EXERCISE REGULATION (PACING) IN STRENGTH TRAINING

By

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ABSTRACT

The purpose of this thesis was to investigate the effect of self-selected rest periods on strength training performance when experienced strength-trained athletes were provided the opportunity to select the rest period between sets of a heavy back squat exercise. To date, minimal research exists with regard to self-regulation *(*pacing) of rest periods during strength training; the majority of research surrounding rest periods in strength training focuses on imposed rest periods and their effect on training volume. Recently, research has begun to compare the differences in training outcomes between self-selected rest periods and imposed rest periods utilising moderate loads in subjects from the general population. It is believed that an understanding of how experienced strength-trained athletes approach heavy strength training when afforded the opportunity to select their rest periods between sets of a heavy back squat will allow coaches to better plan and implement strength training programs.

Sixteen experienced strength-trained male athletes (mean age = 22.8 ± 3.1 a) completed a familiarisation self-selected rest trial followed by two self-selected rest trials (SS), one 3 min rest trial (3M) and one 5 min rest trial (5M). The trials were conducted in random order over a 14 day period with a minimum of 48 h between each trial. Each trial consisted of five sets of 5 repetition max (RM) back squats interspersed with the specific rest period for that trial. A Gymaware™ optical encoder collected kinetic data for each squat and temporal data for each inter-set rest period. Surface electromyography (sEMG) data for the vastus medialis oblique (VMO), vastus lateralis (VL) and biceps femoris (BF) muscles of the right leg was collected and analysed using a portable wireless bio-amplifier system, with all trials recorded at 1000 Hz. Subjective measures of readiness to lift (RTL) and rating of perceived effort (RPE) were taken before and after each set.

The first study investigated the consistency of strength-trained athletes in regulating self-selected rest periods between sets of heavy squat training to maintain performance. Analysis of the data showed that participants demonstrated similar between-set kinetic performance and subjective responses on different days. However, a significant difference was observed between self-selected trial power output (SS1 850 ± 133 W; SS2 831 ± 110 W) and inter-set rest periods for sets 3 (95% CI = [-83; -17]), 4 (95% CI = [-101; -35]) and 5 (95% CI = [-96; -29]), compared to set 1 irrespective of trials, suggesting rest periods were regulated to maintain performance in response to inter-daily biological variation.

The second study compared the kinetic, neuromuscular and psychological responses between the SS and the imposed 3M and 5M trials of strength-trained athletes. Linear mixed modelling revealed that during the SS trial, rest periods increased from sets 1 to 3 with self-selected rest periods prior to the 4 and 5 sets being between three and five min. For the imposed rest period trials, performance across sets 3, 4 and 5 deteriorated when compared to that of set one. For the SS trial, performance across sets 3 and 4 deteriorated when compared to that of set 1. Surface EMG was similar across all trials and sets, suggesting performance decline could be more attributed to peripheral rather central fatigue. A significant main effect of condition ($p<0.001$), indicated that participants reported to feel better prepared to lift in the 5M trial compared to the 3M and SS trials.

The findings from this research provide strength and conditioning coaches and academics with an opportunity to implement and refine self-selected rest strategies in strength training. Coaches should look to utilise these methods with experienced strength-trained athletes, after an appropriate period of familiarisation, to supporting the manipulation of program design to improve training efficiency and performance without impacting on other training modalities. Future studies of this nature should have multiple familiarisation trials and extremely detailed instructions given to participants to ensure valid and reliable data is gathered for analysis. The results from this study are seen as a good basis for which to extend research and knowledge in this field.

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LIST OF ABBREVIATIONS

1RM	1 Repetition Maximum
5RM	5 Repetition Maximum
3M	3 Minute rest trial
5M	5 Minute rest trial
a	Year
BF	Biceps Femoris
CI	Confidence Interval
DC	Direct Current
EMG	Electromyography
h	Hour
ICC	Intraclass Correlation Coefficient
MAR	Missing at Random
min	Minute
MPO	Mean Power Output
RM	Repetition Maximum

RMS	Root Mean Square
RPE	Rate of Perceived Effort
RTL	Readiness to Lift
s	Second
sEMG	Surface Electromyography
SS	Self-Selected rest trial
VL	Vastus Lateralis
VMO	Vastus Medialis Oblique
W	Watts

CONFERENCE PRESENTATION BY THE CANDIDATE RELEVANT TO THE THESIS

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Strength training, sometimes referred to as resistance training, is a commonly utilised method of athletic preparation which aims to enhance an athlete's ability to produce force (24, 85). Within the field of sport science, there has been a considerable number of research studies examining the implementation of strength training practices for athletic purposes. The development of strength has been shown to provide clear improvements for athletic performance (14, 15, 33, 35, 163) in addition to general health and wellbeing (44, 50, 84). Elite athletes devote large amounts of time to developing their maximal strength and the ability to repeat near maximal strength efforts. Strength training components place considerable load on the overall periodised training plan and reduces the time which can be devoted to recovery, an essential component for training adaptation (25, 27).

Strength training is often subdivided into specific categories which aim to tax different neurological and physiological systems, providing improvements in endurance, maximal strength or force development and power (86). These subcategories are commonly broken down along what is referred to as the strength-training continuum (24, 86, 123). Each subcategory requires a different training stimulus to allow for adaptation to occur, and the manipulation of acute training variables provides a means for the strength coach to influence the desired outcome in an efficient manner (24, 86). Consequently, the training goal will dictate which training principles and acute variables are employed in the development and execution of a strength-training program. Best practice requires strength coaches to look at the needs of the individual athlete in order to design and implement a training strategy that aims to enhance a specific muscular attribute (85).

A sound understanding of anatomical and physiological responses to strength training stimuli, as well as an understanding of the key training principles and acute training variables, are required when designing and implementing strength training programs (24, 85). The training principles referred to in most training program literature include overload, progression, specificity, adaptation, individualisation and maintenance (24, 84, 85), yet pacing strategies are not mentioned. The acute training variables commonly discussed in training program literature include muscle action, loading volume, exercise selection and order, number of repetitions, training frequency, and rest period duration; however, the self-selection of rest periods are not mentioned. Manipulation of one or more of these acute training variables provides the potential to vary the training stimulus, to initiate processes for neural, hormonal and muscular adaptation to occur, all while allowing for management of the training load (13, 24, 84, 85).

Manipulation of the rest period has a profound effect on the effectiveness of the program outcome (151, 154, 158) but is the least studied of all the acute strength training variables. The length of the rest period is commonly manipulated, in combination with the loading and number of repetitions during the selected exercise, to establish the training intensity of the set(s) (158). Rest periods can be manipulated to manage acute levels of fatigue, predominantly peripheral fatigue, which manifests within the working muscle leading to a loss of force production and exercise termination (126, 127). Understanding the causes of fatigue, as well as how the body manages and copes with its onset, is critical to ensure strength and performance adaptations (56). To this point, rest periods during strength training sessions have been based on classical concepts of exercise physiology, including energy depletion, replenishment, and metabolic by-product clearance (126, 154, 158).

Historically, sports science research has predominantly focused on the physiological processes involved in fatigue and specifically, which process(es) cause fatigue and limit further physical activity (10, 48, 105). More recently, a growing number of researchers have challenged the idea that fatigue is a purely a physiological response to exercise (62-64, 94, 95, 106, 108). These researchers have proposed that the brain is responsible for the regulation of physical resources so that the body does not overreach to a point of catastrophic failure (106). A number of models such as the Central Governor Theory, Psychobiological Model and Decision Making Model have been proposed which attempt to explain how the brain manages energy resources within the body during exercise (46, 93, 96, 105, 106, 121). These theories and models collectively encompass a broader concept of homeostatic control referred to as 'pacing' or 'exercise regulation'. Pacing has been defined as the 'distribution of energy resources' in an attempt to achieve the training or competition outcome without fatigue interfering with the completion of the task or a person's basic health (141).

Research in this relatively new area has aimed to examine how athletes' approach, conduct, and regulate their performances during exercise and during competitive races of a continuous nature, primarily during activities such as cycling, running and rowing (12, 37, 55, 60, 61, 109, 146). Data analysed from competition (field) and laboratory assessments during exercises of varying lengths and intensities have suggested that athletes decide upon various pacing strategies based on immediate environmental cues, prior training and competition experience, afferent feedback, the presence of competitors, and perceptual and motivational factors (23, 46, 141). Depending on the event and mode of exercise, athletes have been shown to undertake particular pacing strategies in order to maximise their performance (60, 140, 146). Up until recently, there has been a dearth of research considering whether athletes adopt pacing strategies during strength training activities and if they do then for what purpose. This is an anomaly as heavy strength training, as with endurance exercise, has the potential to lead to cumulative fatigue and a deterioration in performance when athletes' complete multiple sets of repetitions. Indeed, athletes undertaking regular strength training know the end-point of the training session and have prior experience of the exercise stress ahead of them so it is likely they will pace their strength training session just as a distance runner completing a set of running repetitions will. In addition, heavy strength training has the potential to cause bodily harm (muscular and tendon injury) if not executed with good technique (31), so athletes undertaking heavy weight lifting will be acutely aware of their state of fatigue and will frequently contemplate the extent of the task lying ahead as they progress through sets of heavy weight lifting. Therefore, it is plausible that experienced strength-trained athletes will pace both their repetitions within each set and their rest periods between sets of repetitions (if allowed). Interestingly, pacing theory would argue that rest periods during strength training could or should be self-selected (39, 67); however, strength coaches will generally prescribe rest periods based on classical physiological studies which have formed our current understanding of peripheral fatigue and the duration of rest required to restore a similar level of exercise performance once peripheral fatigue develops (158-160).

1.2 RESEARCH AIMS

The purpose of this thesis was twofold. It aimed to assess how strength trained athletes regulate (self-selected) rest periods between sets of a heavy squat training activity and whether, when provided the opportunity to self-select rest periods, athletes could maintain the performance outputs generated when prescribed rest periods were applied. Strength training generally conforms to a number of basic training principles. These dictate that when undertaking heavy or maximal strength training 3 to 5 min of rest be prescribed between sets (3, 24, 159). Such a rest period is thought to allow sufficient time to limit the development of metabolic and neuromuscular fatigue, therefore providing sufficient recovery to complete subsequent sets (8, 24, 159, 161). Previous research has revealed self-selected rest periods to be a viable option for maintaining sprint performance in physically active populations once familiar with the task (67). More recently, research has begun to investigate how strength training performance is effected when subjects utilise self-selected and imposed rest periods in moderate intensity strength training sessions when performance was assessed until volitional cessation (39, 68). These studies have revealed little difference between the numbers of repetitions performed when subjects self-selected their rest period or utilised an imposed 2 min rest between sets of strength training activities. It must be noted that the loads utilised in the aforementioned studies were consistent with those used in development of muscle hypertrophy (39, 67). Filling the gap in knowledge with respect to how experienced strength trained athletes regulate their rest periods (applied a pacing strategy) between sets of heavy back squats in order to maintain performance will help strength coaches identify the value of self-selected rest intervals in strength training. Two research studies were conducted as part of this thesis:

- Study one investigated the consistency of strength trained athletes in regulating self-selected rest periods between sets of heavy squat training in order to maintain performance.
- Study two compared the kinetic, neuromuscular and psychological responses between self-selected rest period trials and imposed 3-min and 5-min rest trials of strength trained athletes, during five sets of heavy back squat resistance training.

It is envisaged that the results of these studies will provide a valuable insight into how experienced strength trained athletes maintain performance in response to inter-daily biological variation and provide coaches with an additional viable training variable to manipulate with appropriately experienced athletes.

CHAPTER 2: LITERATURE REVIEW

2. 1 INTRODUCTION

This literature review will initially focus on strength training practices, particularly maximal strength development, and the commonly understood fatigue mechanisms which have led to the dogma of universally prescribed rest periods within strength training sessions. The review will then consider what we currently understand about pacing and how it might influence the strength trained athlete in relation to how they regulate their strength related exercise.

2.2 PERIPHERAL, CENTRAL AND MENTAL FATIGUE

Fatigue is a concept that intrigues clinicians and sports science researchers alike due to its influence on physical and mental abilities. Research delving into what influence fatigue has on an individual's ability to carry out cognitive and physical tasks, whether in a sporting, academic or industrial context, has grown considerably in recent years (92, 101, 117). Mental fatigue has been termed as a psychobiological state caused by prolonged periods of demanding cognitive activity and has been shown to impact performance in sustained tasks of daily living (96). Physical fatigue, often more relevant in the sporting environment, has been commonly divided into central and peripheral fatigue. In simple terms, these can be thought of as fatiguing factors which occur either proximal (central) or distal *(p*eripheral) to the neuromuscular junction (8, 11). These definitions however seem to convey that fatigue manifests itself independently of one another. More recently the concept of fatigue and how it is defined has been increasingly challenged (49, 88). Enoka et al, (49) proposes fatigue to be defined as symptoms in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability. The author goes no to characterize trait level fatigability to represent the average amount of fatigue experienced by an individual over the preceding several days and is predominantly related to perceived fatigability. In contrast state level fatigue reflects the rate of change in key adjustments during a fatiguing task and relates to both performance and perceived fatigability during ongoing activity.

Central fatigue is thought to represent the inhibition of the central nervous system manifesting in a reduced central motor drive to innervate skeletal muscle, which in turn fails to generate the force necessary to carry out basic motor tasks (22, 47). Research into contralateral limb inhibition reveals that spinal and supraspinal afferents can be disrupted as a result of exhausting unilateral activities causing a reduction in voluntary drive in upper and lower limbs (42, 120, 137, 143). While some researchers have suggested that the primary cause relates to the release of chemically mediated hormones such as serotonin (5–HT), dopamine (DA) and noradrenaline (NA) (100, 125, 130, 165). Peripheral fatigue has been described as the inability of the muscle to generate force (59, 82). Like central fatigue, peripheral fatigue is multifaceted and complex; however, it is widely accepted that it involves the depletion of energy substrates, the build-up of metabolic waste by-products such as Adenosine diphosphate (ADP), Adenosine mono-phosphate (AMP), inorganic phosphate (*p*i) and Hydrogen (H^+) ions, or the inhibition of neural transmission at the muscular level (1, 8, 11, 51). The interplay between central and peripheral fatigue is only now starting to be understood, with a recent study by Thomas (139), demonstrating short, high-intensity exercise bouts lead to greater peripheral fatigue while longer exercise bouts are increasingly influenced by central fatigue (139).

2.2.1 Peripheral fatigue and exercise performance

Like central fatigue, peripheral fatigue occurs as a result of repeated or sustained muscular contraction. Muscle contracts due to a neural input, which innervates the muscle and releases chemical substrates to perform functions at the cellular level. A muscle contraction is initiated through electrical signalling via the central nervous system in the form of an action potential (AP). The AP is passed, via a motor neuron, through numerous axon terminals which interact with individual muscle fibres. Collectively, this forms what is known as a motor unit. The transmission of the AP from the neuron to the muscle occurs at the site of the neuro-muscular junction. Here, the neurotransmitter acetylcholine (ACh) allows for the seamless transfer of the AP from the neuron to the surface of the muscle fibre (77, 155). However, it has been suggested that neuromuscular transmission failure (NTF) at both pre- and post- synaptic sites may influence neural transmission and therefore contribute to peripheral fatigue (29, 132). Sieck et al (132) postulated that the most probable cause of failure at the presynaptic terminal is the diminished quantal release of ACh while on the post-synaptic side, the desensitisation of the cholinergic receptors are thought to reduce the excitability of the sarcolemma membrane. Furthermore, it is believed that NTF is more prevalent in the more fatigable high threshold motor units when compared to fatigue resistant low threshold motor units due to the increased stimulation frequency (132). Following on from potential neural transmission failures at the synapse, sarcolemmal excitation is thought to lead to a decline in action potential amplitude in mammalian fast twitch muscle fibres which require greater depolarization for full activation. A fatigue related decline in these fibres is thought to result from a reduction in AP amplitude leading to incomplete activation and loss of force in the muscle fibre (57). These inhibitions to neural transmission in fast twitch muscle fibres may contribute to peripheral fatigue in high intensity activities, such as heavy strength training. In contrast, Bigland-Ritchie et al (21, 22) has shown membrane excitability to remain relatively unchanged when measured through surface electromyography (EMG) during intermittent and maximal voluntary muscular contractions (MVC), while Behm (19) revealed that a number of peripheral factors such as pressure, tensile and chemical changes are known to impact on spinal and supraspinal afferents causing a reduction in force output during submaximal contractions. Indeed this area of fatigue research continues to be a hotly debated topic.

