POTENTIATION OF SPRINT CYCLING PERFORMANCE:
The Effects of a High-Inertia Ergometer Warm-Up

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Abstract

Assimilating current knowledge in the field of acute post-activation potentiation (PAP) of athletic performance, this study attempted to ensure optimal conditions for performance gain, by utilising highly-trained sprint-athletes, a biomechanically similar conditioning activity and following recommendations for the most appropriate conditioning protocol. Employing a randomized, counterbalanced, cross-over design with repeated measures, 4 male and 2 female national and international competitive sprint cyclists (age 19.2 ± 3.2 years; height 175.2 ± 7.0 cm; body mass 75.5 ± 9.8 Kg; training years (sprint cycling) 4.0 ± 1.5 years; training years (strength) 3.5 ± 1.2 years; peak isometric pedal torque 255.85 ± 37.75 Nm) executed multiple sets of short maximal contractions on a custom-built high-inertia ergometer as a potentiating stimulus prior to sprint cycle performance. Three trial conditions were completed on three separate days: a standardised warm-up followed by either dynamic (DYN: 4 x 4 complete crank cycles), or isometric (ISO: 4 x 5-second MVC) conditioning contractions (CC), or a control condition (CON) where subjects actively rested for the total equivalent time post-warm-up. Performance was assessed in a short (~6 seconds) maximal acceleration from standing start to maximum velocity on an inertial-load ergometer at baseline (Pre), 4 (Post4), 8 (Post8) and 16 (Post16) minutes following the CC protocol. Torque-cadence and power-cadence relationships were derived from crank data recorded throughout the sprint. Performance time and peak and average biomechanical measures were assessed over 4 discrete sprint segments. Outcomes were assessed using 2-way repeated measures ANOVA and magnitude-bases inferences. DYN Post4 was the only trial improving performance time, affecting a 3.91 ± 3.74% (92% likelihood of exceeding smallest worthwhile change (SWC)) decrease in time over the first segment of the sprint such that overall performance time was substantially improved. Biomechanical improvements in this trial were predominantly on the ascending limb of the power-cadence relationship, affecting an increase of 6.24 ± 5.95% in peak torque (94% likelihood of exceeding SWC) and 4.04 ± 6.52% (87% likelihood of exceeding SWC) in average power during initial acceleration. Conversely, ISO Post16 enhanced performance over the descending limb of the power-cadence relationship, affecting an increase in optimal cadence (~3.1% increase when compared to change from baseline in control condition, 82% likelihood of exceeding SWC) and augmenting average power (~5% improvement when compared to change from baseline in control condition, 76% likelihood of exceeding SWC) during the maximal velocity phase of the sprint. DYN Post16 affected only small improvements at either extremity of the relationship, while few changes were observed in the remaining trial conditions. Results imply that each trial-time combination presented distinct performance conditions characterised by the predominance of different PAP mechanisms. This study provisionally suggests the efficacy of a including a high-inertia ergometer component in the sprint warm-up. Improvements at the functional extremities of the sprint would benefit starting acceleration or finishing speed, where compromise in gear and pedal length selection strategies would, otherwise, impose limitations on performance.

Keywords: post-activation potentiation, sprint cycling, neuromuscular performance, warm-up

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And to my dad, who has been alongside me every step of the way.

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List of Abbreviations

ADP	adenosine diphosphate
ATP	adenosine triphosphate
BP	bench press
BPT	bench press throw
BS	back squat
Ca^{2+}	calcium ion
CC	conditioning contractions
CMJ	counter movement jump
DJ	drop jump
ECC	excitation-contraction coupling
EMD	electromechanical delay
EMG	electromyography
EPSP	excitatory post-synaptic potentials
ES	effect size
F_0	peak isometric force
FVP	force-velocity-power
GTO	golgi-tendon organ
H-reflex	Hoffman reflex
HC	hang cleans
HFF	high-frequency fatigue
JS	jump squat

LFF	low-frequency fatigue
MA	musculoarticular
MB	medicine ball
MF	metabolic fatigue
MGL	gastrocnemius
MHC	myosin heavy chain
MLCK	myosin light chain kinase
MRLC	myosin regulatory light chains
MTU	muscle-tendon unit
MU	motor unit
MVC	maximal voluntary contraction
NMF	non-metabolic fatigue
PAD	post-activation depression
PAP	post-activation potentiation
pCa^{2+}	plasma ionized calcium
PS	power snatch
PTA	peak torque angle
PTP	post-tetanic potentiation
RFD	rate of force development
RM	repetition maximum
RP	reflex potentiation
SEC	series elastic components
SJ	squat jump
SOL	soleus

SSC	stretch shortening cycle
SWC	smallest worthwhile change
TDC	top dead centre
TJ	tuck jump
TP	twitch potentiation
TT	twitch torque
V_0	maximum unloaded shortening velocity
VJ	vertical jump
VO_2	oxygen consumption
VO_{2max}	maximal oxygen consumption

CHAPTER 1 - INTRODUCTION

In exercise performance previous contractile history is known to affect subsequent activity. Indeed it is widely accepted that prior contractions provoke fatiguing conditions specific to the nature of the activity, hence processes stressed (Fitts, 1996). However, a significant body of research substantiates that previous activity can similarly *positively* influence future contractile activity, post-activation potentiation (PAP) of the contractile mechanisms leading to improvements in performance for the same degree of stimulus (Robbins, 2005). The established co-existence of these two mechanisms creates conflicting conditions for muscular force development, and as such, output of the contractile apparatus will reflect a net balance of those processes enhancing force production and those which diminish it (Rassier & Macintosh, 2000). The potential reconciliation of prior activity in influencing an overall net gain, has led to recent interest in optimising conditions for PAP *in vivo* with the immediate benefits afforded the athletic population (Docherty & Hodgson, 2007).

Historical studies have been unequivocal in confirming the existence of potentiation in human muscle. *In vitro, in situ* and *in vivo* studies have demonstrated increases in twitch response following conditioning contractions (CC) of electrically-evoked repeated sub-maximal (staircase response or treppe)(Desmedt & Hainaut, 1968; Kopman et al., 2001; Krarup, 1981), and tetanic (post-tetanic potentiation, PTP) stimulus (Abbate et al., 2000; Hughes, 1958; Standaert, 1964). Twitch potentiation (TP) studies have suggested that, following application of CC of appropriate intensity and duration, a 'window of opportunity' exists wherein fatiguing affects of the CC have subsided as potentiation is sustained (Houston & Grange, 1990; Requena et al., 2008).Theoretically beneficial to functional performance, *in vivo* studies of TP have successfully replicated outcomes in response to a maximal voluntary contraction (MVC) of a single muscle group (Baudry & Duchateau, 2007a; Vandervoort et al., 1983). However, effects on performance measured in a whole-body setting have been inconsistent (DeRenne, 2010; Docherty et al., 2004).

Examination of PAP in a functional setting seeks to utilise a maximal contraction of compound muscle action, for example, a barbell back-squat, to potentiate mechanical power output in an explosive performance movement, for example, a vertical jump. The equivocal nature of results highlights the complexity of examining compound muscle action where interaction of different fibre types, muscle architecture and distinct force-length-velocity profiles confound results (Tillin & Bishop, 2009). Studies of isolated muscle have demonstrated the influence of conditioning protocol factors on outcome. (Bagust et al., 1974; G. L. Brown & von Euler, 1938; Grange et al., 1998; MacIntosh & Willis, 2000; Vandenboom et al., 1993). Equivalent outcomes in intact muscle present considerations for successful protocol design: conditioning contraction type, intensity, volume and recovery time between CC and subsequent muscle action, directly impact the fatigue-PAP interaction, effectively shaping the window of opportunity (Behm et al., 2004; Houston & Grange, 1990; O'Leary et al., 1997; Vandervoort, et al., 1983). The mechanism of PAP is most often attributed to an increased Ca^{2+} sensitivity of sarcomere cross-bridges through increased phosphorylation of the myosin regulatory light-chains (MRLC) (Parry et al., 2008). However, mechanisms of potentiation appear in many physiological systems providing a means of increasing functional capacity or activating functional reserves (Hughes, 1958). In such a case, exercise performance may benefit from potentiation, not only myogenic in origin, but also neurogenic, hormonal, metabolic and psychomotor (McGregor, 2011). Much as fatigue is specific to the processes and pathways stressed, potentiation can be equally defined. Response to PAP is, therefore, specific to the conditioning protocol applied, further mediated by the subsequent exercise movement (hence, neuromuscular pathways and physiological systems stressed) and individual characteristics of the athlete (Tillin & Bishop, 2009).

