercise may actualise the muscle-tendon and neural adaptations elicited through previous eccentric training.

Considering the large amount of sport-specific training that typically occurs during the late pre-season period, maximising training economy is important. Fast, heavy eccentric exercise has been shown to acutely improve jumping, throwing, and pushing performance in well-trained athletes (Golas et al., 2016). Findings suggest that high-load exercise involving a lengthening action may be particularly beneficial for eliciting a postactivation potentiation (PAPE) effect given the large amount of mechanical tension for a low metabolic cost associated with these exercises (English et al., 2014; Golas et al., 2016; Horstmann et al., 2001; Krzysztofik et al., 2020; Ong, Lim, Chong, & Tan, 2016). Increases in bar velocity and peak power during a bench throw were found within 5 minutes following an upper-body stimulus involving 2-3 x 2-3 at 110% and 130% CON 1RM with a fast eccentric phase of movement in strength-trained athletes (Golas et al., 2016; Krzysztofik et al., 2020). Countermovement jump peak power was similarly improved within 6 minutes following a lower-body eccentric exercise stimulus (1 x 5-6 at 105% and 125% CON 1RM) in trained participants (Ong et al., 2016). Research has demonstrated that the magnitude of PAPE effects may be related to the strength level and resistance training experience of the individual (Seitz & Haff, 2016). As such, previous eccentric training that improves force output may be important to maximise PAPE effects following stimuli involving fast muscle lengthening actions under high-loads. While plyometric exercise can provide a beneficial stimulus for improving motor control (Kyrolainen et al., 1991; Markovic & Mikulic, 2010; Suchomel et al., 2018), training that develops a high level of muscular strength initially may enhance the magnitude of potential adaptations to subsequent plyometric training (Cormie et al., 2010, 2011b). This may have implications for enhancing muscular strength expression when training to improve rugby league performance (Gabbett et al., 2011a; Johnston et al., 2014; Redman, Wade, Kelly, et al., 2021; Redman, Wade, Whitley, et al., 2021).

CONSIDERATIONS AND LIMITATIONS

Although eccentric training appears to be a beneficial strategy to improve rugby league performance, several factors need to be considered. First, eccentric exercise should be integrated (i.e., not prescribed exclusively) into the resistance training plan (Suchomel et al., 2019b). Second, the planning of eccentric training should take into consideration the time course of adaptive responses (Suchomel et al., 2019a). Although eccentric exercise may elicit a protective effect that decreases muscle damage after subsequent training bouts (Chen et al., 2019; Nosaka, Newton, & Sacco, 2005), performance may be attenuated for a period of time (Hesselink, Kuipers, Geurten, & Van Straaten, 1996; Linnamo, Bottas, & Komi, 2000). Therefore, it may be beneficial to schedule adequate rest periods following training sessions involving eccentric exercise (≥ 72 h) (Table 2). Third, the realisation of delayed training effects following eccentric training may require considerable time (Baroni et al., 2013; Coratella & Schena, 2016; Leong et al., 2014; Shepstone et al., 2005). Monitoring systems may provide important information related to athletes' psychophysiological state (DeWeese, Hornsby, Stone, & Stone, 2015) in response to eccentric training. A fourth consideration is the assignment of eccentric exercise loads. As force output is task-specific, prescribing eccentric loads based on tasks limited by concentric strength may not take advantage of the high levels of mechanical tension that can be elicited by eccentric exercise (Harden et al., 2019). Nevertheless, specialised equipment that may not be available in most practical environments is likely needed to establish maximal eccentric strength levels (Harden et al., 2018). Fifth, the training age and technical proficiency of players should be considered when prescribing eccentric training to reduce the chance of maladaptive outcomes (Suchomel et al., 2019b). Sixth, the decision to

Table 2. Typical weekly resistance training schedule during the 17-week pre-season period

Pre-season Calander	Training phase	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Weeks 1-7	GPP 1-2	Full body (60 min)	Upper-body (45 min)	Lower-body (60 min)	Individualised extras** (45 min)	Full-body Eccentric exercise* (60 min)	OFF	OFF
Weeks 8-9	Active Rest	OFF	Full-body (45 min)	OFF	OFF	Full-body (45 min)	OFF	OFF
Weeks 10-13	SPP	Full body (60 min)	Upper-body (45 min)	Lower-body (60 min)	Individualised extras** (45 min)	Full-body Eccentric exercise* (60 min)	OFF	OFF
Weeks 14-17	PCP	Full-body Eccentric exercise* (45 min)	Upper-body (45 min)	OFF	Full-body (45 min)	Captain's run	Trial Game	OFF

Notes: *Session includes upper- and lower-body eccentric exercise (i.e., back squat, bench press); **resistance exercise parameters are selected based on a player's identified physical deficiencies and positional requirements

GPP general physical preparation; *PCP* pre-competition phase; *SPP* special physical preparation