Following neural innervation, intermuscular calcium (Ca^{2+}) is released from the sarcoplasmic reticulum (SR) and acts on the binding sites of the actin and myosin filaments allowing for cross bridge cycling. As the AP travels along the sarcolemma and onto the T-Tubules it triggers potassium (K^+) and sodium (Na^+) ion channels to open and an exchange of K^+ and Na^+, releasing Ca^{2+}. In turn, calcium prompts the exposure of the actin myosin binding sites allowing excitation contraction coupling (6, 8, 11, 70, 77). The ability for the muscle cell to contract is believed to be compromised during high frequency fatigue which is common in activities such as strength training (8, 152). This is thought to be caused by the inadequate stimulation of voltage gated ion channels within the T-Tubules which in turn interact with the Ca^{2+} release channels, responsible for the release of Ca^{2+} into the myoplasm (7, 89). An excessive accumulation of K^+ in the T-Tubules has been shown to inhibit depolarisation in skinned fibres during in vitro studies, where a reduction in Ca^{2+} release leads to reduced muscular force (8, 11, 70). Additionally, Ca^{2+} release channels are known to be inhibited further as a result of a reduction in adenosine triphosphate (ATP) and an increase in the cytoplasmic levels of magnesium (Mg^{2+}) (7, 90). However, *in vivo* skeletal muscle fibres are extremely efficient at buffering the transient build-up of K^+ enabling Ca^{2+} to remain relatively constant (7). This is achieved via the high proportion of Na^+ - K^+ ion pumps and chloride (Cl^-) channels located in the T-Tubules, resulting in the rapid repolarization of the membrane (7). Therefore, while theoretically these mechanisms would reduce the ability of the muscle to contract with appropriate force, it is unlikely to have an appreciable affect due to the number of “fail-safes” built into the muscle system (7).

During exercise, there needs to be an energy source that supplies the energy necessary for muscular contraction to occur (11). Three main energy systems or metabolic pathways have been shown to supply the working muscles with energy to power movement. These are the adenosine triphosphate and phosphocreatine (ATP and PCr), anaerobic glycolysis and the aerobic pathways. Each pathway provides the working muscle with a supply of ATP but at different rates, depending on the muscle fibre type(s) being activated which in turn is dependent upon the muscular force/power requirement (11). It has been postulated that a reduction in ATP to the working muscle due to a decrease in intramuscular and liver glycogen stores is a leading cause of peripheral fatigue during prolonged exercise activities (1). The energy supply model proposes that during endurance based activity an adequate supply of ATP may occur due to an insufficient ability of the metabolic pathways to generate ATP via phosphocreatine re-phosphorylation, glycolysis and lipolysis (1, 69, 107). It has been suggested that a complete depletion of ATP within the muscle would likely result in *rigor mortis* (51, 107). It has been well documented that even in forced contractions in ischemic environments ATP appears to not drop below 40-60% of resting values (1, 51, 69, 107).

Strength training is noticeably different from many other forms of training in that it is completed within a relatively short time frame and so is ordinarily not limited by the body's glycogen capacity (69). Strength training sets will generally take well under one min to complete depending on the mode of training undertaken and training tempo used (84, 85), and is punctuated with recovery periods between each set of repetitions. When the goal of training is to develop the maximal strength capability of a muscle group, relative loads equating to an individual's 1RM to 5RM are commonly utilised to provide the stimulus for adaptation (33). As a result, high threshold motor units and muscle fibres (type IIa and type IIx) are preferentially recruited over more oxidative low threshold fibres (type I) (8, 18, 24), with energy consumption increasing one hundred-fold in high threshold muscle fibres when transitioning from a resting state to those requiring bursts of maximal intensity, such as sprint type activities lasting five to ten s (127, 155, 157).

During heavy strength training, ATP stores will deplete rapidly within the exercising muscle cells during the first few s of the exercise. It has been calculated that the small supply of intracellular ATP contained within muscle fibres (5 - 6 mM) (127, 157), would theoretically become completely exhausted within 2 s during maximal muscle stimulation (157). However, it has been shown that ATP levels remain relatively constant throughout high intensity exercise such sprint cycling (127), as other substrates break down to replenish ATP stores. Indeed, the ability to recycle ATP during high intensity activity to maintain homeostasis appears to be quite resilient (127). Replenishment of ATP is mediated through the hydrolysis of muscular stores of PCr. Similar to ATP, a limited supply of PCr are stored within the muscle fibre limiting the rate at which the resynthesis of ATP can occur. Although the muscle is extremely efficient at replenishing ATP, the availability of PCr is limited and it is commonly accepted that this energy source is largely depleted < 10 s of intense physical activity (127).

A further consequence of PCr metabolism is the production of inorganic phosphate (p_i), which is produced when PCr is broken down into creatine (Cr) and P_i .While Cr has little effect on contractile properties of muscle (103), P_i has been shown to significantly impact on muscular force production, Ca^{2+} sensitivity, and SR Ca^{2+} release (5, 6, 8, 30, 40, 156). Inorganic phosphate is thought to act by inhibiting the ability of the actin myosin cross-bridge to transition from the weakly bound to strongly bound states, thus causing fewer cross-bridges to be in strongly bound or high force states and causing a decrease in force as P_i increases (40, 52, 156). Furthermore, P_i is known to reduce the sensitivity of Ca^{2+} in myofibrils in a similar fashion to H^+ (40, 52). Finally, SR Ca^{2+} release may be compromised if, as theorised, P_i enters the SR and combines with Ca^{2+} producing Ca^{2+} phosphate or where it impedes the release of Ca^{2+}. Irrespective of cause, Pi can result in a reduction in muscle contraction capability in high intensity activities (4, 6, 9, 152, 155).

As described previously, during high intensity activities such as maximal strength training, the majority of energy required for muscular contraction is derived from the ATP – PCr system during the first few s; however, anaerobic glycolysis becomes increasingly important as an energy pathway during repeated repetitions over more than a few s (162). A by-product of anaerobic glycolysis is the accumulation of lactic acid (51). It was commonly thought that lactic acid and the release of H^+ were the main contributors to muscle fatigue (8, 11). Recent studies have shown that lactate has little effect on the force producing abilities of muscle (118, 155). However, H^+ are associated with altering the pH levels of muscle and causing a decrease in calcium release (Ca^{2+}), which can subsequently alter the contractile properties of the muscle and thereby reduce force production (5, 8). A review of intracellular pH and force production suggests that tension following fatigue usually recovers in two phases; a rapid increase complete within 2 min, representing ~ 25% of the total recovery, followed by a slow exponential rise taking 20 to 25 min (51).

2.3 THE IMPORTANCE OF REST PERIODS DURING HIGH-INTENSITY AND STRENGTH EXERCISE

Research has suggested that PCr replenishment after high intensity exercise can take between 3 and 6 min and may not have replenished even after this time (16, 26, 36, 99, 144). Bogdanis et al. (26) investigated the replenishment of intramuscular PCr after bouts of intense 30 s cycle ergometer maximal sprints. Each participant had their individual PCr levels measured after resting 1.5, 3 and 6 min. Results indicated that muscle PCr levels declined to 19.7% ± 1.2% of the resting levels after the 30 s sprint and initially recovered rapidly to 65.0 ± 2.8% after 1.5 min. However, replenishment of PCr only reached 85.5 ± 3.5% of resting levels after 6 min rest. The study also measured peak power output, peak pedal speed and mean power over the initial 6 s in a secondary sprint effort. Results revealed that these measures did not reach that of the control values after 6 min of rest and correlated strongly ($r = 0.71 – 0.86$; $P = < 0.05$) with PCr resynthesis rates. Dawson et al. (36) examined the repletion rates of PCr between two groups of participants completing a single 6 s maximal sprint and five 6 s sprints departing every 30 s. PCr levels were measured pre-exercise and at several intervals post-exercise (10 s, 30 s, and 3 min). The results showed that during the single 6 s effort, PCr had returned to 55%, 69% and 90% of the pre-exercise levels (81.1 ± 7.4 mmol–kg $^{-1}$ DM) for the 10 s, 30 s, and 3 min rests respectively. During the five 6 S efforts, PCr had returned to 27%, 45% and 84% of pre-exercise levels (77.1 ± 4.9 mmol–kg $^{-1}$ DM) for the 10 s, 30 s, and 3 min rests respectively. The depletion of PCr was shown to be faster during the multiple sprint effort than the single sprint and thus it took longer for PCr levels to approach the pre-exercise levels following multiple sprints than a single sprint. Although depletion rates were faster, replenishment rates were also faster during the multiple sprint effort than the single sprint effort, potentially linked to the fast phase of PCr recovery which might be potentiated by a greater depletion in PCr as occurs in multiple sprint efforts (26, 71). It has been suggested that PCr replenishment can be enhanced through oxidative means (144). High levels of aerobic fitness are thought to promote faster recovery rates of PCr in subjects with a high VO_2 max compared to control subjects (136, 144, 164). Despite this, it has been commonly found that, although a substantial amount of PCr is replenished during the first 3 min of recovery, full repletion may take much longer after bouts of repeated high intensity exercise efforts.

The aforementioned research, while not exhaustive, provides an overview of the physiological processes known to affect the ability of muscle fibres to contract when exposed to intense physical activity. The research tends to suggest that acute fatigue can be largely recovered within relatively short timeframes, ranging from 2 to 5 min, but in some cases it may take longer. These time frames correspond with the commonly accepted rest periods employed during maximal strength training (24, 84, 159). However, while these rest periods appear to account for the immediate acute response to fatigue, training for athletic preparation is a continual process which requires the athlete to recover from an accumulation of fatigue brought about by numerous competing internal and external factors (75, 76). As such, it may be prudent to allow athletes to select rest periods based on how they feel on a daily basis, allowing them to respond to internal cues and self-manage their physiological resources in response to inter-daily biological variation. However, the current training 'dogma' is for fixed rest periods to be programmed between sets of heavy weightlifting (13, 20, 24, 158-161).

2. 4 EXERCISE REGULATION (PACING)

2.4.1 Early work

The ability to maintain performance while undertaking repeated bouts of high intensity exercise, which would be expected to lead to cumulative fatigue and a worsening performance, might be explained by recent research investigating exercise regulation or pacing (2, 141, 147). When considering athlete performance, it is important to not only understand how energy resources are used and replenished but also the distribution of the effort during exercise which then allows the athlete to complete the activity. As outlined earlier, early studies attempted to identify physiological parameters that might cause a reduction in exercise performance; however, over the last 25 years a growing number of researchers have begun to focus on parameters which might regulate exercise performance (147). Some of these researchers have attempted to understand how pacing can impact exercise performance and the underlying psycho-biological mechanisms which might achieve the desired performance outcome without fatigue interfering unduly with the completion of the exercise. Early research (37, 54, 55) in this field considered which pacing strategies were most likely to optimise athlete performance in high intensity sprint activities. These studies found that the type of pacing strategy used was dependent upon the length of the physical activity and the environment in which it was performed. A clear distinction in pacing strategy was observed between short, middle or long-distance competitive events. Researchers agreed that different pacing strategies were being employed by athletes across different sports and events in an attempt to regulate performance by balancing metabolite accumulation and the depletion energy substrates to minimise performance decline.

A number of different pacing strategies have been observed in various sporting competition as a result of physiological and psychological stresses placed on the athlete (141). Particular sports seem to have well established pacing strategies for optimal performance (141). An “all out” pacing strategy has been observed in short duration events of less than 1 min which require maximal work rates from start to finish, leading to the athlete rapidly fatiguing. This type of strategy is often seen in short duration sprint type events where approximately 50 to 60% of the event is spent accelerating the body from a resting state. As a result, a negative split is often seen due to a proportionally greater time spent accelerating to top speed compared to the time spent at terminal speed before gradual deceleration (2, 37, 141, 150). Positive pacing requires the athlete to start at a relatively fast pace, but less than maximally (unlike the all-out strategy) before their speed declines throughout the event. This is a commonly used strategy in short events lasting longer than 40 s or in events lasting longer than 2 h (2, 60, 128, 141, 142). In short events lasting more than 40 s, positive pacing is seen as a more appropriate strategy than the all-out strategy due to the reduced importance for achieving maximal starting speeds, the need for energy regulation across the duration of the event and the impact of aerodynamic and hydrodynamic resistance on energy requirements (141).

In contrast to a positive pacing strategy, a negative pacing strategy is one in which the athlete increases speed over the duration of the event. This pacing strategy is often employed in middle and long distance events (2, 141) due to reduced energy utilisation, lower oxygen consumption and reduced accumulation of metabolites early in the event (1, 2, 98). The increase in speed towards the end of the event is thought to coincide with athletes becoming aware of the end point and increasing motor unit recruitment and their anaerobic reserve (2). Even pacing strategies have been observed in prolonged locomotive type events upwards of 2 min in duration (2, 37, 141, 142). This pacing strategy has been shown to avoid unnecessary accelerations and decelerations which allows the athlete to avoid variations in kinetic energy expenditure, thus allowing for better distribution of energy across the event (141).

Parabolic pacing is a strategy whereby an athlete starts the event fast then reduces their speed during the middle of the event before increasing their speed towards the finish. This distribution of work throughout the course of the event commonly results in a U, J or reverse-J shaped pacing pattern (2, 141). This strategy has been observed in rowing and cycling events with a distinctive increase in power output or speed seen in the final stages of an event, termed the “end spurt” (53, 60). Parabolic pacing requires the athlete to access their anaerobic capacity in the early and late stages of an event. In this case, if there is an over reliance of the finite anaerobic capacity in the early stages of the event, then the end spurt may be compromised due to a reduced anaerobic energy capacity being available in the latter stages of the event. A final pacing strategy known to be employed by athletes in competition is a variable pacing strategy (2, 141). Athletes rarely compete in a sterile environment without competing factors influencing their approach to competition. In the real world of competitive sport, an athlete will face a multitude of external factors, including environmental conditions, topography, and other competitors (2, 53, 141). Variable pacing can be described as a method which allows athletes to manage fluctuations in exercise intensity or work rate *(p*ower output) (2). Such fluctuations are thought to be an attempt to maintain a near constant distribution of pace/velocity in response to external factors (2, 141). The previous section is not an exhaustive review of the different pacing models. The reader is referred to Thompson (141) and Abbiss and Laursen (2) for an in-depth analysis and review of the scientific literature related to pacing.

2.4.2 Models explaining exercise regulation (pacing)

Early pioneering studies investigating pacing postulated that knowledge of the event distance would influence the pacing strategy employed. Ulmer (149), suggested that for an optimal adjustment of metabolic rate during heavy exercise, a feedback control system within the body is required to distribute energy resources to complete the task. This system would collate afferent feedback, whereby information would be interpreted in the brain and sent back to the periphery via efferent pathways to optimise the utilisation of energetic resources. Ulmer (149) stated that for this to occur the athlete needed to have had prior experience of the course or knowledge of the end point to allow them to anticipate and construct a pacing template for that event. This concept was termed Teleoanticipation (149).