Nevertheless, a review of existing studies highlights some consistent factors. Gourgoulis et al. (2003) showed that, although no significant group effect was present, when the group was median split by

1RM (repetition maximum) strength, the stronger group showed 4.01% improvement in performance following potentiation. Subsequent studies concur, finding that relative strength and overall training status not only impact the magnitude of response, but also the timeframe of the window of opportunity (Berning et al., 2010; Chiu et al., 2003; Rixon et al., 2007; Young et al., 1998). Athletes of higher training status tend to be better responders and require less time before potentiation manifests, both outcomes likely attributed to their improved fatigue resistance (Chiu, et al., 2003). Early studies further support a predominance of potentiation in fast-twitch fibres (G. L. Brown & von Euler, 1938) and, accordingly, comparisons of endurance and power-trained athletes reveal increased magnitude of response in the latter (Paasuke et al., 2007). In-spite of these findings, there is a paucity of research examining PAP in elite sprinters, i.e. athletes who would appear to be of perfect stature with advanced training status, high absolute and relative strength, fatigue resistant and tending towards a higher percentage fast-twitch fibres. Since potentiated performance improvements may be as small as 1-2%, such athletes would, additionally, be more functionally able to capitalise on small improvements in neuromuscular function and would further demonstrate less performance variability which may otherwise cloud results (Clevidence, 2008; Comyns et al., 2010).

In presenting recommendations on optimal CC protocol, a recent meta-analysis of PAP performance studies, similarly, acknowledged that training status mediated many factors (Wilson et al., 2013). Optimal CC intensity appeared to be only moderately high (65-84% 1RM), recovery duration intermediate (7-10 minutes) and volume reasonably high, utilising multiple rather than single sets. However, training status of the participants affected all variables except intensity. With appropriate moderation in consideration of the level of participants involved, such recommendations provide a useful guide in planning future research. Although no distinctions were reported between dynamic or isometric contractions, PTP studies have previously made recommendations for the use of the latter being between 5-10 seconds duration and >75% MVC (Vandervoort, et al., 1983).

Mechanistic analysis of PAP concedes that, while rate of force development is enhanced by PAP up to maximum levels of recruitment, there is a threshold for absolute force improvement consistent with Ca^{2+} saturation at high motor unit (MU) discharge frequencies (Vandenboom, et al., 1993). Performance at the opposite extreme of the force-velocity relationship may be similarly constrained - maximal unloaded shortening velocity reportedly unchanged in the presence of PAP (Stuart et al., 1988). Accordingly, some authors have suggested that, through the increased acceleration of loads between zero (V_0) and peak isometric force (F_0), only true 'explosive' activities (single effort actions with contractions with an activation time ≤0.25 ms) would demonstrate a discriminatory outcome (French et al., 2003). On the contrary, studies of repeated or sustained power movements such as sprint performance have shown positive outcomes, albeit inconsistently (Matthews et al., 2004; Okuno et al., 2013; Requena et al., 2011; Zois et al., 2011). To maximise specificity and affect performance pathways, biomechanical similarity of the conditioning exercise is essential (Crewther et al., 2011). Matching of the movement kinematics through 'complex pairs' - utilised in strength training - has seen a proliferation of studies based on squat patterns paired with horizontal or vertical jumps (Tillin & Bishop, 2009). These conditioning patterns are far less intuitive for sprint performance and sports characterised by unilateral limb function as well as substantially different kinetic and kinematic profiles. Therefore, lack of success in utilising squats in such instances, is unsurprising. Increasing movement specificity by using training tools or equipment mimicking the goal movement in a loaded dynamic or isometric manner has witnessed successful study outcomes in sports such as rowing, swimming, and cycling (Feros et al., 2012; Hancock, 2004; Lawrence et al., 2010).

Conducting a more detailed analysis of the performance provides further insight into the effect of the potentiating protocol. Many studies which were unable to positively improve the absolute performance measure, have, at least, confirmed significant impact on performance mechanics, for example, ground reaction force, peak power or peak velocity (Comyns, et al., 2010; Esformes et al., 2011; Kilduff et al., 2011). Whether accelerating an implement or body in space, the execution of the movement can be broken down into phases representing neuromuscular performance over distinct segments of the load-velocity relation: the MRLC potentiation mechanism suggests PAP would fail to benefit either extreme of the relationship - it would rather create an upwards and rightwards shift of the mid-portion of the curve which may benefit peak power or, at least, enhance force production at moderate velocities (Sale, 2002); potentiation of the neural system represents the opportunity to reduce transmitter failure at synaptic junctions and increase recruitment of higher threshold motor units which may benefit force production during near-isometric conditions in overcoming inertia and accelerating the object from rest (Tillin & Bishop, 2009); potentiation of the psychomotor system may assist reaction time and skilled execution of the task maintaining performance execution at high movement velocities (Etnyre & Kinugasa, 2002); while effects on muscle stiffness and endocrine and metabolic response may, additionally, provide compensation for fatigue expressed through the course of the effort (Beaven et al., 2011; Dinsdale et al., 2009; Sinkjaer et al., 1992). Effects of a potentiating stimulus and, indeed, its associated fatigue may, therefore, vary through each of the start, acceleratory and peak velocity phases of the performance. Such a definitive analysis is yet to be conducted. However, running studies have hitherto observed distinct characteristics of potentiation response at discrete split times across the course of a sprint (Antonopoulos et al., 2012; McBride et al., 2005; Yetter & Moir, 2008).

Upholding the belief that potentiation is primarily a reflex mechanism, prior research has asserted that an eccentric contraction or stretch-shortening component must be present in the goal movement (Cabrera et al., 2009). Nevertheless, PAP is greatest when the muscle is shortening (Tillin & Bishop, 2009) and PTP studies clearly describe the much higher potential for benefit in concentric contraction, with potentiation in this contractile condition extending to much higher stimulus frequencies (MacIntosh & Willis, 2000; Sale, 2002). Accordingly, cycling presents a unique opportunity to study PAP. Advancements in cycle crank technology, further permit the collection of performance data pertaining to crank torque, velocity and, hence, power throughout the execution of the activity, thus allowing alterations in contractile behaviour to be more readily predicted (Barratt, 2009; Bertucci et al., 2005). Currently, to this author's knowledge, only six PAP studies of cycling have been published (French, et al., 2003; Jo et al., 2010; Lawrence, et al.; Parry, et al., 2008; J. C. Smith et al., 2001; Thatcher et al., 2012). Once again, the results are inconclusive. However, in each case trial conditions were less than optimal: three trials used Wingate tests representing relatively long (30 seconds) sprint times (Jo, et al., 2010; Parry, et al., 2008; Thatcher, et al., 2012); all bar one had little biomechanical similarity of CC, including one utilising a solely single joint exercise (knee extension) (French, et al., 2003); none used trained cyclists; and none utilised the opportunity afforded by crank measurement technology.

Although the ergogenic effects of a warm-up are still in dispute, athletes continue to follow individualised warm-up routines prior to performance (Bishop, 2003b). Research currently attributes warm-up benefits predominantly to increased temperature and acidosis, each advised within moderation (Bishop, 2003a). However, power athletes frequently include higher intensity components to increase arousal and preparedness for subsequent task demands, risking the metabolic fatigue they may induce (Madon, 2007). A recent study by Tomaras and MacIntosh (2011) demonstrated that standard warm-ups currently used by sprint cyclists were, in fact, less than optimal: a shorter, less intense, experimental routine produced better performance. With successful PAP outcome offering potential performance gains in the order of 2-10% (Contreras, 2010), inclusion of an appropriate CC protocol in the pre-competition routine may beneficially supplement the metabolic warm-up by optimally 'priming' the neuromuscular system of the athlete.