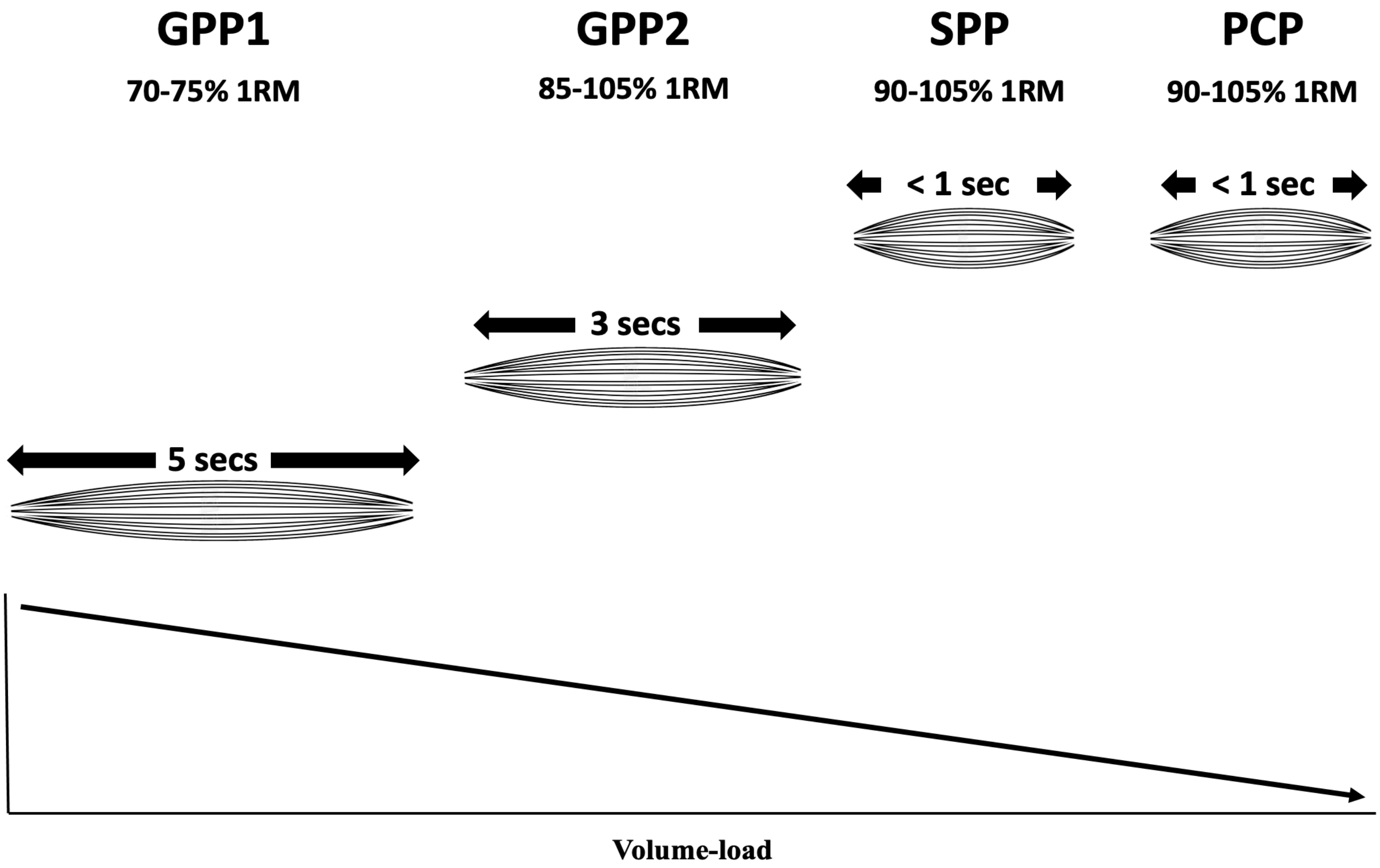

Figure 2. Volume-load (sets c repititions x load [%1RM] x eccentric time under tension [sec]) of eccentrically-integrated resistance training during a pre-season phase. *GPP* general preparation phase, *PCP* pre-competition phase, *RM* repetition max, *SPP* special preparation phase.

prescribe eccentric training should be informed by the physical demands of competition together with an individualised approach that addresses movement deficiencies and consideration of other sport-related training. Importantly, the pre-season programme illustrated is a general representation and does not reflect possible modifications due to changes in player health and performance and positional requirements that will ultimately guide resistance training prescription. Lastly, eccentric resistance training should be appropriately periodised to elicit a systematic and progressive overload over the pre-season phase (Figure 2).

CONCLUSION

Successful performances in rugby league require the ability to engage in repeated contact efforts with minimal recovery while maintaining a high running intensity (Johnston & Gabbett, 2011; Johnston et al., 2014). The capacity to express high levels of time-limited force appears to underlie many important physical attributes that are required to meet the repeated-effort demands of rugby league play (Gabbett et al., 2011a; Johnston et al., 2014; McMaster et al., 2013; Redman, Wade, Kelly, et al., 2021; Redman, Wade, Whitley, et al., 2021). If appropriately periodised and integrated into the training plan, resistance training that sufficiently loads the eccentric phase of movement and progressively increases the rate of muscle lengthening velocity over the pre-season phase can provide a beneficial stimulus to elicit morphological and neural changes that culminate in improving muscular strength expression.

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