More recent research has considered the theoretical basis for how the body organises its available energy resources. The Central Governor Model (106, 133) theorised that an athlete will continuously regulate intensity throughout the course of an activity in order to prevent premature fatigue, taking into consideration sensory feedback and an understanding of the quantity of work remaining. The 'governor', considered likely to be the brain, would subconsciously regulate the ability of the body to avoid the over-recruitment of physical resources during exercise, circumventing physiological trials under which oxygen delivery to vital organs might be sufficiently reduced to threaten whole body homeostasis (106, 108, 110). Noakes et al. (111), presented their idea based on research first proposed by Hill et al. (78) who suggested a controller somewhere in the body regulated the delivery of oxygen to the heart in response to afferent feedback from chemoreceptors. As a response to this feedback, the controller would send signals via the nervous system to reduce muscle fibre recruitment in the heart, lowering cardiac output and subsequently the exercise intensity. Noakes et al.(110) expanded on this idea to state the central governor acts via the motor cortex to reduce efferent neural activation of the exercising muscles (central motor drive), thereby reducing the mass of muscle being recruited and thus the exercise intensity. This in turn would limit the possibility of hypoxia in any of the vital organs (110). Furthermore, Noakes suggested that fatigue is a sensation that results from an anticipatory response to the conscious perception and interpretation of subconscious regulatory processes of the brain. As a result, this regulation aims to preserve homeostasis of all physiological systems throughout exercise regardless of intensity, duration or environmental conditions (105, 106).

Marcora (94) proposed that perception of effort was primarily responsible for the conscious regulation of pace. Termed the Psychobiological Model, Marcora (94) theorised that conscious decision making is responsible for the regulation of intensity throughout an event. Marcora (93) challenged the idea that afferent feedback mechanisms were responsible for ratings of prceived exertion (RPE). He proposed that sense of effort is centrally generated and forwarded via neural signals termed corollary discharges from motor to sensory areas of the cerebral cortex. Expanding on the theory of conscious awareness of fatigue, Marcora et al. (96) investigated mental fatigues effect on physical performance. The results indicated that after completing a demanding cognitive task, a subject's time to exhaustion was significantly reduced while physiological responses remained largely unaffected. Additionally, mentally fatigued subjects rated their perception of effort significantly higher during exercise and reached their maximal perceived exertion and disengaged from the physical task earlier than the control group (96). More recently Martin et al (97), assessed the impact mental fatigue had on anaerobic performance tasks. These researchers assessed the effect of a 90 min computer based demanding cognitive task on counter movement jump (CMJ), isometric leg extension, and 3 min all-out cycling performance. They found that performance was not significantly different in the mentally fatigued group compared to the control group, despite a (non-significant) tendency for RPE to be greater and intrinsic motivator measures to be reduced in the mentally fatigued subjects. The researchers suggested that peripheral mechanisms predominantly regulate anaerobic performance but that mental fatigue might have a greater (negative) effect on submaximal exercise performance.

Pageaux (113) has recently postulated that the conscious regulation of pace is determined via five different cognitive/motivational factors: perception of effort, potential motivation, knowledge of distance/time to cover, knowledge of the distance/time remaining, and previous experience/memory of perception of effort during exercise of varying intensity and duration Pageaux explained that this model was an effort based decision-making model, which would take into account these five factors during self-paced endurance performance. When defining the perception of effort, Pageaux referred to the conscious sensation of how 'hard, heavy, and strenuous' a task was and this formed a key feature of pacing based on the effort perceived by the athlete. Furthermore, it was indicated that perception of effort would be increased by muscle and mental fatigue, or could be reduced by pharmacological manipulation (113).

The Decision Making Theory Model is a combination of the Central Governor Model and the Psychobiological Model. The Decision Making Theory Model proposes that a conscious, rather than an subconscious, 'governor' regulates performance through continuous decision-making based on sensory and perceptual feedback both before and during the exercise activity (121). Renfree et al. (121) proposed a model focusing on decision-making and situational factors relating to competitive events within the context of decision-making during self-paced activity. The researchers postulated the concept of rational decision making and heuristic decision-making models. In relation to the rational model and pacing, the researchers state that feedback from the periphery provides information in relation to energetic cost and the current physical state or work rate. It is this knowledge which informs a pacing algorithm to determine the potential threat of physical harm. A decision is then made to increase, reduce or maintain the efferent neural drive based on the perceived benefits to be obtained from each option. The researchers imply that the individual would be more likely to experience a higher degree of physiological disruption if the perceived 'payoff' is high. Heuristic principles of decision-making involve decisions being made on the basis of incomplete available information whereby the outcome of an action cannot be accurately calculated with confidence, such as during athletic competition. The researchers highlight that Rate of Perceived Effort (RPE) represents an integration of all signals, perceptions and experiences and is suggested to be the primary regulator of work (145). They state a conscious RPE template is constantly compared with a subconscious RPE template throughout exercise and if the conscious RPE exceeds the subconscious RPE template then the central motor drive to the muscles is reduced, while the opposite is true if the subconscious RPE template is greater than the conscious RPE. This model posits around the concept of the conscious RPE being an interpretation of afferent information gathered from peripheral systems. The template is set in advance of the activity to ensure maximal tolerable levels of RPE are not achieved prior to reaching the endpoint of the activity. With respect to regulation of performance, the researchers explain decision-making is often 'herd-like' with respect to competitive endurance events, with competitor's decisions often influenced by those of their rivals. When this is the case, individuals can become less responsive to their internal information relating to their own physiological status. As a result, competitors make poor decisions regarding pacing strategies leading them to underperform while those likely to perform well in these situations are those who are less influenced by rivals and make decisions based on knowledge of their own physiological capacity (121).

Edwards and Polman (45)provide a different opinion on pacing strategies, describing pacing as the "goal directed distribution and management of effort across the duration of an exercise bout". They proposed a Pacing Awareness Model, whereby rather than a central governor located in the subconscious brain (106, 108) or the complete conscious control of exercise regulation (95), the brain as a whole operates on varying levels of awareness. This would mean that minor homeostatic challenges require minimal conscious awareness and it is only when homeostatic disturbances reach a certain threshold that the person becomes consciously aware of the need to up-regulate their physiological input. Edwards and Polman (46) suggested that performance is often limited by voluntary behaviour or effort rather than by athletes running to the point of exhaustion. Furthermore, they indicated that it is unlikely cessation of exercise is due to the depletion of energy, excessive build-up of metabolic by-products, or other examples of system failure. They propose that afferent feedback from the periphery is fed via the thalamus to the sensory cortex of the brain where this input is monitored and processed. This information, along with historical data based on the prior experience, knowledge of the exercise or event and previous sensory feedback, determines a template whereby the athlete can make an appropriate decision to alter their behaviour.

2.4.3 Pacing during high-intensity exercise

Thomas et al. (139), have shown that longer exercise trials are increasingly influenced by central fatigue, whereas shorter high-intensity trials display greater peripheral fatigue, as would occur during heavy strength training. The researchers assessed thirteen experienced cyclists across three different time trial distances, consisting of 4, 20 and 40 km respectively. Subjects' twitch response from the knee extensors was assessed pre- and post-time trial, along with electrical stimulation of the femoral nerve and transcranial magnetic stimulation of the motor cortex to assess neuromuscular and corticospinal function. Their results indicated that the 4 km time trial resulted in greater peripheral fatigue as evidenced by a 40% reduction in potentiated twitch response compared to 31% and 29% reductions for the 20 km and 40 km respectively. In contrast, central fatigue was more evident in the longer time trials where greater reductions in voluntary activation of the motor nerve were found; 11% and 10% for the 20 km and 40 km time trials respectively compared to 7% for the 4 km. Cortical stimulation showed similar reductions of 12% and 10% for 20 km and 40 km trials respectively compared to 6% for 4 km trial. These results are in opposition to those of Tucker and Noakes (147) and support the theory that there is a level of reciprocity between peripheral and central fatigue.

In recent years, researchers have begun to investigate how pacing influences high-intensity exercise such as sprint and strength type activities (23, 74). Billaut et al. (23), investigated the effect of prior knowledge of sprint number on mechanical work, surface EMG and RPE during repeat cycling sprints. This study involved the participants undertaking a control trial consisting of ten 6 s sprint efforts with 24 s of rest between efforts. A deception trial was then conducted whereby participants were informed they would only undertake 5 sprint efforts; however, upon completion of these they were then informed that they needed to complete a further 5 sprint efforts. Finally, participants were instructed to carry out an unknown number of sprint efforts without being informed how many they needed to perform in total and they were then stopped after the tenth effort. Their results showed the initial 5 efforts during the deception trial to be significantly greater in terms of initial and accumulated work and EMG activity than the corresponding sprint efforts in the control and unknown trials. Additionally, EMG activity and work done were significantly lower in the 'unknown' trial compared to the other trials. The researchers concluded that pacing had occurred during all-out sprint activities which would have practical implications for repeat sprint testing involving five or more efforts.

To counter this assertion, Hureau et al. (79-81) conducted studies which indicate the likelihood of a pacing strategy may be limited during repeated maximal sprint efforts due to the requirement of peak muscle activation. Hureau et al. (81) conducted a study which looked to circumvent confounding effects associated with the option to voluntarily change power output or cease the event, such as when completing time trial or constant workload events, while assessing the influence pre-existing quadriceps fatigue had on exercise performance and cycling EMG prior to maximal sprint efforts. Using a neuromuscular electrical stimulation (NMES) to pre-fatigue the quadriceps muscle, the investigators had subjects completed 10 repetitions of 10 s on two occasions in an un-fatigued state (Control) and 10 repetitions of 10 s following induced NMES fatigue. The results revealed that although there were significant differences in quadriceps fatigue, power output and cycling EMG between the control and pre-fatigue conditions, exercise induced locomotor muscle fatigue at the termination of exercise was identical. The researchers theorised that power output was adjusted to limit the development of peripheral fatigue to a critical threshold dependant of pre-existing levels of fatigue. Following on from this study, Hureau et al. conducted a similar study whereby they investigated the development and recovery of peripheral and central fatigue during repeated cycling sprints and its influence of power output. Subjects completed 1, 4, 6, 8 and 10 sets of 10 s cycle sprints with 30 s of passive recovery between efforts as well as 8, 10 s sprints with 10 s passive recovery. Peripheral and central fatigue as assessed through pre and post-exercise potentiated quadriceps twitch force along with quadriceps voluntary activation along with power output. The results revealed that significant reductions in all assessment indices were noted from sprints 1 to 6, before a plateauing for the remaining efforts. Researchers assessed that the reduction in passive recovery led to a significant reduction in power output and EMG amplitude, but no change in peripheral or central fatigue. This led the researchers to hypothesise that central motor command and power output during all out repeated sprints are limited to prevent excessive locomotor muscle fatigue, while both peripheral and central fatigue contribute significantly to the decline in power output elicited by repeated sprints.

Halperin et al. (74), conducted a similar study to that of Billaut et al. measuring maximal voluntary muscle contractions (MVC) of the biceps brachii muscle during three different protocols. As with the previous study, the researcher investigated the effects of previous knowledge of the number of repetitions to be completed on force production and EMG output with participants completing control, deception, and unknown trials. In the unknown trial participants were not told the number of repetitions to be performed and were stopped after 12 repetitions. During the deception trial, participants were told to complete 6 repetitions before being told to complete a further six. As with the previous study, results showed greater forces during the deception trial for the first six efforts.In all trials, the last repetition of the participants was more powerful in comparison with the previous repetition. The authors suggested that both the increased force production in the initial six repetitions of the deception trial and the increased force production in the final repetition compared to the previous repetition in all of the trials, was an indication that pacing occurred during high-intensity, short-duration exercise (74). The results of these studies (Thomas et al. (139), Billaut et al. (23) and Halperin et al. (74)) would suggest that athletes might regulate high-intensity exercise to primarily manage the deleterious effect of peripheral fatigue rather than central fatigue.

It would seem that an all-out pacing strategy would be best suited during high intensity activities such as sprinting and strength activities (141). As previously mentioned (23, 74) subjects with a prior knowledge of the number of repetitions to follow produce higher force outputs when compared to a deception trail or unknown trial (23, 74). During heavy strength training, individual sets comprised of numerous repetitions are completed in an all-out pacing fashion. Unlike locomotive type activities the training stimulus during heavy strength training is the constant external resistance the individual must work against rather than the distance or time in which the individual has to complete the activity, therefore offering the individual a conscious decision to as to increase force output to complete the task in a shorter timeframe. It is therefore plausible that exercise regulation during high intensity exercise such as sprinting and heavy strength training may be more suited to the ability of an individual to regulate energetic resources between sets of high intensity activity rather than the individual repetitions themselves. However, to the author's knowledge there have been no specific studies investigating the regulation of rest periods in strength training to date.

2.4.4 Self-selecting rest or "pacing" the rest period

Research has begun to investigate self-selected rest periods during sprinting and strength training (39, 67, 68). These studies suggest that athletes with appropriate experience are able to self-regulate their rest periods to maintain performance when compared to traditionally imposed rest periods. Glaister et al. (67), investigated the effect that self-selected recovery had on multiple sprint exercise and to determine if a self-selected recovery duration was a reliable means of quantifying an individual's ability to resist fatigue during this type of exercise. This study had subjects perform four trials consisting of twelve 30 m sprints, whereby familiarisation effects noted across the first two trials were utilised as a familiarisation while trials three and four were used for the purpose of reliability. Subjects were instructed to allow sufficient recovery between efforts to enable the maintenance of sprint performance throughout each trial. The results indicated subjects were able to maintain performance across trials when utilising self- selected recovery times. Mean self-selected recovery times between trials tended not to differ significantly, with recovery times for each trial being 73.9 ± 24.7, 82.3 ± 23.8, 77.6 ± 19.1, 77.5 ± 13.9 s respectively. The researchers deemed the variability in recovery times between trial one and two to be evidence of learning effects as such, reliability was assessed between trials three and four. These results indicated a good level of reliability between trials with a coefficient of variation (CV) of 11.1% and an intra-class correlation coefficient (ICC) of 0.76. Additionally, the RPE was assessed after every third sprint effort and was shown to significantly increase across efforts. The researchers suggested that this was evidence that subjects regulated their recovery time based on the knowledge of the number of sprints that needed to be performed (they regulated their exercise), despite the subjects being instructed to give themselves sufficient recovery to maintain performance.

Goessler et al. (68), compared how self-selected, one min and two min rest periods affected the number of repetitions performed during bench press, guided bar squat, bicep curl and leg extension exercises at 75% of each subject's one repetition maximum (1RM). They found that during the self-selected rest intervals, the subjects rested for an average of 157 ± 37 s which was not significantly different to the two min rest interval but was significantly longer than the one min rest period. The mean number of repetitions for the exercises did not differ between the self-selected and two min rest periods but were significantly fewer for the one min rest interval. An additional aspect of this study was to assess the cardiovascular behaviour after resistance exercise. The researchers concluded that self-selected rest conferred a similar level of recovery to the two min rest periods, likely due to the completion of similar training loads.

Expanding on this research, De Salles et al. (39) directly compared upper and lower body resistance training exercises consisting of squat, leg press, bench press, and bicep curl exercises when using a two min and self-selected rest period between sets utilising 75% of subjects 1RM. Similar to the results of Goessler, they found that there was no significant difference between the total number of repetitions performed between trials. It was noted that during the self-selected intervals, subjects spent less time recovering than in the two min fixed rest period, indicating a potential for self-selected rest intervals to offer a more time efficient training strategy. A finding of this study was the differences in performance behaviour in smaller and larger muscle groups. A greater decline in repetitions was observed in the smaller upper body exercises compared to the larger muscle groups of the lower body during both rest conditions. These findings highlight the potential for self-selected recovery to affect strength training differently across different muscle groups. Finally, the researchers argued that previous conditioning might reduce the requirement for longer rest periods (161). They also suggested that prior training experience may confer an ability for the individual to shorten their self-selected rest period based on various performance enhancing psycho-biological adaptations

(39). Collectively, these studies indicate that appropriately experienced athletes may possess the ability to regulate their rest periods when conducting sprint and strength activities to allow for a non – significant reduction in performance.