This study will, therefore, seek to examine the effects of potentiation on sprint cycling performance by adding a CC component to a standardised warm up based on the Tomaras and MacIntosh protocol (2011). Assimilating current knowledge, the design will attempt to ensure optimal conditions for observation of PAP by utilising highly-trained sprint-cyclists, a high-inertia cycle ergometer to provide CC specificity and following recommendations for the most appropriate CC protocol. Response to two types of contraction (isometric and dynamic) will be compared and provision of multiple recovery times will allow assessment of the optimal timeframe for beneficial outcome. With the sprint conducted on an inertial-load ergometer, performance data will be recorded at the crank allowing determination of the torque-cadence and power-cadence relationships. Primary performance measures will then be assessed across four distinct phases of the sprint. This analysis will facilitate a more profound understanding of the effects of the CC protocol and, indeed, evoked potentiation, throughout the course of sprint performance.

1.1 HYPOTHESIS

The primary null hypothesis (H0) for this research were:

$H0_1$: A high-inertia ergometer warm-up intervention will not potentiate subsequent sprint cycling performance.

$H0_2$: A high-inertia ergometer warm-up intervention will not alter the biomechanical profile of subsequent sprint cycling performance.

CHAPTER 2 – LITERATURE REVIEW

2.1 INTRODUCTION

The following chapter is intended to provide an extensive review of published literature relating to the post-activation potentiation (PAP) of athletic performance. The influence of prior exercise and key mechanisms and attributes of potentiation will be discussed with an emphasis on published laboratory-based experimental work. With these in mind, discussion will then focus on how this knowledge can be applied to produce performance gains in the applied setting. Context for application will be provided through discourse on the optimisation of athletic performance, in particular, sprint cycling. A critical review of acute PAP studies will then be conducted with a view to identifying recommendations for a consistently successful PAP protocol.

2.2 INFLUENCE OF PRIOR ACTIVITY ON SUBSEQUENT PERFORMANCE

In order to develop effective strategies for optimising performance, the contractile conditions within which the performance is realised must be understood. However, the contractile conditions exist in a dynamic state of flux influenced by performance itself (Cormie et al., 2011; Fitts et al., 1991).The interplay of a number of physiological systems affects potential gains and potential losses based on the degree of stress applied and, at any point in time, the contractile history of skeletal muscle influences its future performance (Rassier & Macintosh, 2000).

Fundamental to this is our understanding of fatigue. While the experience of fatigue is somewhat subjective, physiologically it may be defined as failure in the ability to maintain the required or expected force or power output (Faria et al., 2005b). It is generally accepted that, in whole body exercise, mechanisms of fatigue may involve multiple factors at multiple sites throughout the chain of command (Fitts, 1996). Enoka and Duchateau (2008) suggest that the dominant mechanism is dependent on the processes stressed and, in such a case, the type, duration and intensity of activity. In contrast, evidence upholds that potentiation of the systems and processes contributing to contraction may affect an *increase* in force production or rate of force development in response to both volitional (PAP) and electrically induced (PTP) stimuli (M. Hodgson et al., 2005). Effects of potentiation appear equally dependent on the type, duration and intensity of contraction stimulus applied (Khamoui, 2011).

Analysing quadriceps force recovery after a sprint cycling protocol, Skurvydas et al. (2007) describe a complex interaction of metabolic fatigue (MF), non-metabolic fatigue (NMF) and potentiation. On-going contractility is then dependent on the characteristics of the exercise and the prevailing response. In endurance performance, repeated sub-maximal contractions recruit low order motor units that discharge at relatively low rates. Where MF in endurance performance is concurrent with depletion of intramuscular glycogen, NMF sees impaired excitation-contraction coupling result in low-frequency fatigue (LFF), a disproportionate loss in low- (versus high-) frequency tetanic force (Keeton & Binder-Macleod, 2006). In these conditions, a required increase in central drive sees a concomitant increase in existing motor unit (MU) firing rates, higher-order MU recruitment and, hence, increases in perceived effort and metabolic stress (Sale, 2002). However, Fowles and Green (2003) demonstrated that potentiation induced by the contractions themselves will affect either a compensatory force increase combating LFF or else a reduction in firing frequency required to maintain the same force, offsetting the impairment of central drive.

In contrast, fatigue in explosive sports is characterised by substantial disturbance of metabolic profile caused by high levels of inorganic phosphates and adenosine diphosphate (ADP) in addition to the inability to fully restore ionic gradients (Westerblad et al., 2002). Here, the presence of *high-*

frequency fatigue (HFF), a decline in force at high firing rates associated with maximal force performance, appears unaffected by PAP. In fact, Sale (2002) suggested that a potentiating stimulus may well have a negative impact on peak isometric force (Figure 2.1). Maximum unloaded shortening velocity has, similarly, been reported as remaining unaffected by PAP (Stuart, et al., 1988), suggesting that PAP can only benefit the central portion of the force-velocity relationship.

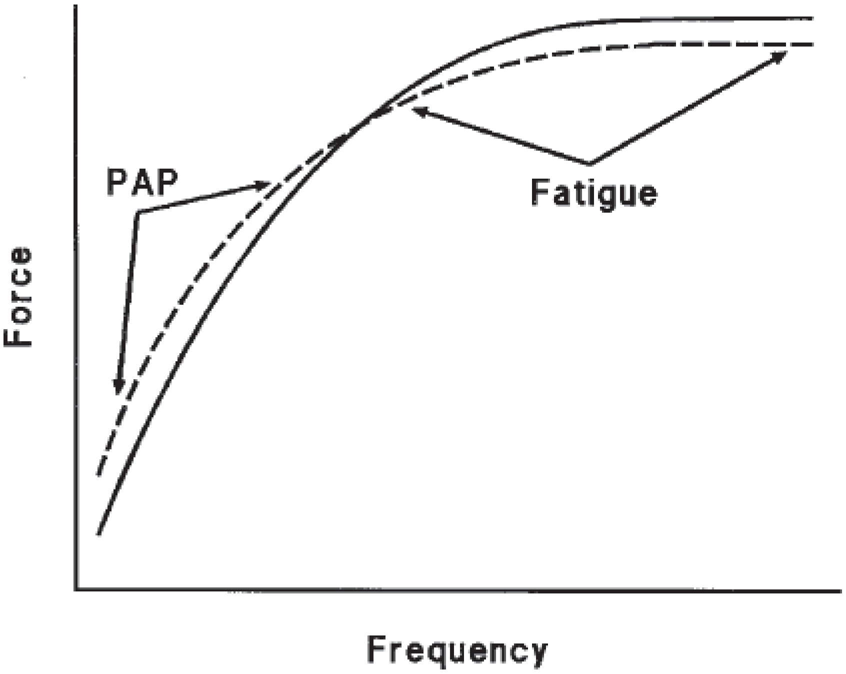

Figure 2.1 Effect of PAP on the Isometric Force-Frequency Relationship.
After a conditioning activity, the induced PAP (dashed line) increases low-frequency tetanic force, where induced fatigue decreases high-frequency force. Source: *(Sale, 2002)*

Applying an electrically-evoked tetanic conditioning contraction (CC) as stimulus, Vandenboom et al. (1993) found that, while an increase in *rate* of force development (RFD) continued to be affected at even the highest rates of firing, a threshold existed for a potentiated force increase. A later PTP study by Abbate et al. (2000) upheld this result in isometric conditions, but found that peak force increased to all but the very highest frequency in dynamic concentric conditions. Rate of force development was enhanced in all frequencies of dynamic and to all but the highest frequency of isometric conditions. The Abbate et al. study further tested mechanical power output over a range of shortening velocities post-CC and found increased power at all but the slowest velocity; magnitude of response was dependent on the stimulus frequency of the contraction. An upwards shift in the velocity associated with peak power was, additionally, observed. In a series of studies testing both electrical stimulus and ballistic contraction of the adductor pollicis in response to MVC, Baudry et al. (2004, 2007a, 2007b), have since confirmed these findings in a PAP setting.

Implication of these outcomes for explosive sports is that potentiation gain may extend to much higher frequencies in concentric muscle action: increased RFD may benefit maximal dynamic (and near-maximal isometric) conditions; increased dynamic force production may be observed to all but the highest firing rates; mechanical power output may be enhanced to varying degrees dependent on shortening velocity and firing rate; and maximum *loaded* shortening velocity increased (Lorenz, 2011). Since athletes who participate in explosive sports will never function at the absolute extremities of the load-velocity relationship, potentiation may augment dynamic strength, power and speed performance (Tillin & Bishop, 2009). In sprint cycling, where each of these performance conditions is observed through the course of a single effort minimally lasting ~10 seconds (Craig & Norton, 2001), distinct mechanisms of potentiation may, therefore, be found through each phase of the performance.

2.3 UNDERLYING PHYSIOLOGY

In spite of their conflicting effects on contractile function, Rassier and MacIntosh (2000) established that fatigue and potentiation co-exist. The primary mechanism of fatigue is specific to the stress applied. However, the final consequence of its action is at cross-bridge level where either a decreased myoplasmic free Ca^{2+} concentration, or decreased sensitivity to Ca^{2+}, results in depression of active force. Where failure of excitation-contraction coupling (ECC) is implicated in LFF (Fowles & Green, 2003) and depressed action potential conduction in HFF (Rassier & Macintosh, 2000), in MF Ca^{2+} sensitivity appears to be negatively affected by rising levels of inorganic phosphates (and disputably acidosis) in the intracellular compartment (Skurvydas, et al., 2007).

The authors assert that, irrespective of the mechanisms involved, the ultimate conclusion of potentiation must also be at cross-bridge level, affecting an interplay with fatigue on the force-pCa^{2+} (plasma ionized calcium) relation (Figure 2.2). In fact, this is consistent with the observations of Hoh (1992), who found potentiation affected a left-shift of the force-pCa^{2+} curve allowing greater levels of force at lower levels of Ca^{2+} leading to enhanced work output of the contractile unit for the same degree of stimulus.

Quantification of the effects of prior activation on subsequent force production has most commonly been made by assessing either twitch force or amplitude of the Hoffman reflex (H-reflex) in response to electrical stimulation (M. Hodgson, 2005). Studies have shown that when a single muscle twitch, evoked by percutaneous electrical stimulation of a superficial nerve, is preceded by a stimulus train of high-frequency pulses to the same nerve, succeeding twitch force is augmented (Clevidence, 2008). Twitch potentiation (TP), therefore, provides a means of assessing the effects of a CC stimulus on the force producing characteristics of the contractile apparatus.

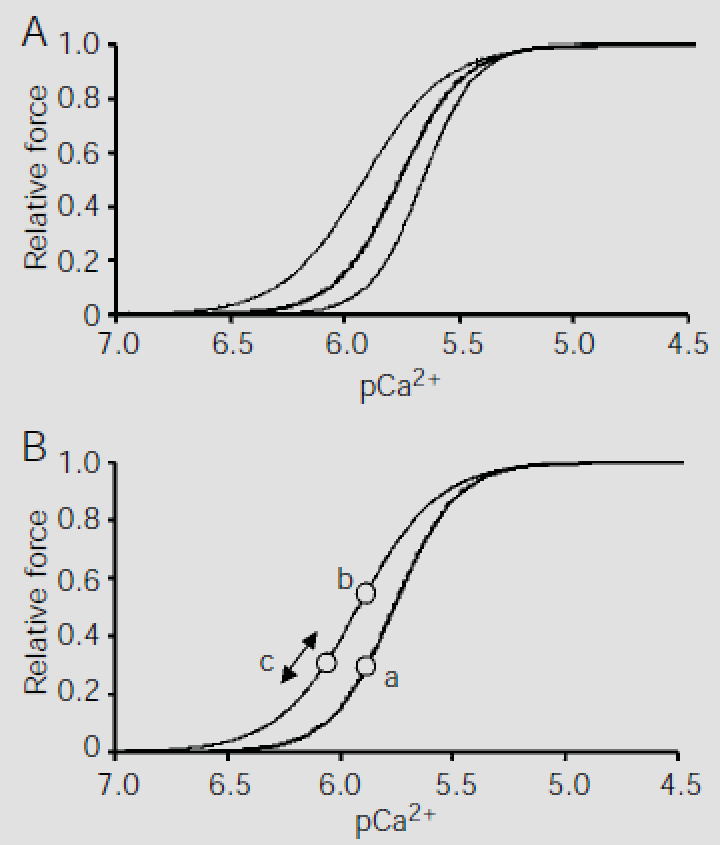

Figure 2.2 Hypothetical Force-Calcium Relationships Demonstrating Combinations of Potentiation and Fatigue.

The thick line in Figure A represents the control condition, where Ca^{2+} sensitivity is neither increased nor decreased. The thinner lines on either side represent enhanced (to the left) or decreased (to the right) sensitivity of the contractile proteins to Ca2+. B, shows the transition from a control situation (a) to an enhanced condition (b) which could represent potentiation. When fatigue is superimposed on potentiation, the force of contraction could be at c, which is indicated to be mobile. That is, the position of c could represent the same active force as a, or something above or below that.

Source: *(Rassier & Macintosh, 2000)*

The H-reflex, recorded at the muscle through electromyography, has commonly been used to quantify the effects of a conditioning stimulus on the neural pathways (Tillin & Bishop, 2009). Stimulation of afferent and efferent pathways of a mixed peripheral nerve, evokes an M-wave of direct stimulus alongside an H-wave of reflex response provided the signal is above activation threshold of the Ia afferents. H-reflex amplitude is, therefore, a function of the number and size of MU recruited and modulation of the H-reflex is commonly interpreted as a measure of altered α-motorneuron excitability: increased H-wave amplitude suggests an increased excitability and, hence, higher order MU recruitment (Holtermann et al., 2007). It is noted that Zehr (2002) has since cautioned full interpretation of the H-reflex in the light of additional evidence on its influencing mechanisms. Analogous to TP research, application of an appropriate CC induces an ensuing increase of H-wave amplitude characterising the effects of reflex potentiation (RP) (Gullich & Schmidtbleicher, 1996).

TP and RP methodologies have not only established the existence of neuromuscular potentiation but have further provided evidence of the characteristics and mechanisms underpinning its effects.

2.3.1 Established Characteristics

Using TP and RP methodology, many early studies tested non-human mammalian skeletal muscle and established a number of critical response characteristics. Replication of these studies in human skeletal muscle has consistently confirmed results (Docherty, et al., 2004; M. Hodgson, et al., 2005). Progression towards the use of maximal voluntary contraction as CC stimulus has further conferred outcomes, albeit with occasional deviation (Babault et al., 2008).

Experimental process for TP in isolated muscle fibres and intact joint action follows similar methodology: measuring twitch properties pre and post application of an electrical CC stimulus or following maximal voluntary contraction (MVC) of the muscle group concerned. Critical findings of this research are the increase in peak force and increased rate of force development of post-CC twitch contraction (Grange et al., 1995; Vandenboom et al., 1995). MacIntosh and Willis (2000) tested unfused tetanic stimuli across a range of frequencies comparable to that of voluntary action and confirmed a force-frequency relationship of the potentiated state in rat muscle. The aforementioned study of Vandenboom et al. (1993) elaborated, finding a 15% increase in peak twitch force at lower frequencies which subsided to a threshold frequency over the region 20-150 Hz. Beyond this improvements in rate of force development continued to be observed. In presenting conclusions that may be of further significance to athletic performance, Gittings et al. (2012) determined that the threshold frequency for observing maximal concentric force potentiation could be extended by increasing the shortening speed of subsequent muscle contraction.

An early study in cats by Brown and Von Euler (1938) documented that the magnitude of potentiating effects of CC was dependent on the CC frequency itself, further mediated by the duration of the CC stimulus. Brown and Von Euler's research also demarcated the different magnitude of response in slow and fast twitch fibres, finding the latter to be markedly greater. Elaboration of frequency analysis has since found that 'optimal' stimulus frequencies exist for potentiation of different muscle groups (and, indeed, different neurophysiological systems), thereby implicating the complexity that will exist in achieving appropriate CC loading for compound muscle action (Hughes, 1958). Feng et al. (1938) determined that the degree of response was, additionally, related to temperature. Potentiation at lower temperatures appears to be proportionately higher, possibly providing a means of increasing activation of only partially activated fibres. While contradictory findings have been reported (O'Leary, et al., 1997), it is clear that the warm-up and environmental conditions in which a PAP protocol is being conducted may have a bearing on outcome.