2.5 CONCLUSION

There is a growing body of research investigating the effects of pacing in a variety of locomotive type activities (12, 60, 61, 102, 122, 128, 140, 146). The purposes of these studies have been twofold with early studies aiming to investigate the theoretical basis of exercise regulation and its effect on fatigue while more recent studies utilised this early work to analyse athletic performance and the use of pacing strategies in events of different distances and durations. This growing knowledge base is now beginning to be used to influence training methodology, program design and planning event strategy (141). However, research into exercise regulation is inherently complex due to the psycho-biological nature of pacing and a number of control models have been proposed. Recently, researchers have begun to look at the how individuals self-regulate performance in intermittent activities high intensity activities (39, 67, 68). However, research assessing if strength trained athletes can better maintain performance when allowed to regulate *(p*ace) their training by self-selecting their rest periods between sets has not been conducted to date. Rather, strength trained athletes are generally prescribed fixed duration rest periods based on an understanding of peripheral fatigue rather than psycho-biological models of exercise regulation.

CHAPTER 3: HOW DO EXPERIENCED STRENGTH TRAINERS REGULATE THEIR REST PERIODS DURING HEAVY STRENGTH TRAINING?

3.1 ABSTRACT

The aim of this study was to investigate the consistency of strength-trained athletes in regulating self-selected rest periods between sets of heavy squat training in order to maintain performance. Sixteen highly strength-trained male athletes (mean age = 22.8 ± 3.1 a) completed a familiarisation trial followed by two 'experimental' trials 48 h apart. The experimental trials consisted of five sets of 5RM squats interspersed with self-selected rest periods. An optical encoder (Gymaware) collected kinetic data for each squat and temporal data for each inter-set rest period. Subjective measures of readiness to lift (RTL) and rating of perceived effort (RPE) and were taken before and after each set. Mean total rest time between the trials differed significantly *(p* < 0.01, 95% CI = -61.66; 10.04). Irrespective of trial, rest increased after sets 3 (95% CI = 25.78; 98.43) and 4 (95% CI = 49.02; 122.34) compared to set 1. Mean power output was lower in trial 2 compared to trial 1 *(p* < 0.05 850 ± 133 W; SS2 831 ± 110 W). Regardless of trial, power output decreased between sets 3 (95%CI=-83; -17), 4 (95% CI = -101; -35) and 5 (95% CI = -96; -29) compared to set 1. Within participant test re-test reliability between trials demonstrated fair reliability for both rest interval and power output (mean ICC = 0.55, CI = 0.24; 0.76). RPE increased significantly in set 3 (95% CI = 0.68; 1.51), 4 (95% CI = 0.86; 1.70) and 5 (95% CI = 1.35; 2.19) compared to set 1 (*p* = <0.001). While RTL showed a significant decrease from set 3 (95% CI = -1.68; -0.58), 4 (95% CI = -2.43; -1.32) and 5 (95% CI = -2.99; -1.88) compared to set 1 (*p* = <0.001). RPE and RTL demonstrated good and excellent reliability between trials (mean ICC = 0.63 and 0.80) respectively. In conclusion, highly trained strength-athletes demonstrated comparable profile between set kinetic performance and subjective responses on different days. However; a significant difference between trial power

output and inter-set rest period was found between trials, suggesting rest periods were regulated to maintain performance in response to inter-daily biological variation.

3.2 INTRODUCTION

Strength training is a commonly utilised training method to enhance physical qualities in many sporting endeavours. Exercise programming for the development of maximal strength involves the manipulation of various acute training variables in order to provide a stimulus for physical adaptations to occur. The duration of the rest period between sets is one of those variables. The length of the rest period will influence the degree of substrate replenishment, recovery of neuromuscular function, and psychological state of an athlete, and if insufficient can adversely affect the ability to maintain performance across the set and even lead to an inability to complete the assigned repetitions (3).

Recommendations based on research studies have varied widely with regard to the duration of the rest period required to maintain performance between sets which are designed to develop maximal strength, with suggested rest periods ranging from 2 to 8 min (24, 159). Rest periods upwards of 3 min have been suggested to replenish energy substrates and diminish metabolite accumulation (20, 24, 154, 160). In practice, rest periods of 3 to 5 min between heavy training sets are frequently prescribed by strength coaches (20, 85, 158). However, it is possible that rigidly imposing rest periods which are not long enough may not allow for appropriate recovery for strength performance in some athletes and that allowing the individual to self-select their rest periods between sets based on their subjective feelings of recovery might be more effective. To date, there is a lack of research investigating the variability and efficacy of self-selected rest periods during strength training. Glaister et al. (67) studied the ability of physically active students to reliably self-select recovery periods between 30 m sprint efforts.

They found that, after participants became familiar with the task, they were able to maintain sprint performance by self-regulating the rest taken between sprint efforts.

It is plausible that a strength training session, which allows for the self-selection of rest periods between sets, could enable participants to consistently maintain their power output across the session. This is an important consideration for the strength coach as it allows for training performance to be quantified progressed in a manageable fashion. Yet to the author's knowledge, no studies have investigated the regulation of rest periods during training sets with loads designed to improve strength performance in a highly trained cohort. De Salles et al. (39) compared the effect of imposing a 3 min rest period with a self-selected rest period when participants lifted a 75% 1 Repetition Maximum (1RM) load to volitional cessation. Participants were either assigned to a 'lower body group' consisting of squat and leg press exercises, or to an 'upper body group' consisting of bench press and bicep curl exercises. They found no significant difference in the number of repetitions completed in the two groups for either trial. Goessler and Polito (68) compared the effect of imposing 1 min of recovery and 2 min of recovery with self-selected rest periods, while participants completed squat, leg press, bench press and bicep curl exercises using loads set at 75% of 1RM. Similar to De Salles et al. (39), they found no significant difference in the number of repetitions completed between the imposed and self-selected rest trials. However, these findings were based on loads known to elucidate muscle hypertrophy and might not be applicable to heavier training loads intended to elicit improvements in strength (114, 115, 123).

The aim of this study was to investigate the consistency of strength-trained athletes in regulating self-selected rest periods between sets of heavy squat training in order to maintain performance.

3.3 METHODS

3.3.1 Participants

Sixteen male athletes (age = 22.8 ± 3.1 a; body mass = 96.8 ± 15.5 kg; height = 179.4 ± 5.4 cm) volunteered for this study. All participants were members of a Super 15 Rugby Union franchise elite player development academy program and had participated in competitive club Rugby for an average of 10.3 ± 4.1 a. All participants reported undertaking structured, supervised resistance training under the direction of a strength coach for an average of 4.2 ± 1.9 a. All participants gave their written, informed consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and approved by the University of Canberra Human Research Ethics Committee.

3.3.2 Study Design

Participants completed an assessment of 5RM back squat strength assessment to determine the load to be used during each experimental trial. Concentric mean power was assessed via an optical encoder (Gymaware) with no data smoothing or filtering, utilising methods described in other studies (43, 138). Gymaware uses variable rate sampling with level crossing detection to capture data points and then limits this to a maximum of 50 data points per s (50 Hz). Subjective RTL scores, based on a visual analogue scale (148) were measured to assess participants' perceived readiness immediately prior to commencing each set. The Visual analogue scale was anchored with "Not Ready to Lift maximally/ Not Very Fatigued" at one end and "Ready to Lift maximally/Not Fatigued" at the other. RPE utilising Borg's CR 10 Scale was utilised to assess participants' perceived exertion immediately at the end of each set (28).

Each participant performed a series of five repetition back squats sets, during which load was incrementally increased until voluntary failure. Starting loads were set at approximately 75% of each participant's 1RM score, which was provided by the parent sporting organisation. Participants were advised to rest as long as they needed to perform each subsequent set attempt. A squat attempt was deemed successful when the participant lowered the body from an erect standing position with hips and knees fully extended in a continuous fashion until the thigh had reached a position below parallel with the ground and then returned to a standing position in as forceful a manner as possible. The 5RM score was defined as the load last lifted successfully for five repetitions prior to the set in which failure occurred.

Each participant completed four data collection sessions over a period of two weeks; each training session was separated by a minimum of 48 hrs rest. These consisted of a 5RM repetition, based on 5RM testing of each athlete, a familiarisation trial and two experimental trials with self-selected inter-set rest periods. Athlete availability prevented an additional familiarisation trial. The familiarisation and experimental trials involved participants conducting 5 sets of 5RM back squats at their individually prescribed 5RM load. With the exception of one participant who did not complete all five sets in one of the self-selected training trials, participants completed all sets in all training trials.

Throughout the duration of the study, participants did not undertake any additional strength training but conducted rugby specific skills-based training twice per week.

3.3.3 Test Procedure

After completing a standardised warm-up procedure under the direction of the researcher, consisting of cycling and body weight activities specific to the joints and muscles involved in the following trials, participants were then given time to conduct individually preferred warm-up activities. After the warm-up, participants completed two back squat sets of five repetitions at 80% and 90% of each participant's 5RM. Participants then rested until they informed the researcher that they felt ready to commence the training trial. No guidance or indications were given regarding the length of rest between the warm-up and training trial. Prior to beginning the first set and following each set of the experimental trials (SS), participants were instructed to "choose a rest period you feel will allow you to complete a maximal effort during your next set".

When ready to lift, participants un-racked the bar and positioned themselves on a marked starting position. After assessing that the participant was in a stable position, the researcher indicated for the participant to begin. On completion of a successful set the participant steadied themselves in a standing position and waited for the researcher to stop the measurements and re-racked the bar. Participants then rested passively until they felt ready to commence the next set. The rest between sets was assessed as the period between when the researcher stopped and started the measuring device. Immediately prior to commencing each set, participants indicated their RTL score and at the end of each set they indicated their RPE score.

At all times participants were blinded to any external timing devices, to avoid bias based on previous training experiences and to require participants to regulate themselves based on subjective feelings of recovery.

3.3.4 Statistical analysis

Descriptive statistics are presented as mean ± SD unless otherwise stated. All data were analysed with a general linear mixed model using the R package lme4 (17, 119) to identify if any interactions of main effects were evident between individual sets and Trails and interactions between them. ICC were calculated using the R statistical software (R Core Team, 2016) with the package irr (58). A two-way random effects model was used to compute inter-rater agreement between trials. An ICC estimate of 1 indicated perfect agreement, with 0 indicating random agreement which relates to results due to chance (73), and anything negative indicating systemic disagreement which tends to encourage type 1 errors (87). Estimates for positive ICC's were defined as; less than .40 = poor, .40 - .59 = fair, .60 – 74 = good and .75 – 1 = excellent (73).

3.4 RESULTS

The mean rest period duration for experimental trials was 283 ± 101 s for self-selected trail 1 (SS1) and 249 ± 76 s for self-selected trial 2 (SS2) (Figure 1). The average rest time between trials was significantly shorter in SS2 compared to SS1 (p < 0.01, 95% CI = -61.66;10.04). Irrespective of trial, the rest period increased significantly (p < 0.001) after sets 3 (95% CI = 25.75; 98.43) and 4 (95% CI = 49.02; 122.34) compared to set 1 (Fig 1).

A significant difference (p=<0.05) was observed for trial mean power output (SS1 850 ± 133 W; SS2 831 ± 110 W). Irrespective of trial, mean power output for set 3 (95% CI = -83; -17), 4 (95% CI = -101; -35) and 5 (95% CI = -96; -29) was significantly lower compared to set 1 (p=<0.001) (Fig 1).

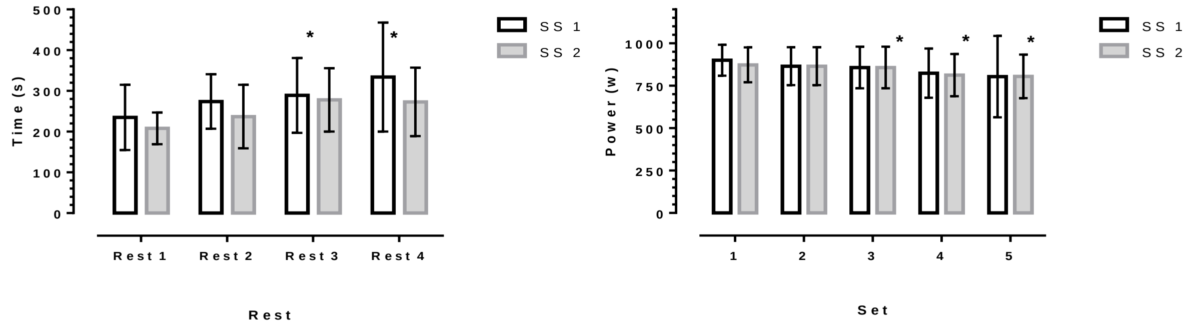

Figure 1. Mean self-selected rest periods and Mean Power Output (MPO) per set between self-selected 1 (SS1) and self-selected 2 experimental trials. Values are mean ± SD. * denotes a significant difference compared to Rest 1 and Set 1 respectively.

The participant (see Fig 2.) who failed to complete the final set in SS1 was shown to have started with a greater power output in set 1 and a shorter rest period prior to set 2 in SS1 than in SS2. This participant displayed the lowest 5RM strength score out of the subjects, and anecdotally stated that he had rarely participated in this type of strength training. It would appear that a lack of experience of similar training protocols might have impacted on this participant's ability to self-regulate due to a lack of prior experience. The importance of prior experience in order to pace successfully during demanding exercise is widely understood (149). Glaisiter et al.(65), have previously reported that experienced participants were able to consistently perform multiple sprint efforts when utilising self-selected rest intervals.

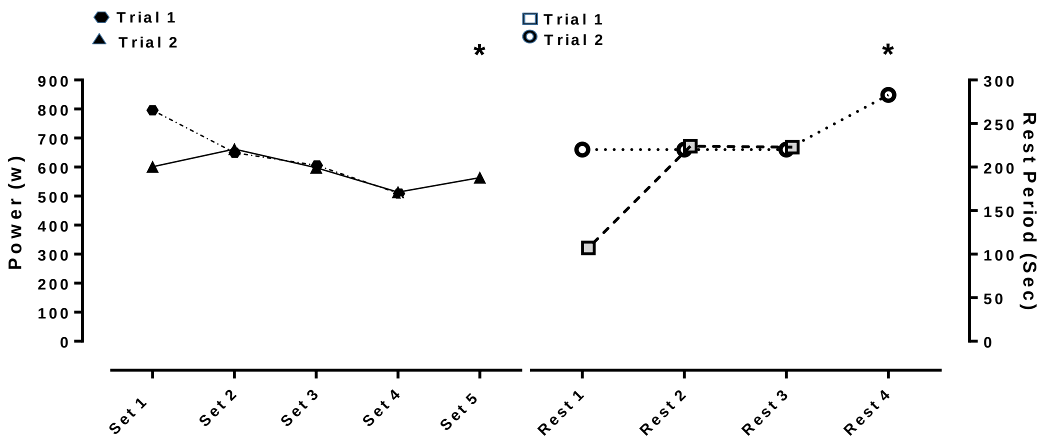

Figure 2. Mean raw power output and self-selected (left) rest periods (right) between Trial 1 and Trial 2 for the participant who failed to complete all sets in Trial 1. * denotes missing data point due to failure to complete set 5 in self-selected 1 trial.

Mean RPE scores across sets were 7 ± 1 for both SS1 and SS2. No significant difference was found between trials for RPE (95% CI = -0.47; 0.06). Irrespective of trial, RPE increased significantly in set 3 (95% CI = 0.68; 1.51), 4 (95% CI = 0.86; 1.70) and 5 (95% CI = 1.35; 2.19) compared to set 1 ($p < 0.001$).