Further *in vitro* studies have provided insight into the influence of CC protocol on the time-course of twitch response (Alway et al., 1987; Close & Hoh, 1968). Examining results of Close and Hoh, it appears that the number and frequency of pulses in the stimulus train has distinct effects on the decay of the potentiated state and on the peak and duration of the twitch contraction. Whereas a short high-frequency stimulus increases the degree of activation leaving the contraction time unaltered, a longer lower-frequency volley increases contraction time, half-relaxation time and hence twitch duration. The implication of these results has been confirmed by Vandervoort et al. (1983) in a voluntary setting. Testing ankle plantar- and dorsi- flexion, the study determined that the intensity and duration of MVC was critical to achieving both greater force and an earlier occurrence of peak in the post-conditioning twitch response. A minimal intensity of 75% MVC was concluded as being required to induce potentiation, with magnitude of effect maximal following a contraction of ~10 seconds; these observations have since formed the basis for protocols using isometric exercises in whole-body settings (Bulow et al., 1993; O'Leary, et al., 1997).

In volitional and electrical stimulation of human muscle, Alway et al. (1987) demonstrated a potentiated decrease in both twitch contraction time and half-relaxation time when compared to control state. Repeat trials following ischemic exercise conditions further demonstrated the enduring benefits of potentiation in conditions of fatigue when compared to unoccluded conditions. In contrast, Baudry et al. (2004) found contraction and relaxation time unaffected by CC stimulus. Examining the effects of different modes of contraction in voluntary CC stimulus, they did, however, observe potentiated increases in peak twitch torque, rate of torque development and rate of twitch relaxation that were comparative in isometric, concentric and eccentric contractions. The study also crucially observed a present, though declining, potentiation in the second and third pulses of a 3-pulse test train suggesting on-going effects in repeat contraction conditions.

Studies of TP present a somewhat detailed analysis of the effects of CC stimulus on twitch properties. Further noteworthy findings include an increased response in twitches of shorter contraction times (Hamada, Sale, MacDougall, et al., 2000), increased response in muscles with lower twitch/tetanic ratios (Bagust, et al., 1974; Olson & Swett, 1971) and increased effects at shorter muscle lengths (I. E. Brown & Loeb, 1999; Vandervoort, et al., 1983). Miyamoto et al. (2010)

also demonstrated that differences in the magnitude of potentiation response in synergistic muscles observed a co-dependency of joint angle and fibre type. These findings highlight the inherent relation between potentiation and the conditions of contraction. Although muscle properties are essentially beyond control in performance conditions, the specificity of PAP to movement pattern is underscored.

Findings of studies using voluntary CC are more meaningful for optimisation of functional strategies. Baudry et al. (2007b) demonstrated potentiation following a ballistic CC with intensity as low as 20% MVC, concluding that dynamic and isometric CC present different conditions for the observation of PAP; although the degree of potentiation induced appears independent of CC modality. Babault et al. (2008) demonstrated distinct presentation of PAP in shortening, lengthening or isometric contractions post-stimulus, while further determining that magnitude of PAP increased with shortening angular velocity. Houston et al. (1985) confirmed a duration of effect lasting up to 10 minutes, correlating to the time course of phosphorylation. The study further provided the insightful observation that a shorter MVC caused significantly less metabolic disturbance. Confirming that MVC duration influences the degree of fatigue, Miyamoto et al. (2012) concluded that manipulation of CC properties impacts both potentiation characteristics and time window of effect. The duration of CC appears to affect the magnitude and decay of both fatigue and potentiation and while shorter CC’s may reduce fatigue, the magnitude of concomitant potentiation in this condition may be insufficient to observe a beneficial change in performance. Conversely, while Vandervoort et al. (1983) concluded that a longer, 10-second MVC produced the greatest magnitude of twitch potentiation, increasing CC duration extends the influence of fatigue; Miyamoto et al. (2012) determined that, in a dynamic functional setting, a 5-second MVC provided the optimal trade-off.

Finally, Hamada et al. (2000) tested four distinct groups of participants (runners, triathletes, recreational-weight trained and sedentary non-athletes) and found that training status influenced results. Applying 10-second isometric MVC as CC and examining twitch contraction in muscles of the upper and lower body, the study found that the magnitude of effect was related to the degree of training and, in fact, the muscles used *in* that training. Outcomes were greater in active versus sedentary and athletes versus recreational; and, whereas triathletes and active-weight trained demonstrated PAP in both upper and lower muscle groups, only the lower limb muscles potentiated in runners. These results have a far reaching consequence in the interpretation of acute PAP performance studies.

During their examinations of transmitter failure, Luscher et al. (1983) determined that, as with TP, RP is equally dependent on stimulus frequency, volume and duration. A minimum stimulus frequency of 100 Hz appears necessary to evoke response, with subsequent potentiation observed as lasting as much as 16 minutes post-CC. In one of the first performance studies to demonstrate concurrent neuromuscular potentiation and performance improvement, Gullich and Schmidtbleicher (1996) reached similar conclusions while, additionally, observing a relation to fibre-type and participant characteristics.

Applying 5 repetitions of a 5-second MVC as CC, the Gullich and Schmidtbleicher study tested H-reflex of the triceps surae complex alongside force measurements during plantar flexions. Results showed a high correlation (r=0.9) between the time courses of H-reflex and explosive force post-activation response in gastrocnemius (MGL), though lower magnitude of effect and more moderate correlation (r=0.75) in soleus (SOL). The predominant fibre type and, therefore, relative sizes of MU in each of MGL (fast twitch) and SOL (slow twitch), is suggestive of the discrepancies in results. The study highlighted the inherent inter-individual variability in potentiation response, as well as recognising the influence of training on RP: distinct H-reflex results were observed in speed-strength trained versus untrained participants. *Intra*-individual consistency was, however, observed with high (r=0.89) correlation between time points of maximal H-reflex and explosive force response and high (r=0.91) retest reliability between 2 series of measurements. Assessing results, Gullich and Schmidtbleicher concur with the mechanistic analysis of Luscher et al. suggesting that the preload stimulus opens up activation reserves affecting an improved "input-output relationship".

In a further study of volitional contraction, Trimble et al. (1998) found consistent results following a high volume CC (8 sets of 10 repetitions) of reciprocal concentric-eccentric contractions of the triceps surae at maximal intensity. These results support the contention by Gullich and Schmidtbleicher that RP requires a maximal stimulus contraction, while, in addition, revealing that different modes of contraction may achieve similar outcome. The studies observed comparable time courses of response, with an initial H-reflex depression lasting 1-3 minutes and subsequent potentiation lasting up to at least 10 minutes. This is in contrast to TP studies where most have reported a near immediate potentiation response which falls off in an exponential manner over the following minutes (Baudry & Duchateau, 2004; Bulow, et al., 1993; Gossen & Sale, 2000; Hamada, Sale, MacDougall, et al., 2000; Vandervoort, et al., 1983). In a revealing, and largely unique, comparison of TP and RP, Folland et al. (2008) examined the time courses of each effect in the quadriceps femoris before further assessing strength performance at the optimal time point in recovery. Following a 10-second isometric MVC, TP was observed immediately with an exponential decay replicating that of previous TP studies. Similarly, RP conferred with prior research, demonstrating a delay in effect with PAP observed between 5 and 11 minutes post-stimulus. Measures of strength in an isokinetic knee extension failed to improve when tested 5 minutes after CC (believed to represent the optimal trade-off between potentiation time courses). The authors surmise that the time point may have actually compromised, rather than optimised, response and that an earlier recovery time favouring TP or longer time favouring RP may have been more beneficial. In a PAP setting, Tillin and Bishop (2009), have actually proposed that the potentiation-fatigue relation may actually show two windows of opportunity; the first immediately following CC, the second following a rest of 3-4 minutes.

Evidently, while commonalities exist in the expression of TP and RP, each observe unique time courses of effect. This may well be reflective of distinct mechanisms of potentiation. TP and RP studies that have additionally tested performance measures reveal both correlations and discrepancies in functional conditions, highlighting the complexities of multiple inter-relating and modulating factors in whole-body analysis (Gullich & Schmidtbleicher, 1996) (Baudry & Duchateau, 2007b), (Gossen & Sale, 2000). The characteristics of PAP in this environment will, probably, represent a consolidated response of central, peripheral and, indeed, other systemic mechanisms of PAP and fatigue, governed by the type, intensity and duration of the CC and, hence, potentiating stimulus applied.

2.3.2 Mechanisms of Potentiation

Potentiation of function in response to an applied stimulus has been demonstrated in a number of physiological systems. In the auditory system, application of a pure tone creates a sensitising effect that benefits a lowering of the auditory threshold, while bright light stimulus lowers the threshold for phosphene response in the visual system: each of these may be considered the system's equivalent of a tetanus (Hughes, 1958). Evidence for the existence of potentiation of the neuromuscular system dates back to 1858 studies by Schiff et al. who electrically evoked a tetanic contraction in frog muscle and observed an initial depression followed by potentiation of twitch tension relative to preceding values (Hughes, 1958). As distinguished by RP and TP, and analogous to the phenomenon of fatigue, mechanisms of neuromuscular potentiation appear to be both central and peripheral in origin (Tillin & Bishop, 2009). In simple terms, it is evident that execution of a prior tetanic or maximal voluntary contraction would cause fatiguing conditions centrally affecting recruitment of higher order MU in subsequent contractions, while peripherally resulting in increased levels of sarcoplasmic Ca^{2+}, supporting an increased rate of actin-myosin cross-bridging. However, TP and RP studies have each validated more eloquent processes behind potentiation effects.

The most commonly cited mechanism of potentiation is that of an increased phosphorylation of myosin regulatory light chains (MRLC) (Parry, et al., 2008). Following Manning and Stull's (1982) original study demonstrating correlation of the time courses of MRLC phosphorylation and TP, a number of studies have since confirmed their relation (Houston & Grange, 1991; Klug et al., 1982; Moore & Stull, 1984; Xeni et al., 2011). Increased Ca^{2+} as a result of prior contraction increases activation of myosin light chain kinase (MLCK) making more adenosine triphosphate (ATP) available to the actin-myosin complex and, thereby, increasing the rate of cross-bridging. However, MLCK further catalyses phosphorylation of the MRLC binding site. The stimulated increase in phosphorylation process not only potentiates subsequent contractions by altering the structure of the myosin head, but, additionally, renders the binding site more sensitive to Ca^{2+} (Lorenz, 2011).

Supplementary studies in skinned fibres determined that, in conditions of potentiation, contraction force at a given submaximal Ca^{2+} concentration is increased while maximal force remains unaltered (Rassier & Macintosh, 2000). This is certainly intuitive given that increased phosphorylation would have a greater effect at lower concentrations of Ca^{2+}. The mechanism, therefore, satisfies the observed force-frequency relation, further explaining Vandenboom et al.'s observation of a ceiling on force increase, since benefit of Ca^{2+} sensitivity would become less effective at increasingly saturated levels of Ca^{2+} (Szczesna et al., 2002).

Established characteristics, such as the predominance of TP in fast-twitch fibres and a length-dependency of potentiation effect, are further supported through correlation with the phosphorylation mechanism. Moore and Pershini (1990) observed that the phosphorylation process is increasingly depressed at longer muscle lengths, while Moore and Stull (1984) also demonstrated a greater magnitude of phosphorylation response in fast- versus slow- twitch fibres.

Ascertained through RP research, neural basis for potentiation suggests that the application of an intense CC stimulus increases synaptic excitation within the spinal cord, causing an increase in excitatory post-synaptic potentials (EPSP) for the same input potential in subsequent activity (Lorenz, 2011). Studies elaborating the all-or-none principle of activation have observed the occurrence of transmitter failure at synaptic junctions as autonomous protection of activation reserve (Hirst et al., 1981). Luscher et al. (1983) proposed that transmitter failure could be offset by a potentiated increased neurotransmitter release, increase in transmitter efficiency or reduction in axonal branch-point failure along afferent nerves. Testing EPSP response to electrical stimulation in cat α-motorneurons, they discovered that transmitter failure shows increasing effect in larger MU and that effects can be reduced through prior application of a 10-second tetanic contraction. Potentiation would, therefore, increasingly benefit higher order MU and, following the principles of orderly recruitment, fibres with higher force-generation and rate of force development characteristics - benefits again particularly associated with fast-twitch fibres. Applying 20-second tetanic isometric contractions as CC in cats, Hirst et al. (1981) achieved a 54% improvement in EPSP for the same stimulus confirming that prior CC creates more favourable conditions for α-motorneurons reaching firing threshold. The effect has been attributed to the positive influence of CC on a residual elevation in pre- and post- synaptic Ca^{2+} (Gullich & Schmidtbleicher, 1996).

Consequently a likely increase in α-motor unit firing would affect a potentiated increase in action potential initiation and ultimately the number of fibres involved in contraction.

Increased higher order recruitment may be the result of increased excitation, decreased presynaptic inhibition or simply greater central drive (Aagaard et al., 2000). However, Docherty et al. (2004) additionally, suggest that improved neural function may be reflected in increased MU synchronisation following preload stimulus of the relevant performance pathways. Largely unsubstantiated, improved coordination of contraction would certainly increase performance capacity in the goal movement (Ross et al., 2001). Decreased reciprocal inhibition would, equally, allow improved performance of the movement pattern. A recent study by Baker and Newton (2005) saw athletes perform a preload bench *pull* prior to the performance of a 40 kg bench *press* throw (BPT). Performing 8 repetitions of the antagonist exercise with a load of 50% bench press 1RM (56.2 kg (± 3.8 kg), produced a 4.7% improvement of power output in BPT. Suggesting that a heavy CC stimulus may simply unlock "performance potential", Baker and Newton further propose that preloading may inhibit golgi-tendon organ (GTO) and Renshaw cell activation, benefiting performance through the reduction of their limiting effect on maximal MU activation.

A number of authors have suggested that potentiation may simply be a positive effect on muscle-tendon unit (MTU) stiffness through increased excitation of the myotatic reflex or changes in the intrinsic properties of the series elastic components (SEC) (Baker, 2003; Cabrera, et al., 2009; Walshe et al., 1998). The benefits of increased stiffness to explosive exercise through improved force transmission, reduced electromechanical delay (hence increased rate of force development) and improvements in stretch-shortening cycle function, have been established (Wilson & Flanagan, 2008). Longitudinal studies of strength and plyometric training consistently report performance improvements associated with changes in MTU stiffness (Burgess et al., 2007; Kubo et al., 2007;

Markovic et al., 2007; Spurrs et al., 2003; Turner et al., 2003). Acute effects are less clear. Kubo et al. (2001) have shown that *tendon compliance* increases following maximal isometric contractions, while Sinkjaer et al. (1992) demonstrated an increased *muscle stiffness* benefiting torque production in dorsiflexion of the ankle following a PTP protocol. Though these results may appear ambiguous, in active movement stiffness of the muscle and its surrounding parallel elastic components far exceed that of the tendon, suggesting that perhaps an increase in muscle stiffness may outweigh an increased compliance of SEC (Brughelli & Cronin, 2008). Indeed potentiated cross-bridge phosphorylation would result in a parallel rise of muscle stiffness with active force due to a greater transition from weak to strong cross-bridge binding (Rassier & Macintosh, 2000).

Observations of mechanical stiffness in PAP studies support this contention. Comyns et al. (2007) have shown that a high preload (93% 1RM) back-squat produced improvements in counter movement jump (CMJ) performance variables, accompanied by a relatively large (10.9%) increase in leg stiffness. Moir et al. (2011) similarly found a significant increase in vertical stiffness measures following a high load (but not high volume) protocol. Here performance of CMJ height failed to reach significance although only a short, 2 minute, recovery time was provided prior to retesting. Boullosa et al. (2012) found increased vertical stiffness following two different 5RM half-squat CC protocols further establishing correlations between stiffness and peak force and power in CMJ. Assessing upper-body power output, Baker (2003) suggested that a favourable increase in stiffness is achieved with a CC load of 65% 1RM where heavier resistances, above 85% 1RM, are less than optimal. Baker does, however, acknowledge the unlikelihood of a more modest load affecting neural stimulation and, indeed, these results are in contrast to those of Comyns et al. where lighter squat loads failed to produce favourable results. The studies highlight potential distinctions in upper versus lower limb response to PAP.