Mean RTL scores across sets were 7.1 ± 1.3 and 7.2 ± 0.8 for SS1 and SS2 respectively. No significant difference was observed between trials (95% CI = -0.29; 0.41). Irrespective of trial, RTL decreased significantly in set 3 (95% CI = -1.68; -0.58), 4 (95% CI = -2.43; -1.32) and 5 (95% CI = -2.99; -1.88) compared to set 1 ($p < 0.001$). Group RPE and RTL scores are presented in Table 1.

Table 1. Group rate of perceived effort (RPE) and readiness to lift (RTL) scores between and within experimental trials.* 1 Participant did not complete set 5 in self-selected 1 (SS1) trial and therefore no RPE was recorded

	Trial 1					Trial 2				
	Set 1	Set 2	Set 3	Set 4	Set 5	Set 1	Set 2	Set 3	Set 4	Set 5
mean RPE	6	6	7	8	8*	6	7	7	7	8
mean RTL	8.5	8.0	7.3	6.4	5.7*	8.2	7.8	7.2	6.6	6.3

Test-retest reliability scores between trials for rest period, power output, RPE and RTL for SS1 and SS2 (n = 16) are presented in Table 2. Results for rest period and power were rated as fair respectively indicate (ICC = 0.55). RPE reliability was rated as good (ICC = 0.63), while RTL was rated as excellent (ICC = 0.80).

Table 2. Reliability (intraclass correlation co-efficient (ICC)) scores between experimental trials for rest period, power output, rate of perceived effort (RPE) and readiness to lift (RTL).

n = number of positive or negative results for each variable

	Mean positive ICC results	Range mean positive ICC results		n positive ICC results	n negative ICC results
rest period	0.55	0.09	0.99	11	5
power output	0.55	0.03	0.87	16	-
RPE	0.63	0.1	0.88	14	2
RTL	0.8	0.26	0.98	12	4

3.5 DISCUSSION

The primary purpose of the study was to investigate the consistency of experienced strength-trained athletes in regulating their rest periods between sets of heavy strength training when afforded the opportunity to do so. Within trial, participants were observed to lengthen their rest periods from set 3 to 5. This trend was observed for all but one participant. However, it appears that this strategy was insufficient to maintain participants' kinetic performance as set mean power output was found to decrease in sets 3, 4 and 5 compared to set 1. This would suggest that participants experienced sufficient fatigue to be unable to maintain their set 1 performance despite increasing their inter-set rest period, although as performance was similar between sets 2 to 5 then fatigue does not appear to have worsened after set 1. This would suggest that lengthening the rest interval after set 3 provided sufficient recovery for performance to be maintained in sets 2 to 5, albeit below that of set 1. Prior to each set, participants were instructed to "choose a rest period you feel will allow you to complete a maximal effort during your next set". It is possible that had the instruction been worded "maximal performance" or "performance the same as set 1" rather than "maximal effort", participants might have rested longer; however, this is highly speculative as it is common for sports science studies to instruct participants to provide a maximum effort in order to elicit a maximal performance.

Between experimental trials, a significant difference was detected for trial mean rest period with the mean total time rested in SS2 being less than SS1. This suggests that an adjustment in exercise regulation occurred, perhaps due to biological variability, although this could also be attributed to participants further habituating to the test protocol. Trial mean power output also differed, with SS2 exhibiting a reduced trial mean power output compared to SS1. It is plausible that this reduction in power output was due to the reduction in rest time in SS2 compared to SS1. The similarity in the RTL and RPE responses between experimental trials suggests that participants achieved a similar psycho-physiological state during trials despite their being an overall difference in mean trial resting time and kinetic performance, suggesting some degree of homeostatic regulation occurred.

The performance data in the present study is not in agreement with previous, similar studies which observed a maintenance in kinetic performance when participants were able to self-select their rest periods following a single familiarisation trial (39, 67). Set mean power output was not maintained compared to set 1 in either trial, indicating an inability for participants to maintain their performance despite being well versed in strength training at these intensities. Variations in set-to-set mean power outputs were similar between trials with ICC scores demonstrating a fair level of reliability. It is plausible that participants adjusted their rest periods between trials in response to inter-daily biological variation. The increase in rest period after set 2 and changes in RTL and RPE, observed in both trials, would suggest that participants consciously adjusted their rest in response to afferent feedback following sets 1 and 2 to allow for sufficient recovery thereafter, to stave off any further reduction in performance. The gradual increase in RPE and gradually decline of RTL suggests that there was a change in psychological state. The adjustments in rest periods were successful in the sense that all but one of the participants anticipated correctly that they would complete the next set with a similar performance.

To the author's knowledge, no study to date has investigated the adjustment of self-selected rest periods with regard to strength training performance. Two studies (6, 12) did find that similar numbers of repetitions were completed at 75% of 1RM with either a 1 or 2 min inter-set recovery period compared with a self-selected rest period. In these studies, the mean self-selected rest periods between sets, for the back squat exercise used in their protocols, were 102.80 ± 39.20 and 106.67 ± 29.69 s (6) and 152.7 and 148.0 s (12). These are substantially shorter rest periods than were observed in the current study, probably due to the lower relative loading in these studies. Interestingly, although participants in both studies (6, 12) were utilising loads assessed as 75% of the individual's 1RM, the participants in the study by De Salles et al (39) self-selected rest intervals 14 to 18 s less than 2 min, while in contrast the study by Goessler and Polito (68), observed that participants using the same loading parameters self-selected rest periods 28 to 32 s longer than 2 min. The differences in resting periods between these studies, at the same relative loading, demonstrates there is a high degree of variability between participants undertaking strength training protocols.

A high degree of variability in rest periods was also evident in the present study with recovery between the three and five min duration, a rest period often outlined in the strength training literature as optimal for maintaining strength training performance (24, 84, 159, 161). Given the loading parameters of the current study, it would be likely that neuromuscular fatigue had a greater influence on recovery in the present study than the previous mentioned studies (6, 12).

To date, relatively few studies have attempted to assess neural aspects of fatigue during loaded strength training activities. Walker and colleagues (153) aimed to assess neuromuscular fatigue during hypertrophic and maximal strength loading protocols assessed pre, during and post-loading phases. They found that during the maximal strength loading protocol, neural drive to the muscles seemed to have contributed to fatigue, whereas during the hypertrophic protocol several peripheral factors were the likely cause. In a similar study, Cometti et al.(32) had participants complete 6 sets of 10 repetitions of quadriceps isokinetic contractions at 120° per s. Electromyography was used to assess the level of fatigue present after the completion of each set of the protocol. A progressive reduction in maximal contraction velocity, suggestive of neuromuscular fatigue, was observed across sets with significant reductions found after set 3 despite utilising different passive and active recovery modalities during 3 min rest periods between sets. The reduced kinetic performance from set 3, in the present study is therefore likely to be due to neuromuscular fatigue as a result of altered neural drive to the muscle.

A possible cause of the differences in overall rest period duration between trials might be due to the single familiarisation trial completed by participants in the present study. Participant availability did not afford the opportunity to conduct a second familiarisation trial. Glaister et al (67) showed that participants could consistently select recovery periods between sprints efforts after two familiarisation trials. Similarly, Phillips et al (116) found improved reliability in cycling sprints after two preceding trials. It has also been observed that participants undertaking strength training protocols, with no previous experience, require a number of familiarisation trials to produce reliable results (124). Ritti-Dias et al (41) have suggested that even experienced participants might require 2 or 3 familiarisation trials to provide accurate results when assessing maximal strength assessments. Although participants in this study were identified as highly experienced and proficient in strength training, it cannot be presumed that a single familiarisation trial was sufficient to maximise reliability and is a limitation of the study. Indeed, the mean rest period ICC for the experimental trials was only classified as fair.

Another factor influencing the variability in rest periods between experimental trials might have been the requirement for participants to indicate their RTL prior to beginning each set. The instructions provided to participants would have reinforced to them that they should rest for as long as required to ensure they were able to provide a maximum effort. This may have affected their decision to start each set, perhaps even overriding their usual internal bias to conform to familiar resting periods. It was hypothesised that participants would assess their RTL as being completely ready to lift as they could theoretically rest for as long as required. However, participant's actual RTL scores during the experimental suggest that the majority of participants could have rested for longer than they actually did. Despite the best efforts of the researcher to remove all external time pressures, participants presumably felt an intrinsic motivation to commence the next set prior to consciously feeling completely recovered. This could have been due to their habitual training practices and/or the limitation of only one familiarisation trial. An increased level of anticipation and uncertainty due to the unfamiliar rest strategy may also have affected their perception of readiness (72). Additional research in this area is required to explain how athletes psychologically approach repeated sets of strength training. Educating athletes on assessing their recovery between sets may yield important performance outcomes.

3.6 PRACTICAL APPLICATIONS

Rest periods between sets play a vital role in the development of maximal strength. The time spent resting between sets needs to provide sufficient recovery for the maintenance of strength and power throughout the session. The results of this study suggest that while experienced strength-trained athletes can self-select rest periods which allow them to complete all sets of a heavy back squat exercise protocol, they did not rest sufficiently enough early in the trial (sets 1 to3) to maintain their power output during sets 3, 4 and 5 compared to set 1. One participant failed to complete all five sets in the first experimental likely due to a lack of prior exercise and subsequently began SS2 with a more conservative manner/pacing strategy. The trend for RTL to reduce and post-set RPE to increase across sets would suggest that participants should have allowed more recovery time between sets. That said, strength training is both physically and mentally demanding so a cumulative increase in perceived exertion might occur even with a substantially increased rest period of many more min. To conclude, the data suggest that the utilisation of self-selected rest periods provides a viable option for appropriately experienced athletes to complete strength training sets; however, some education and further habituation might be required to ensure that maximal performance is maintained across multiple sets of strength training.

Future research should address the ability of appropriately experienced athletes to regulate their rest between sets of strength training exercise to assess if any pattern exists once sufficient familiarisation has occurred. Research should also focus on investigating how athletes select their rest in response to internal feelings of fatigue on a day-to-day basis and whether they are sufficiently informed on the purpose of rest to appropriately self-select rest periods. A comparison of self-selected rest periods during strength training with the traditional 3 or 5 min fixed recovery periods is also warranted to determine if self-selecting rest periods is potentially more beneficial for performance.

CHAPTER 4: THE EFFECT OF SELF-PACED AND IMPOSED REST STRATEGIES ON KINETIC, NEUROMUSCULAR AND SUBJECTIVE MEASURES DURING HEAVY BACK SQUAT EXERCISE.

4.1 ABSTRACT

A number of pacing theory models have been postulated in relation to the neurological and psycho-physiological regulation of short- and long-term endurance based exercise. During heavy strength training, a 3 or 5 min recovery period is generally imposed between sets of repetitions meaning that strength trained athletes have little if any exposure to self-pacing of rest periods. The purpose of this investigation was to assess the pacing strategies employed by experienced strength trained athletes when afforded the opportunity to self-select rest periods during heavy strength training rather than following an imposed rest period. Sixteen male experienced strength trained athletes aged between 18 and 25 a volunteered to participate in this study. Participants, having first had their 5 repetition maximum (5RM) established, completed four heavy strength training sessions (five sets of 5 repetitions) over a 14 day period with a minimum recovery of 48 h. The study comprised a familiarisation training trial followed by three experimental training trials, each with a different rest period. For the experimental training trials, athletes were able to self-select their rest period (SS) or had the rest period imposed (one 3 min rest period trial (3M) and one 5 min rest period trial (5M)). Linear mixed modelling revealed significant interactions for inter–set rest duration ($F(6, 162) = 2.93$, $p = 0.01$). Self-selected rest periods increased from sets 1 to 3, but remained similar thereafter.. Concentric mean power output showed an interaction between rest trials ($F(4, 1147) = 161.88$, $p < 0.001$), .For the imposed rest period trials, performance across sets 3, 4 and 5 deteriorated when compared to that of set 1. For the self-selected rest period trial, performance across only sets 3 and 4 deteriorated when compared to that of set 1. Surface EMG was similar across all rest trials and sets, suggesting peripheral rather central fatigue being the primary cause of performance decline. Significant interactions for rate of perceived effort (RPE) were evident

between Condition ($p < 0.001$), with the 3M (7.32 ±1.53) trial being significantly higher than both the 5M (6.6 ± 1.95) and SS (6.9 ± 1.89) trials. Additionally, significant interactions for Set ($p < 0.001$), indicated that irrespective of trial RPE increased across sets. A significant main effect for Condition ($p < 0.001$), indicated that participants reported to feel better prepared to lift in the 5M trial compared to the 3M and SS trials respectively. Readiness to lift (RTL) scores declined across all sets in all trials, irrespective of whether the rest period was imposed or self-selected by the participant. Three participants failed to complete all sets in the 3M trial whereas all participants completed all sets in the other trials, indicating that for some athletes three min is insufficient rest between sets of heavy strength training. This data adds to previous research whereby self-paced exercise seemingly provided participants the ability to adopt a resting strategy which attenuates fatigue and enables participants to maintain performance.

4.2 INTRODUCTION

Contemporary interest in pacing began in earnest in the 1990s with Foster et al. (54, 55) and has since expanded with research exploring the central, peripheral and psycho-physiological regulation of exercise. In recent years, a number of exercise regulation models have been proposed such as the teleo-anticipatory theory (133, 149), central governor model (108, 111), perception based model (145), psychobiological model (93, 113), individual critical threshold (10), pacing awareness model (46) ,and the decision-making model (121). In general, these models have been based on studies involving endurance events in cycling, speed skating, and running exercise modalities. Potentially due to the low aerobic component, there has been little attention directed to pacing and exercise regulation of strength-based exercise, even though the failure of muscles to generate force (or power) during repeated sets of strength training might relate to peripheral fatigue, where biochemical changes produce an attenuated response to neural output as well as central fatigue, where a failure of the central nervous system leads to a reduction in central motor drive (165).

Pacing has been defined as the distribution of energy during exercise and is considered optimal when the athlete has used all available energy resources efficiently (2). Pacing strategy has been defined as the achievement of the desired outcome, without fatigue (physical or mental) interfering with the (successful) completion of the task (adapted from Foster et al, p3. (141)). Implied but not specifically mentioned in these definitions are the psychological aspects of pacing. Edwards and Polman (46) have described pacing as the goal directed distribution and management of effort across the duration of an exercise bout. The different emphases expressed in these definitions is evidence that pacing is a complex construct, affected by prior experience, anticipation, knowledge of the end-point of the exercise and sensory feedback during the exercise task.

Strength training generally involves multiple sets of repetitions separate by a rest period. Modification of rest duration will be a component of the pacing strategy as it affords time for partial, or even full, recovery of performance. Sets of repetitions are generally completed as closed-loop events; athletes have time during rest intervals to consider and modify their behaviour for the next set based on sensory neural feedback, knowledge of the work remaining and prior training experience. These aspects form a teleo-anticipatory component (149) preceding the onset of physiological fatigue, influencing how the athlete approaches the next set of repetitions. The approach will be further modified during each rest interval as the sets progress based on afferent feedback and work remaining. During cycling, skating, and running exercise modalities, a reduction in force production often results in only a loss of speed (80, 104, 112). This is very dissimilar to heavy weight training where a reduction in force production can lead to a catastrophic failure with the potential of serious injury. This risk awareness may enter the conscious thought of an athlete and affect their behaviour as they decide whether to attempt another set or even another repetition as fatigue increases. Pacing in strength training is therefore an important consideration to understand.