Architectural changes in response to CC have, additionally been observed. Mahlfeld et al. (2004) measured pennation angle of the vastus lateralis before and after a 3-second isometric MVC. Following a recovery period of 3-6 minutes, a significant decrease in pennation angle was observed equivalent to a 0.9% improvement in force transmission to the bone. But little supporting evidence exists for the effects on potentiation of structural and architectural changes (Tillin & Bishop, 2009). In point of fact, it may be difficult to determine whether changes are through intrinsic properties or neural control of functional behaviour.

In addition to neuromuscular consequences, it is likely that the CC stimulus will have metabolic and psychomotor impact (Ebben & Watts, 1998). Addition of high-load exercise to an existing warm-up protocol may introduce further elevation of muscle temperature, blood lactate and heart rate. It is noteworthy that few potentiation studies have reported metabolic measures. Dinsdale et al. (2009), testing a heavy back-squat protocol as CC stimulus for a CMJ, found a significant rise in lactate due to the protocol, but failed to show performance improvement. Thatcher et al. (2012) improved cycle sprint performance at multiple recovery times following 5 repetitions of 85% 1RM deadlift and reported a significantly greater oxygen consumption and blood lactate at only the shortest times. However, the authors failed to establish correlation to performance results. Performing three different types of CC activity prior to a judo performance test, Miarka et al. (2011) established significant differences in post-test heart rate/throw ratio in each condition but drew no mechanistic correlation to the response. In one of only a few studies comparing a CC with other introduced warm-up components, Zois et al. (2011) determined that in fact a 5RM leg press CC resulted in comparably *lower* metabolic strain as indicated by core temperature, blood lactate and heart rate.

Potentiation research has also observed conflicting effects on hormonal profile. Crewther et al. (2011) tested hormonal milieu in a PAP protocol following a single set of 3RM back squats and found no significant changes in salivary concentrations of either testosterone or cortisol despite improvement in subsequent CMJ. Comparing order effects of strength and power exercises on salivary hormones, Beaven et al. (2011) found that preceding a power exercise with a 3RM squat protocol significantly elevated testosterone, but not cortisol, when compared to each other exercise combination. While equally using 3RM back squats, the protocol utilised 3 sets which may suggest that a higher CC volume may positively benefit levels of the hormone. Few PAP studies have made assessment of hormonal profile and further research is required to elucidate outcomes.

Very few PAP studies have included tests of psychomotor function. However, in the study of learned movement response, post-contraction effects on limb-positioning and anticipation timing have frequently been assessed (Etnyre & Kelley, 1989; Shea et al., 1991). In this research, a preceding isometric contraction has been shown to affect improved response in coincident timing tasks, suggesting enhancement of cognitive interaction and information processing. Following a similar stimulus, improved reaction time coincident with an increase in H-reflex further suggests that heightened neural excitability enhances motor command and motor control (Etnyre & Kinugasa, 2002). In an elegant study by Etnyre and Kinugasa (2002), participants learned to execute a knee extension task as fast as possible, in response to auditory tone. Having mastered the task, reaction time was measured in response to a randomised stimulus tone, pre- and post- execution of a 3-second maximal isometric contraction of the knee extensors. Reaction time (defined by pre-motor and motor times), processing time and muscle contraction time improved following the contraction. Etnyre and Kinugasa conclude that these effects may be incorporated into skilled athlete performance. However, results of the only reaction measures evidenced to date in PAP studies are mixed. Guggenheimer et al. (2009) found no difference in sprint reaction time of collegiate track and field athletes following 3 repetitions of a 90% 1RM power clean, while Zois et al. (2011) found prior execution of 5RM leg press improved performance of amateur soccer players in a reactive agility test.

A number of mechanisms may therefore contribute to potentiation of contractile function. Indeed, evidence refutes the likelihood of a single, predominant source. Tubman et al. (1996) demonstrated that the correlation in time courses of MRLC phosphorylation and TP, fails under certain contractile conditions; highlighting circumstances where neurogenic mechanisms might, otherwise, prevail. Equally Hodgson (2008) failed to observe RP through increased H-wave amplitude, despite post-CC increase in twitch force and rate of force development during plantar flexion. Standaert (1964), examining PTP *in situ*, found a different pronunciation of effects of neurogenic or myogenic origin in slow and fast twitch fibre types respectively. Finally, Sinkjaer et al. (1992) confirmed that potentiation of muscle stiffness prevails where fatiguing reduction of reflex-induced stiffness would otherwise compromise functional integrity. These studies not only confirm that potentiation of skeletal muscle contraction must be attributable to a combination of mechanisms, but that the predominant mechanism is related to the contractile properties and contractile conditions of the muscles concerned (Standaert, 1964).

2.4 EXPLOITATION OF POST-ACTIVATION POTENTIATION FOR PERFORMANCE GAIN

The methodology used in both TP and RP has been extended to evaluation of functional performance: a performance measure is tested, maximal or near-maximal CC applied through either volitional command or electrical stimulus and, following an appropriate recovery period, performance measure retested (Robbins, 2005). Prior discussion reveals that the nature of both the

CC stimulus and performance measure will affect the expression of potentiation and, equally, that of fatigue. The holistic response to CC reflects the net effects of their co-existence on many structures and processes of the electro-mechanical system; accordingly, different elements or phases of movement execution may experience an overriding improvement, impairment or equilibrium in functional capacity. In the functional hierarchy, performance in the post-CC test will then represent the net balance of those outcomes that aided, and those that detracted from, overall performance.

Successful conclusion requires prescription of CC type, intensity and volume appropriate to the athlete and goal movement (Xenofondos et al., 2010). Since mechanisms of fatigue and potentiation appear to develop and dissipate at distinct rates, ensuing performance is, additionally, dependent on the time and conditions of the performance testing itself (Docherty, et al., 2004). In response to the CC protocol, it appears that an initially predominant fatigue decays quickly leaving residual PAP. A small window of potential performance increase is, therefore, available before PAP itself finally decays. A theoretical foundation for the effect lies in the ‘fitness-fatigue paradigm’ first presented by Plisk and Stone (Figure 2.3) (Comyns, 2009). Where ‘fitness’ represents the positive response or adaptation to a training stimulus, the effects of ‘fatigue’ mask full performance potential or ‘preparedness’. As fatigue subsides first over time, at some point preparedness reaches a relative peak and performance transiently exceeds pre-stimulus baseline performance. Since the fitness and fatigue responses emanate from the same source, the model can be applied to both acute and chronic training - in this case aptly describing the window of opportunity for potentiation (Stone et al., 2008).

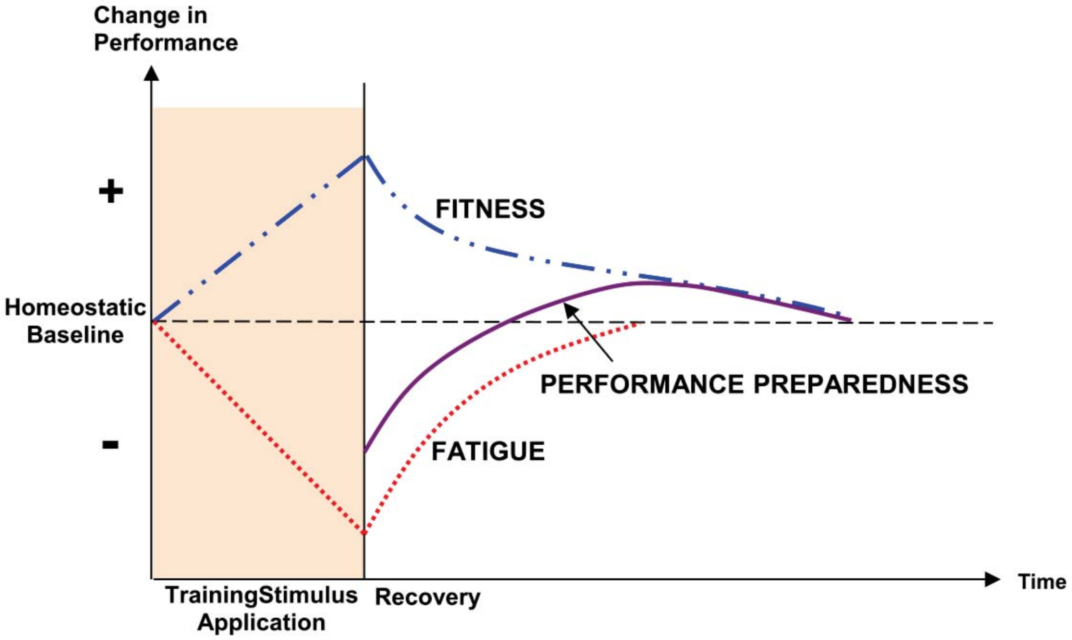

Figure 2.3 Adapted Fitness-Fatigue Model.
Source: (Comyns, 2009)

With careful manipulation of the PAP protocol variables, it is, therefore, theoretically possible to conduct a PAP intervention at an appropriate time-frame ahead of competition and benefit acute improvements in athletic performance (Macintosh et al., 2012). In a recent review Contreras (2010) highlighted the potential ergogenic value, summarising performance gains across successful PAP studies of between 2 and 10%. Realisation of these acute benefits in a competitive environment would require integration of a PAP protocol into the overall pre-competition preparatory strategy. Consideration must, therefore, be given to whether the ergogenic benefits of PAP can supplement existing preparatory gains, or else prevail over alternative strategies.