In many sports the development of maximal strength capacities are highly sought after (14, 15). Recommended recovery durations between sets of heavy resistance training vary markedly with proposed recovery times range between 2 and 8 min (3, 24, 159). During heavy resistance training (131), rest periods between sets are manipulated to ensure that the athlete is considered sufficiently recovered to ensure successful completion of the following set. Resting upwards of 3 min between sets is recommended to limit the development of neuromuscular fatigue, allowing time for the replenishment of metabolic substrates and subsidence of metabolite accumulation (20, 24, 154, 160). Resting upwards of 5 min allows for the replenishment of high energy substrates and the dissipating of waste by-products produced by muscular contraction, supporting completion of a higher number of repetitions (129, 160, 161). Prescribing rest periods shorter than 3 min or greater than 8 min can adversely affect the desired training outcome or the session length. Rest periods of 3 to 5 min are commonly prescribed by strength coaches (20, 85, 158) as a compromise between limiting the development of neuromuscular fatigue and the available time in which training can be conducted. There is no research that assesses the effect of rest intervals on kinetic variables associated with strength training and how these effects differ when athletes self-select their rest period rather than having a rest period imposed.

De Salles et al. (39) observed that healthy participants with at least six months training experience were able to perform the same number of repetitions on upper and lower-body weight lifting exercises, over three sets of 8 to12 repetitions at 75% of 1 repetition maximum (1RM) per exercise, when they rested for 2 min and when they self-selected their rest duration. However, participants' self-selected rest periods were observed to be less than 2 min prior to set 5, which might have limited recovery from peripheral fatigue. Glaister (67) investigated the ability of physically active students to self-select rest periods between 12 repeated 30 m sprint efforts over four trials. They reported that participants were able to reliably self-select rest intervals, which allowed sprint performance to be maintained across trials. However, neither of these studies utilised highly trained participants and De Salles et al. (39) did not consider kinetic measures or pacing responses. Allowing experienced strength athletes to self-select the rest periods between sets in weight training may potentially provide the opportunity to maximise performance.

The aim of this study was to compare the kinetic, neuromuscular and psychological responses between self-selected rest period trials and imposed 3 min and 5 min rest trials in highly strength trained athletes, during five sets of heavy back squat resistance training.

4.3 METHODS

4.3.1 Participants

Sixteen male athletes (age = 22.8 ± 3.1 a); body mass = 96.8 ± 15.5 kg; height = 179.4 ± 5.4 cm) volunteered for this study. All participants were members of a Super 15 Rugby Union franchise elite player development academy program and had participated in competitive club rugby for an average of 10.3 ± 4.1 a. All participants reported undertaking structured, supervised resistance training under the direction of a strength coach for an average of 4.2 ± 1.9 a. No musculoskeletal or health problems that could influence the testing were noted on completion of a pre-exercise screening questionnaire. No participants reported taking any medications, drugs or dietary supplements proven to influence strength training performance prior to or during the course of the study. All participants gave their written, informed consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and approved by the University of Canberra Human Research Ethics Committee.

4.3.2 Study design

Each participant attended the laboratory on five separate occasions over a 14 day period with a minimum of 48 h recovery between each training session. During the first session, participants completed an assessment of their 5 RM back squat strength to determine the load to be used during all subsequent experimental trials. This session was also used to collect anthropometric data (height and body mass). The second session served as a familiarisation trial during which participants were habituated to self-selecting their inter-set rest period, testing procedures, the subjective measurement scales, and the surface electromyography (sEMG) kinetic data collection equipment. Lack of participant availability prevented there from being two familiarisation trials. In the following three experimental trials, participants completed five sets of five repetitions of back squats at their pre-determined 5RM load under one of three inter-set rest period trials: self-selected rest (SS), three min rest (3M) or five min rest (5M).

The first experimental training session was the SS trial, this ensured that the 3M and 5M trials which were conducted after the SS trial did not influence the athlete's behaviour during the SS trial. The following two experimental training sessions were either the 3M or 5M trials, assigned in a randomised and counter-balanced order. All five sessions were conducted at the same time of day and under similar environmental conditions. For the duration of the study participants did not undertake any additional resistance training but conducted rugby specific skills-based training twice a week. Session supervision and feedback was provided by a professional strength and conditioning coach.

4.3.3 5RM determinations

Participants were required to report to the testing venue for their 5RM strength assessment in a well-rested state having refrained from any strength training in the previous 48 h. Each participant performed a series of five repetition back squats sets, during which load was incrementally increased until voluntary failure. Starting loads were set at approximately 75% of each participant's 1RM score, which was provided by the parent sporting organisation. Participants were advised to rest as long as they needed to perform each subsequent set attempt. A squat attempt was deemed successful when the participant lowered the body from an erect standing position with hips and knees fully extended in a continuous fashion until the thigh had reached a position below parallel with the ground and then returned to a standing position in as forceful a manner as possible. The 5RM score was defined as the load last lifted successfully for five repetitions prior to the set in which failure occurred.

4.3.4 Rest trials

During all sessions, participants were required to passively rest in a seated position between sets until indicated by the researcher to commence the next set (during the 3M and 5M trials) or until they felt ready to commence the next set (during the SS trial). During the SS trial, there were no clocks or timing devices available and participants were allowed to rest for as long as desired. For all trials, the rest period timing commenced from when the researcher stopped the optical encoder measuring device as soon as the participant re-racked the bar at the end of a set.

For the 3M and 5M trials, the rest periods were timed using an electronic timing device incorporated into an Apple Ipad (Apple Inc, Cupertion, USA) for the designated 3 or 5 min. Participants were given a 30 sec warning prior to beginning the next set which allowed for the completion of subjective measures assessment prior to the next set commencing. Participants were then advised by the researcher when they were to begin the following set and so commenced the first repetition of the next set as close to the designated rest time as possible.

For the SS trial, the rest periods were timed using an electronic timing device that was manually started by the researcher when the participant re-racked the bar, up until the bar was lifted off for the next set. Participants were advised at the beginning of the session and at the start of each rest period to complete the subjective measures assessment when they had rested sufficiently long enough that they felt capable of completing a maximal effort during their next set.

4.3.5 Test procedure

At the commencement of each session, participants completed a standardised, coach-led warm-up and any individually preferred pre-strength training warm-up activities. All individual warm-up activities were recorded on paper during the first session and replicated in subsequent sessions. After the warm-up, participants completed two back squat sets at 80% and 90% of their 5RM after which they rested until they felt ready to lift.

When ready to lift, participants removed the bar from the rack and situated themselves on a marked starting position. Feet were approximately shoulder width apart and the loaded barbell was placed across the upper trapezius muscle at a level approximating the acromion process. After attaining a stable position the participants were instructed to begin the first repetition. After finishing a set the participant would steady themselves in a standing position, wait for the researcher to stop the measurements and re-rack the bar. Any participant who could not complete a repetition or required assistance was stopped and did not participate in any further sets during that session.

4.3.6 Kinetic parameters

An optical encoder (Gymaware, Kinetic, Canberra Australia), was used to collect kinetic data being concentric power, total work, lift duration, concentric movement velocity, eccentric movement velocity and displacement. The optical encoder was attached by a tether to the right side of the barbell utilising methods described elsewhere (43, 138). Gymaware uses variable rate sampling with level crossing detection to capture data points and then limits this to a maximum of 50 data points per s (50 Hz). A linear encoder is considered a valid and reliable tool for measuring mean mechanical power during strength training activities (34, 138). The mean value per set for each kinetic parameter was recorded for analysis.

4.3.7 EMG parameters

sEMG data was collected and analysed using a portable wireless bio-amplifier system (Megawin WBA; Mega Electronics Ltd., Kuopio, Finland), with all trials recorded at 1000 Hz. The sEMG data was recorded for the vastus medialis oblique (VMO), vastus lateralis (VL) and biceps femoris (BF) muscles of the right leg. The sEMG electrode site location and placement were completed in accordance with published recommendations (33). Electrode location sites were prepared by shaving and cleaning the intended site with an alcohol swab to reduce impedance (>10 KΩ). Disposable Ag/AgCl bipolar pre-amplified disc electrodes (Ambu A/S, Ballerup, DK). Electrodes were stuck to the skin in parallel with the muscle fibres with a one cm separation distance between electrodes. Electrodes were contained within medical flexible tubing, minimising measurement interference and signal contamination artefacts caused by hardware movement and allowing the participant an unimpeded range of motion (134). The bio-amplifier system used both a high-pass filter (18 dB/Octave; 20 Hz) to remove direct current offsets due to membrane potential and a low pass filter for frequencies above 500 Hz.

Using the bio-amplifier system software package, raw sEMG signals (measured in millivolts) recorded from each squat were visually checked for measurement interference and signal contamination artefacts and removed if necessary (38). A 20Hz Butterworth filter incorporated into the bio-amplifier system removed high frequency noise from the system. A root mean square (RMS) was applied at a window length of 50 ms. Themean peak RMS sEMG amplitudes were recorded from the time preceding the first squat to the completion of the last squat in each set. Each repetition sEMG values were normalised against the peak mean value for each set and presented as a percentage. The normalised values were then used for subsequent analysis.

4.3.8 Subjective parameters

RPE was recorded immediately after the completion of each set using Borg's CR 10 scale (28). RTL was assessed immediately prior to the commencement of each set using a visual analogue scale (148). To rate RTL, each participant would manually mark down on a 10 cm line how ready they felt to complete the next set of squats. The 0 cm anchor represented 'not ready at all to lift' and the 10 cm anchor represented 'completely ready to lift'.

4.3.9 Statistical analysis

All data were analysed with a general linear mixed model using the R package lme4 (17, 119). This study applied a Missing At Random (MAR) mechanism when participants did not complete all sets because the non-completion was assessed as most likely due to build-up of fatigue from the previous sets. The MAR mechanism was judged to be appropriate as there was no immediate indication that the missing data depended on data from future sets (91).

The different measurements were included as dependent variables in subsequent analyses. Independent variables were included as fixed factors for the Condition (3M, 5M, SS), Set (1 to 5), and Repetition (1 to 5), including all two-way and the three-way interactions. Non-significant higher-order interactions were dropped from the model. As RPE, RTL and Condition were only measured on a Set level, no effect for Repetition is included in these models. In the random effects structure of the model, a random intercept for Subjects was included to account for the dependence between the repeated measurements. Assumptions of normality and homogeneity of variance were visually assessed using the model residuals and no obvious deviations from these assumptions were detected. Statistical significance of the fixed effects was assessed using Type II Wald F tests with Kenward-Roger degrees of freedom. Significance was set at $p < 0.05$.

4.4 RESULTS

4.4.1 Test completion

Every participant was able to complete all five sets in the SS and 5M trials; however, one participant failed to complete set 4 and two participants failed to complete set 5 in the 3M trial. For those participants, the 3M trial was halted at the point of failure.

4.4.2 Kinetic parameters

There was a significant interaction between Condition and Set for inter-set rest duration ($F(6, 162) = 2.93$, p = 0.01), as result of the resting time instructions for each rest trial. For the SS trial, rest duration increased until set 4 (95% CI = 23.87; 101.63) and then remained similar for set 5 (95% CI = -45.76; 34.33) (Figure 3). The SS set 1 rest interval was similar to that of the 3M set 1 rest interval (95% CI =-26.49; 28.49), after which rest intervals gradually increased until set 4. The SS rest intervals were not as high as the 5M rest intervals (95% CI = 28.95; 83.93).

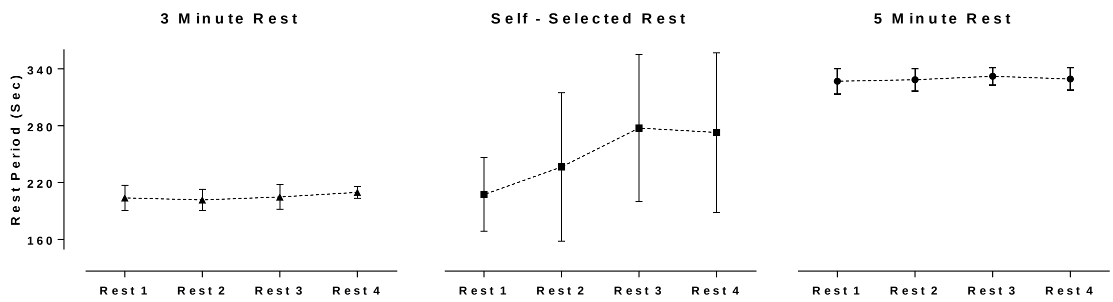

Figure 3. Inter-set rest duration for self-selected, 3 min and 5 min trials. * Signifies 15 participants completed set 4, ** Signifies 13 participants completed set 5.

There was a significant decrease in power output (PO) across repetitions ($F(4, 1147) = 161.88$, $p < 0.001$), independent of Set or Condition (Figure 4). The interaction between Set and Condition ($F(8, 1147) = 2.1985$, $p = 0.026$) indicates that the PO across sets differs between rest trials. There was a large inter-individual variability in mean PO (MPO) as evidenced by the large standard deviation. Notably, the MPO profile for the three rest trials were different. The 5M trial was the only one in which there was a slight increase in MPO between sets 1 and 2 (95% CI = -9.99; 74.09) and the SS trial was the only one in which there was a slight increase in MPO between sets 4 and 5 (95% CI = -36.22; 46.79).

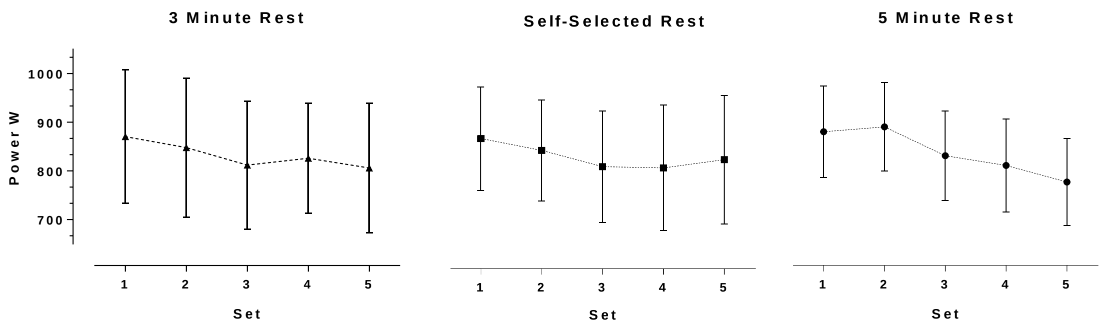

Figure 4. Mean power output and standard deviation per set for each rest duration. * Signifies 1 participant failed to completed set 4, ** Signifies 3 participants failed to completed set 5 in the 3M trial.

There was no evidence of an interaction effect for Repetition duration and condition ($F(8, 1092) = 1.00$, $p = 0.433$), and mean differences between rest trials were non-significant. The Set effect for Repetition duration indicated a non-significant, gradual increase in repetition duration across sets after set two.

There was no difference between rest trials in peak and mean concentric movement velocity ($F(2,1005) = 0.88$, $p = 0.415$ and $F(2,1092) = 0.16$, $p = 0.848$). A reduction in mean concentric velocity across repetitions was observed within Sets ($F(4,1092) = 61.64$, $p < 0.001$).

There was also a significant effect of Repetition across rest trials with an increased peak eccentric velocity evident for repetitions 2 to 5 compared to repetition 1 ($F(4,1055) = 7.19$, $p < 0.001$).

A significant interaction between Condition and Set indicates that the work profiles over sets were different between Conditions ($F(8,1148) = 3.79$, $p < 0.001$). There was a decrease in work over the first three sets in the 5M trial (95% CI = -140.49; -53.54) before rising in sets 4 and 5 (95% CI = -10.76; 71.55); however, work fluctuation for the 3M and SS trials was minimal (Figure 5). Independent of Condition and Set, there was a small effect for Repetition ($F(4,1148) = 5.17$, $p < 0.001$), due to work done in repetition one being significantly lower compared to that in repetitions 2 to 5 (95% CI = -49.70; -14.13).

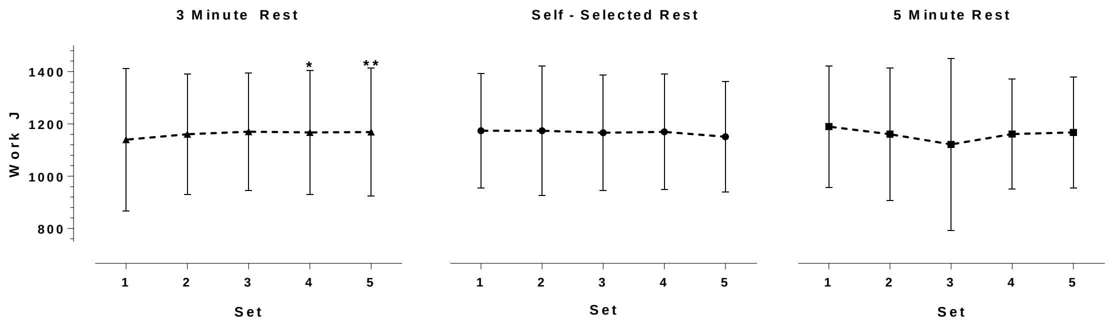

Figure 5. Mean work and standard deviation per set for self-selected, 3 min and 5 min rest trials. * Signifies 1 participant failed to complete set 4, ** Signifies 3 participants failed to complete set 5 in the 3M trial.

A significant Condition by Set interaction was noted for displacement ($F(8,1143)=3.65$, $p<0.001$), with different displacement profiles over sets between rest trials (Figure 6). A significant effect was also evident for Repetition ($F(4,1143)=9.2801$, $p<0.001$) across rest trials, with repetition 1 displacement being lower compared to that in repetitions 2 to 5 (95%CI=[0.007;0.018]).

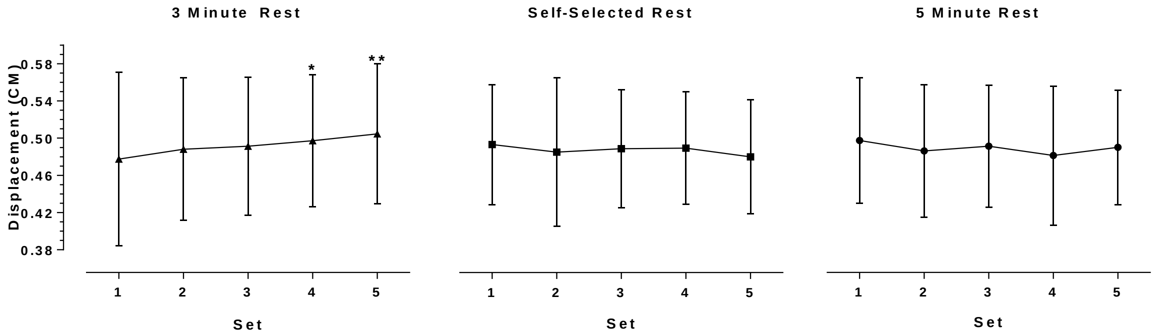

Figure 6. Mean displacement and standard deviation per set for self-selected, 3 min and 5 min rest trials. * Signifies 1 participant failed to completed set 4, ** Signifies 3 participants failed to completed set 5 in the 3M trial.

4.4.3 sEMG parameters

There was no significant difference between Conditions for VMO, VL or BF sEMG. There was a significant effect of Set in the VMO sEMG ($F(4,1081) = 3.73$, $p = 0.005$) driven by a decrease in VMO sEMG between set 5 and sets 1 to 4. Mean normalised sEMG set data between trials are presented in Table 3. Significant effects of Repetition for VL, VMO and BF sEMG data across all rest trials was also evident with sEMG activity increasing across sets.

Table 1. Mean normalised sEMG (mean ±SD) data for each muscle between each inter-set rest period condition.

SET	VM			VL			BF		
	3 Min	SS	5 Min	3 Min	SS	5 Min	3 Min	SS	5 Min
1	90.57 ± 4.44	90.01 ± 3.91	90.03 ± 6.67	90.84 ± 5.14	87.02 ± 4.88	90.58 ± 4.81	80.65 ± 8.17	83.19 ± 8.50	85.11 ± 6.27
2	89.85 ± 3.70	89.69 ± 4.77	89.93 ± 5.88	88.33 ± 4.97	89.37 ± 4.35	89.57 ± 4.72	85.01 ± 6.31	84.09 ± 7.63	85.21 ± 5.19
3	89.23 ± 5.19	90.90 ± 4.83	88.83 ± 5.50	89.69 ± 4.32	88.57 ± 5.17	88.75 ± 6.00	85.23 ± 6.44	82.90 ± 5.88	84.01 ± 6.44
4	87.63 ± 4.17	89.11 ± 4.16	89.77 ± 4.07	88.95 ± 5.40	88.41 ± 3.37	89.37 ± 3.75	82.31 ± 4.82	83.29 ± 6.78	85.03 ± 3.75
5	87.65 ± 5.39	86.59 ± 6.62	89.40 ± 4.29	86.97 ± 5.76	88.27 ± 5.99	89.07 ± 5.49	84.20 ± 3.50	84.91 ± 5.20	83.81 ± 6.58

Abbreviations: VM, Vastus Medialis; VL, Vastus Lateralis; BF, Biceps Femoris

4.4.4 Subjective parameters

There was a significant main effect of Condition ($F(2,205) = 11.01$, $p < 0.001$) and Set ($F(4, 205) = 30.16$, $p < 0.001$) for RPE. The significant effect on Condition appears to be heavily influenced by RPE being higher for the 3M trial compared to the 5M (95% CI = 0.38; 0.92) and SS trials (95% CI = 0.13; 0.67). Linear increases in RPE were observed between sets 1 [mean ± SD: 6.1 ± 1.6] and sets 5 [mean ± SD: 7.9 ± 1.9] across all rest trials.

There was a significant main effect on Condition for RTL ($F(2,208) = 8.33$, $p < 0.001$) which was likely heavily influenced by RTL being higher for the 5M trial compared to the 3M (95% CI = 0.36; 1.10) and SS trials (95% CI = 0.24; 0.97). For all trials, RTL was significantly higher in set 1 [mean ± SD: 8.4 ± 1.3] than set 2 [mean ± SD: 8.0 ± 1.3, 95% CI = 0.006; 0.952], set 3 [mean ± SD: 7.3 ± 1.6, 95% CI = 0.63; 1.58], set 4 [mean ± SD: 6.7*± 2.0, 95% CI = 1.22; 2.16] and set 5 [mean ± SD: 6.3* ± 2.6, 95% CI = 1.62; 2.57].

4.5 DISCUSSION

The present study aimed to investigate how self-selected rest periods effected kinetic, neuromuscular and psychological responses when compared to imposed 3 and 5 min rest periods. Our results showed that during the SS trial, participants initially selected rest periods similar to those of the 3M trial. As sets continued, rest periods increased until set 3 where rest duration peaked before plateauing after set 4. This indicates a feed-forward approach was used by participants when allowed to self-select their rest intervals. By anticipating the work ahead and adjusting their rest period accordingly they were able to make allowances for sufficient substrate replenishment and metabolic waste product removal. This allowed all participants to complete each subsequent set without failure. The ability to self-select rest periods between sets presumably has the individual following a similar decision making model to those observed when pacing during aerobic activities. Renfree et al. (121) describes a number of decision making theories with respect to muscular work rate, inferring that athletes commonly make poor decisions as evidenced by decisions to select work rates that are unsustainable. This study found that when afforded the opportunity, athletes made sound decisions in relation to their rest period as evidenced by all participants completing all sets in the SS trial.

The longest rest period in this study across all rest trials was 5 min (5M trial). Each set involved approximately 20 to 25 s of exercise during which highly fatigue sensitive type II muscle fibres would be recruited given the high loads utilised (24). Based on the findings of Hurea et al. (80), it is reasonable to conclude that both central and peripheral fatigue contributed to reductions in performance measures. In this study central fatigue was moderate because sEMG activity was similar across sets for all rest trials. It is reasonable to conclude that peripheral fatigue was high with incomplete recovery between sets as evidenced by the MPO reduction across sets for all rest trials. It is possible that the increase in rest periods prior to sets

3 and 4 for the SS trial was an attempt to attenuate neuromuscular fatigue and may have contributed to lessening of the MPO reduction after set three.

Of interest and unexpectedly, the self-selected rest periods in the SS trial were all less than that imposed for the 5RM trial, yet the PO, peak and mean concentric velocity were not significantly different. This indicates that the additional rest afforded in the 5M trial did not provide an immediate and obvious performance benefit, despite the potential increased peripheral fatigue recovery. The participants who failed to complete all sets in the 3M trial may have suffered from greater peripheral fatigue, rather than central fatigue, than during the rest trials as the sEMG for VL, VMO and BF were similar between trials. This may indicate a benefit in allowing participants to self-regulate their approach to strength training and biological variation.

For all trials, lift duration increased, concentric mean velocity decreased and eccentric movement velocity was maintained as the exercise progressed. The increase in lift duration supports expectations that participants would make technical adjustments throughout each set as a result of progressively increasing neuromuscular fatigue. The reduction in concentric mean velocity demonstrates that the participant's ability to produce force was progressively reduced during the concentric phase. The maintenance of eccentric movement velocity was possibly due to the greater capacity of skeletal muscle to generate force during heavy weight strength-training allowing the participant to control the movement velocity under load.

The reduction in RTL shows that participants were conscious that neuromuscular fatigue had not subsided prior to commencing the next set and is likely to be strongly influenced by peripheral fatigue. It is likely that central fatigue rapidly subsided between sets irrespective of rest period as sEMG was similar for all trials and sets (80). The reduction in RTL for the SS trial was unexpected as participants had the opportunity to rest for as long as required. It is possible that the participants are conditioned to feel a certain way before each lift based on their extensive previous experience with this type of activity and so felt unconsciously pressured to commence the next lift.

This study demonstrated that participants will choose to lengthen rest intervals as neuromuscular fatigue develops, supporting the assertion that rest periods should be both individualised and flexible during heavy strength training exercises. Allowing experienced athletes the option to self-select rest periods affords individuals the opportunity to adjust the rest period based on their own perceived ability and wellness factors, which may differ on any given day. Self-selection of rest periods may be especially important in maintaining performance for individuals who struggle to complete the required sets and repetitions when prescribed 3 min rest periods.

Studies have shown that experienced athletes can adjust rapidly to optimise performance when self-pacing (within two to three trials) in 4 km and 20 km cycling time trials respectively and demonstrate only subtle changes to their pacing profile at the start and finish of the trials (135, 140). The failure for participants to self-select a rest period in the SS trial that was sufficient for them to self-assess as completely ready to lift prior to each set suggests that the single familiarisation trial in this study may have been inadequate. It is possible that the selection of a more optimal rest period duration may have been observed if more familiarisation sessions had been conducted. Having only ever previously conducted similar weight lifting sessions under prescribed rest trials (with the exception of the single familiarisation trial), it is possible that participants perceived they had rested for too long and so commenced the next set before completely recovering. It is also possible that the lack of immediate feedback of the benefits gained from increasing the rest period (such as potential increased PO) makes it more difficult to optimise performance for strength training activities than aerobic training activities which have markers such as time and distance. As the self-selected rest periods did not exceed those of the 5M trial yet provided similar performance outcomes, affording athletes the ability to self-select rest periods may provide an alternative, less time-consuming training option providing athletes are well versed in applying this training method.

4.6 CONCLUSION

The present study is the first to be published that assesses kinetic measures and pacing strategies of highly trained participants when conducting heavy strength training activities. The data supports the theory that when afforded the opportunity in the SS trial, participants were able to adopt a pacing strategy which appeared to diminish fatigue. The study identified that when prescribed 3 min rest periods, participants experienced on average a greater RPE than that when prescribed a 5 min rest period or allowed to self-select a rest period. It also showed that for some athletes, a 3 min rest period was insufficient for recovery from previous efforts. Variability between the first and fifth set rest periods for the SS trial differed between participants, suggesting an individual approach and greater familiarisation may be needed if applying this method in a training environment.

Irrespective of the participants' increased perception of RTL, a prescribed 5 min rest period did not demonstrate any obvious performance gain when compared to the shorter rest periods selected in the SS trial. The sEMG responses from selected muscles groups for all trials suggest that peripheral fatigue may have had a greater influence, rather than central fatigue, for decreased performance across sets 1 to 5.

4.7 PRACTICAL APPLICATIONS

This study shows that when considering rest periods for heavy strength-training exercises with experienced participants, a standardised prescribed rest period may not achieve the desired outcomes. Allowing athletes to self-select rest periods may enhance the quality of training performance at higher training loads than that achieved when a 3 min rest period is imposed. Additionally, allowing athletes to self-select rest periods may prove to be a more time efficient training method than imposing 5 min rest periods.

Future experimental research into this topic should aim to incorporate additional familiarisation trials, analyse multiple muscle groups, and consider the effects of load combinations and known rest periods that achieve full fatigue recovery.

CHAPTER 5: DISCUSSION

5.1 DISCUSSION

The purpose of this thesis was to assess how strength training athletes self-regulate (pace) their strength training when conducting a heavy back squat protocol when afforded the opportunity to. To date, a large proportion of research relating to pacing has revolved around the locomotive type sports such as running, cycling and swimming (12, 60, 61, 102, 122, 128, 139, 146). More recently, research has begun to explore intermittent high intensity activities like repeated sprinting and strength training (39, 66-68). Specifically, this research has aimed to investigate the ability of subjects to consistently select rest periods between sets of heavy backs squats in an attempt to maintain kinetic performance while additionally assessing subjective performance measures of RPE and RTL. Furthermore, this research addressed how subjects then went about self-selecting their rest periods compared to two traditional prescribed rest periods commonly cited in the literature when undertaking maximal strength training.

When afforded the opportunity to self-select their rest periods, it was identified that participants significantly lengthened their within trial, rest periods from set 3 to 5. It was noted that all bar one participant exhibited this trend. The application of this pacing strategy was shown to be insufficient to maintain participants' kinetic performance as set mean power output was found to decrease in sets 3, 4 and 5 compared to set 1. These results indicate that participants experienced sufficient levels of fatigue to be unable to maintain their set 1 performance despite increasing their inter-set rest periods, although as performance was similar between sets 2 to 5 then fatigue does not appear to have worsened after set 1. It was hypothesised that the specific instruction to participants to "choose a rest period you feel will allow you to complete a maximal effort during your next set" may have influenced the rest period differently had alternate language such as “maximal performance” or “performance the same as set 1” been used.

Between trials results indicated a significant difference detected for trial mean rest period, with the mean total time rested in SS2 being less than SS1. It was speculated that these results may have been due to daily biological variation, or as a result of participants becoming further habituated to the protocol. Trial mean power also displayed a decreasing trend with SS2 exhibiting a reduced trial mean power output compared to SS1. It is plausible that this reduction in power output was due to the reduction in rest time in SS2 compared to SS1. Similar scores for RTL and RPE between SS trials indicate that participants achieved a similar psycho-physiological state during trials despite their being an overall difference in mean trial resting time and kinetic performance, suggesting some degree of homeostatic regulation occurred.

In contrast to other similar studies (39, 67), this research showed that mean power output was not maintained compared to set 1 in either SS trials despite the cohort being assessed as well versed in strength training. A fair level of reliability was observed for set-to-set mean power outputs, with similar ICC results between trials (73). A plausible explanation for this result may be that participants adjusted their rest periods between trials in response to inter-daily biological variation. It was suggested that the increased observations in the rest periods after set 2 and changes in the RTL and RPE in both SS trials indicate participants consciously adjusted their rest as a response to afferent feedback in sets 1 and 2 in an attempt to maintain sufficient recovery and reduce further performance decreases. However, despite the adjustments in rest period duration, RPE gradually increased and RTL gradually declined suggesting that there was a change in psychological state.

Data analysis showed that during the SS2 trial participants initially chose rest periods similar to those of the 3M trial. Rest periods then increased from set to set until eventually peaking at set 3 before plateauing at set 4. We speculate that this is a feed-forwards approach used by participants in anticipation of the work ahead; they would adjust their rest accordingly to allow sufficient replenishment of energy substrates and removal of metabolic waste by-products. This allowed for all participants to complete all sets without failure for the SS1, SS2 and 5M trials. Somewhat unexpectedly, the self-selected rest periods in the SS trials were all less than 5 min. Despite this, the PO, peak and mean concentric velocity were not significantly different than the 5M trial. This result indicates that the additional rest provided in the 5M trial did not provide an immediate and obvious performance benefit, despite the potential increased peripheral fatigue recovery. Results for sEMG across all trials were similar, which tends to indicate that central fatigue was moderate and supports claims made by Hureau et, al. (80). It is reasonable to conclude that peripheral fatigue was high with incomplete recovery between sets as evidenced by the MPO reduction across all sets and trials. Therefore, it appears the rest periods prior to sets 3 and 4 for the SS2 trial were an attempt to attenuate neuromuscular fatigue and may have contributed to a lessening of the MPO reduction after set three.

Lift duration increased which supported our expectations that participants would make technical adjustments throughout each set in response to progressively increasing neuromuscular fatigue. Concentric mean velocity showed a reduction across all sets, demonstrating a diminished capacity to produce force concentrically as sets progressed. Finally, eccentric movement velocity was maintained throughout, this was thought to be due to the greater capacity of skeletal muscle to generate force during heavy weight strength-training.

5.2 PRACTICAL OUTCOMES

Rest periods between sets play a vital role in the development of maximal strength. The time spent resting between sets needs to provide sufficient recovery for the maintenance of training performance throughout the session (66, 67). When considering rest periods for heavy strength-training exercises with experienced participants, a standardised prescribed rigid rest period may not achieve the desired outcomes. Study one suggests that while experienced strength trained athletes can self-select rest periods which allow them to complete all sets of a heavy back squat exercise protocol, they did not rest sufficiently enough early in the trial (set 1-3) to maintain their power output during sets 3, 4 and 5 compared to set 1. One participant failed to complete all five sets in the first experimental trial likely due to a lack of prior exercise experience and subsequently began SS2 with a more conservative manner/pacing strategy. The trend for RTL to reduce and post-set RPE to increase across sets, would suggest that participants should have allowed more recovery time between sets. That said, strength training is both physically and mentally demanding, so a cumulative increase in perceived exertion might occur even with a substantially increased rest period of many more min. The data suggest that the utilisation of self-selected rest periods provides a viable option for appropriately experienced athletes to complete strength training sets; however, some education and further habituation might be required to ensure that maximal performance is maintained across multiple sets of strength training.

Following on from the first study, the second indicated that allowing athletes to self-select rest periods may enhance the quality of training performance at higher training loads than that achieved when a three-min rest period is imposed. Additionally, allowing athletes to self-select rest periods may prove to be a more time efficient training method than imposing five-min rest periods. Ultimately, training programs work most effectively when the athlete has a vested interest and input into the conduct of a training plan (83). In the case of strength training, allowing appropriately experience athletes to make decisions (in this case about their rest periods) based on their intrinsic feeling of readiness to carry out the task may aid in enhancing athlete engagement in strength training. Therefore, it is imperative that the strength coach provides feedback that is timely and relevant to enable the athlete to make these decisions and enhance their performance.

5.3 FUTURE DIRECTIONS

This research is amongst the first to look at pacing strategies undertaken by experienced strength trained athletes and provide a number of unique opportunities to conduct further research in this area. Future research is needed in addressing familiarisation trials to establish if any patterns begin to develop with regard to the self-selected rest periods chosen by experienced athletes. Previous research (41) has suggested that 2 to 3 familiarisation trials may be required to gain reliable results when assessing maximal strength qualities. Gaining a better understanding of how strength trained athletes approach self-regulation of their rest periods will help researchers and coaches to understand athletes responses to internal feelings of fatigue on a day to day basis. Additionally, providing participants with a clear goal to attain for each repetition or set for example, a power output target or maintenance of velocity, may provide a greater conscious awareness of fatigue and readiness to lift for each set as opposed to a goal of merely completing the set. It is possible that a different goal would alter the pacing strategy and approach to training.

The participants utilised for this research were derived from Rugby Union. While this sport requires a high level of strength ability to underpin sprinting, scrummaging, tackling and specific skill capabilities, the various positional requirements demand different approaches to strength development. Athletes in field based sports spend a large majority of their time developing aerobic and anaerobic capacities which have an adverse effect on maximal strength development and leaves the individual in a residual state of fatigue. It may be prudent that future research aims to utilise a subject group where maximal strength development is prioritised, such as in sprint cycling, throwing based sports (Hammer, Shot) or Olympic weight lifting. Results gained from these subject groups may yield valuable insights into pacing strategies employed by highly experienced strength trained athletes. Future researchers may wish to investigate the different strategies employed by appropriately experienced athletes when utilising other strength training modalities (strength endurance, hypertrophy and power). Likewise, research which aims to investigate alternate muscle groups, such as upper and lower body or agonist versus antagonist, may produce valuable insights.

5.4 LIMITATIONS

Several limitations have been identified throughout the course of this research. The most obvious of these were the single familiarisation trials. Training schedules and participant availability limited the ability to conduct a second or even third familiarisation trail. Despite this, it was assumed that the training experience of the subject group would have compelled participants to rest for longer and therefore rate themselves as "completely ready to lift" when afforded the opportunity to select the appropriate rest periods based on how they felt at the time. This did not occur, with participants indicating subjectively they were not fully recovered before they started their subsequent sets in the self-selected trials. Previous research with regard to familiarisation trials in strength training has outlined that even experienced strength trained athletes may require a number of familiarisation trials to provide accurate results (41, 124).

Another limitation may have been the requirement for each participant to indicate their RTL before each lift. A conscious bias may have affected participants approach to conducting each set due to habitual practices of utilising prescribed rest periods in their normal training environment.

5.5 CONCLUSIONS

To the author's knowledge, this study was the first of its type to assess the adjustment of self-selected rest periods with regard to strength training. Several other studies have assessed a similar concept utilising training loads at 75% of the participants 1RM (39, 68). The results of these studies revealed the mean self-selected rest periods between sets, for the back squat exercise used in their protocols, were 102.80 ± 39.20 s and 106.67 ± 29.69 s (39) and 152.7 and 148.0 s (68); which are substantially shorter rest periods than were observed in the current study, probably due to the lower relative loading in these studies. However, these do place the relative rest periods selected around 2 min which is commonly accepted in the literature as the optimal rest duration at this load (159). This research revealed that the average rest for SS1 and SS2 trials was 283 ± 101 (SS1) and 249 ± 76 s (SS2) respectively. This places athlete recovery between the 3 and 5 min duration, which is often outlined in the strength training literature as optimal for maintaining strength training performance (24, 84, 159, 161). Additionally, subjective measures of RTL and RPE across studies indicate a conscious awareness of participants fatigue state and revealed that adjustments were made with respect to recovery time to limit fatigues influence on next set performance. Furthermore, sEMG indicated minimal change across trials and between muscle groups. Therefore, it is likely peripheral fatigue rather than central fatigue played a more significant role in muscular performance.

The findings from this study provide strength and conditioning coaches and academics alike with an opportunity to implement and refine self-selected rest strategies in strength training. Coaches should look to utilise these methods with experienced strength-trained athletes, after an appropriate period of familiarisation. This may allow strength and conditioning coaches to manipulate program design to improve training efficiency and performance without impacting on other training modalities that are commonly required to be undertaken during strength training sessions. Academics may wish to refine the current protocols with regard to the number of familiarisation trials conducted and to instructions given to participants to ensure valid and reliable data is gathered for analysis. The results are seen as a good basis for which to extend research and increase the knowledge in this field.

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APPENDICES

APPENDIX A

COACHES INFORMATION

Project title: Rest Interval Length and the Effect on Neuromuscular, Kinetic and Psychophysiological Responses to Strength training in Elite Rugby Union Athletes

Principle Researcher: Peter Ibbott, ACT Academy of Sport & University of Canberra, Masters of Sports Science

Purpose

Strength training forms an integral part of the training process for elite and sub-elite athletes. The development of maximal strength forms an underpinning physical attribute essential in many athletic endeavours, and forms a basis for the development of other important athletic qualities such as power and speed, essential in many team sport activities.

Resistance training generally forms the primary training method for developing maximal strength in many sports that require the athlete to exert high forces in order to overcome large external resistances. In the case of maximal strength development, athletes are often required to perform multiple sets of an activity at high loads which can elicit considerable fatigue. Accumulated fatigue can in turn impact on training performance by reducing the athlete's ability reproduce acute performance markers *(p*ower output, movement velocity), or to complete subsequent sets of the same exercise which therefore may impede desired training adaptations. To counter this, rest periods between sets of a strength training activity are often prescribed by the strength and conditioning coach to allow sufficient recovery. Commonly, rest periods can range between 2 and 5 min (Willardson, 2008) depending on the training goal, load lifted and number of sets and repetitions intended to be performed. However, in busy team sport training environments the rest period between sets may need to be altered to accommodate other training requirements.

It is the purpose of this study to assess the effect standard rest periods have on strength training performance and quality of training. Further to this, athletes will be assessed to identify if they can reliably self-select their own rest periods based on perception of effort and internal feelings of fatigue, with an aim to compare training quality and performance of self-selected and commonly prescribed rest periods in strength training.

Benefits

This project will provide information that will allow you to;

- Gain insight into the effects rest periods have on the quality of strength training performance.

- Assess if athletes can reliably self-select their own rest periods and how this impacts on training.
- Provide training specific information that may better allow you to organise your training sessions and program for you athletes.

Requirements

If you agree to allow your athletes to participate in this project your athletes will be asked to attend five testing sessions over a two week period. These sessions will be organised in consultation with you so that the testing can be incorporated into the regular training schedule. This will assist us in minimising disruption to the athletes training schedule.

Initially your athletes will be required to come to a baseline testing session where their 5 repetition maximum (5RM) squat and general physical characteristics will be assessed.

Following on from the baseline testing, your athletes will be required to attend four testing sessions (2 x self-selected rest, 2 x imposed rest) over a two week period, with a minimum of 48 h rest between sessions.

Your athletes will be asked to perform a standard warm-up routine, followed by five sets of five repetitions of a back squat protocol at their pre-determined 5RM load.

Between sets of each squat protocol athletes will be required to passively rest at a self-selected or imposed rest period (3 and 5 min). During each set of squats power output and velocity will be measured via linear position transducer. Internal muscle activity is to be assessed by electromyography (EMG), while subjective measures of ratings of perceived exertion (RPE) and readiness to lift will be monitored via subjective measures. Total volume load lifted and length of rest period taken when self-selecting will also assessed to ascertain what effect the above rest periods have on training performance and quality.

It is asked that your athletes wear normal training attire, and minimise any alternations in their diet and lifestyle (e.g. sleeping times and training load) 48 h prior to testing.

Ethical considerations:

This research has gained ethical approval from University of Canberra Committee for Ethics in Human Research. Should you have any questions relating to the information provided above, please feel free to contact me for further explanation. If you have any concerns about this research, or would like to speak to an independent person, you may contact by telephone the Ethics Compliance Officer on (02) 6201 5220.

Queries and Concerns

If you have any queries or concerns about the project, I can be contacted via email at Peter.Ibbott@act.gov.au or phone [redacted].

APPENDIX B

PARTICIPANT INFORMATION

Project title: Rest Interval Length and the Effect on Neuromuscular, Kinetic and Psychophysiological Responses to Strength training in Elite Rugby Union Athletes

Principle Researcher: Peter Ibbott, ACT Academy of Sport & University of Canberra, Masters of Sports Science

Purpose

The use of strength training has become an essential component of athletic development in modern sporting endeavours. The careful manipulation of key training variables by the strength and conditioning coach is needed to ensure that the athlete is exposed to a gradual overload in training volume and intensity which in turn allows for the physiological adaptations to the imposed stimulus to take place (Baechle and Earle, 2008, Bompa and Haff, 2009, Siff et al., 1993). Of these variables, the rest period is often overlooked by coaches and athlete's alike when considering the individual training program. The purpose of the proposed research is to identify the effect differing inter-set rest periods have on Kinetic, Electromyography and Perceptual responses on an athlete during a strength training session. This will be assessed by having the athletes conduct sets of a strength training exercise with both self-selected and prescribed rest periods.

Requirements

If you agree to participate in this project you will be asked to attend to five testing sessions over two weeks which will be assigned based on the athletes availability. On these occasions, the exercise tasks will require approximately 1 – 1.5 h of your time. You will be asked to perform a warm-up routine, followed by five sets of five repetitions of a back squat exercise at your five repetition load which will be determined at your first testing session. You will be required to perform five sets of five repetitions as forcefully as possible. At the end of each set you will be required to rest for a specified time which the researchers will inform you of on the day. It is asked that you wear normal training attire, and minimise any alternations in your diet and lifestyle (e.g. sleeping times and training load) 48 h prior to testing.

Risk and Ethical considerations:

We would like to make you aware that due to the physical nature of the tasks you will be exposed to a low level of risk by your involvement, in terms of possible physical symptoms such as muscle soreness and tiredness. To minimise the risk, you will be monitored by the researchers and will be free to cease performing the task at any time. In addition, you will be asked to report whether you have any existing or pre-existing injuries that would make you susceptible to further injury. We would like to make you aware that you only need to try your best and there is no particular level of performance that you need to reach. If you feel uncomfortable at any time, you should feel free to cease participating, take a break from participating or discuss your concerns with the researchers. You will be free to withdraw from this study at any stage and for any reason without prejudice. All personal information and test results recorded will remain confidential in terms of the study, and only be reported to you and your coach. Moreover, no data analysis will include your name or information that may identify you specifically as a subject.

This research has gained ethical approval from University of Canberra Committee for Ethics in Human Research. Should you have any questions relating to the information provided above, please feel free to contact me for further explanation. If you have any concerns about this research, or would like to speak to an independent person, you may contact by telephone the Ethics Compliance Officer on [redacted] [redacted].

Queries and Concerns: If you have any queries or concerns about the project, I can be contacted via email at

APPENDIX C

INFORMED CONSENT FORM

Project Title: Rest Interval Length and the Effect on Neuromuscular, Kinetic and Psychophysiological Responses to Strength training in Elite Rugby Union Athletes

Principle Researcher: Peter Ibbott, ACT Academy of Sports & University of Canberra, Masters of Sports Science

This is to certify that I, ________________________ hereby agree to participate as a volunteer in the scientific investigation stated above. The investigation and my part in the investigation have been defined and fully explained to me by Mr Peter Ibbott, and I understand the explanation. A copy of the procedures of this investigation and a description of any risks and discomforts has been provided and discussed with me in detail.

- I have been given an opportunity to ask whatever questions I may have had, and all such questions and inquiries have been answered to my satisfaction.
- I understand that I am free to decline to answer any specific items or questions in interviews or questionnaires.
- I understand that I am free to withdraw consent and to discontinue participation in the project of activity at any time.
- I understand that any data or answers to questions will remain confidential with regard to my identity.
- I certify to the best of my knowledge or belief, I have no physical or mental illness or weakness that would increase the risk to me of participating in this investigation.
- I am participating in this project of my own free will and I have not been coerced in any way to participate.

Signature of participant:____Date:_________

Print Name: ____ Date:________

If under the age of 18 years old, a parent or legal guardian/head coach must sign below.

Signature of parent/guardian/coach:__________________________ Date:________

Print Name: ____ Date:________

I, the undersigned, was present when the study was explained to the participant/s in detail and to the best of my knowledge and belief it was understand

Signature of Researcher:___________________________________ Date:________