Comparing a number of preparation strategies in volleyball players, Saez Saez de Villarreal et al. (2007) observed equivalent improvements in explosive jump performance following both loaded squat protocols designed to induce PAP and a standard volleyball-specific preparation; although the PAP protocol was distinguished in sustaining performance improvements over a longer time frame (6hours). Burkett et al. (2005), and Faigenbaum et al. (2006) found that a loaded exercise component was superior to both unloaded dynamic exercise and stretching pre-performance, while, in contrast, Turki et al. (2011) found that addition of a high-load deadlift protocol did not further supplement the benefit offered by stretching alone. Similarly, where Gonzalez-Rave et al. (2009) compared a loaded squat component, stretching and combined squats and stretching, and found no distinction in subsequent jump performance, Needham et al. (2009) determined that a combined protocol of squats and stretches enhanced the existing benefits of dynamic stretching alone. Fletcher (2012) expanded the analysis testing jump performance at each stage of a sequential pre-performance strategy concluding with heavy loaded squats. Progressive gains were observed across the trial, demonstrating that a PAP protocol could indeed supplement benefits afforded by prior components.

These studies suggest that the benefits afforded in an isolated PAP protocol are not guaranteed to augment the effects of a wider preparation strategy. The sport or performance measure is equally influential: where Needham et al. found that a loaded CC protocol enhanced preparation for jump performance, no such outcome was observed in a sprint test conducted in parallel. While protocol variables and biomechanical similarity of the CC certainly affect PAP response, the inter-relation of the global preparatory strategy, CC protocol and performance measure is critical. In assessing the viability of PAP as a strategy for optimising sports performance, it is necessary to consider the context in which that assessment is made; with particular reference to the sport concerned.

2.4.1 Optimising Sports Performance

In elite-level competition small percentage differences in power demarcate outcome. As a result, a substantial body of research has been committed to establishing ergogenic aids or protocols facilitating performance gains (Juhn, 2003). Hopkins et al. (2009) have determined that an improvement in performance of as little as 0.3 times the athlete's performance variability will have a meaningful effect on competition outcome. With coefficients of variation in sprint cycling documented as 0.7-1.3% for race lengths between 200 m and 1 km - this suggests that an ergogenic effect producing a change in race time of as little as 0.2-0.4% is worthwhile (Flyger, 2009; Paton & Hopkins, 2006).

While numerous studies attempt to confirm the efficacy of supplementing performance with mechanical, pharmaceutical, physiological and nutritional aids, the foundation of performance readiness lies in the pre-exercise preparation, commonly known as the warm-up (Wittekind et al., 2012). Studies in this field have demonstrated percentage improvement that would apparently be worthwhile. However, scientific evidence supporting the effectiveness of specific warm-up components or protocols is largely equivocal: results have found performance improved (Bishop et al., 2003; A. M. Jones et al., 2003), unchanged (Bishop et al., 2001; Koppo & Bouckaert, 2002), or declined (De Bruyn-Prevost & Lefebvre, 1980) following a warm-up intervention. In spite of this, athletes universally conduct pre-competition warm-up routines seeking the physiological and psychological benefit they purport (Palmer et al., 2009).

Bishop (2003a) provided a review of warm-up studies and mechanisms, concluding that many of the benefits are simply temperature-related effects that could equally be achieved by passive warming without the concomitant depletion of substrates (Table 2.1). Whereas additional gains can be achieved through activity, an active warm-up imposes some particular demands in ensuring optimal performance in short- or long- duration events. Endurance performance benefits from temperature-related increase in baseline VO_2. However, a high warm-up intensity will increase thermoregulatory strain and accelerate glycogen utilisation - a primary limiting factor in long-duration events (Coyle, 1999). Explosive performance is, instead, related to the ability to breakdown high-energy phosphates, such that the appropriate warm-up for short-duration events must elevate muscle temperature without depleting phosphate stores (Madon, 2007). With temperature increase related to exercise intensity, increasing exercise intensity additionally benefits short-duration performance through a temperature-related up-right shift of the force-velocity curve in dynamic conditions (Bishop, 2003a). Trade-off for short-duration events would appear to be around 60% VO_{2max} beyond which high-energy phosphates are increasingly depleted: in fact, an inverse-relation between warm-up intensity and short-duration performance has been reported (Bishop, 2003b).

In contrast, recent shifts in understanding the role of lactate in physiological function, suggest that increased levels of the metabolite support maintenance of force production at higher intensities (Nielsen et al., 2001; Pedersen, 2004). Studies by Burnley et al. (2003), Jones et al. (2003), and Palmer et al. (2009), confirm that a high intensity warm-up component may, therefore, benefit subsequent exercise through elevated muscle lactate counteracting fatigue-related depression of force output. Burnley even suggests that 'warm-up' may be a misnomer, with increased acidosis the primary ergogenic effect of an active preparatory protocol. Since temperature effects reach a relative plateau between 10 and 20 minutes (Bishop, 2003a), the compromise may be that a warm-up for explosive performance can include higher-intensity efforts if it is restricted in time and followed by an appropriate recovery duration pre-performance to allow recycling of high-energy phosphates (requiring at least 5 minutes), at the same time, avoiding drop in muscle temperature (within 15-20 minutes) (Bishop, 2003b). Previous reference to the study of Tomaras and MacIntosh (2011) on sprint cycling warm-up substantiates these recommendations.

This model of an idealised warm-up is somewhat different from the longer, more intense protocols currently used in power and speed sports (Madon, 2007; Tomaras & MacIntosh, 2011). In being primarily focussed on thermogenic and metabolic effects, it also fails to account for the high demand explosive performance places on psychomotor and neural function (Ross, et al., 2001). Adequate preparation should ensure the athlete is fully aroused, particularly given the short timeframe of task demands and the requirement for highest-order motor unit recruitment and fastest discharge rates. Where inclusion of maximal intensity components in a warm-up may otherwise compromise metabolic performance, the opportunity to prepare these systems through a potentiation protocol is, therefore, evident. Bishop (2003a) certainly acknowledges PAP as a contributing mechanism in warm up (Table 2.1). This may suggest that inclusion of a specific PAP protocol is beneficial. Nevertheless, the trade-offs in intensity, volume and duration of a standard warm-up are equally applicable to PAP and have, as yet, to be fully established (Docherty & Hodgson, 2007). Moreover, the structure of the ideal warm-up (including PAP protocol) will, additionally, depend on training status of the athlete, environmental conditions and event-specific constraints or timeframes (Robbins, 2005). One substantial barrier to the successful application of PAP is certainly the means and time in which to be able to execute a high-load CC pre-competition. Providing a solution to these is a primary focus of current PAP research.

Table 2.1 Possible Effects of a Warm Up.

Temperature Related Effects
Decreased resistance of muscles and joints
Greater release of O_2 from haemoglobin and myoglobin (temperature related shift in O_2 dissociation curve)
Speeding of metabolic reactions
Increased anaerobic mechanism (acceleration of muscle glycogen breakdown, increased ATP supply)
Increased nerve conduction rate
Increased thermoregulatory strain
Decreased resistance of muscles and joints
Greater release of O_2 from haemoglobin and myoglobin (temperature related shift in O_2 dissociation curve)

Non-Temperature Related Effects
Increased blood flow to muscles
Elevation of baseline oxygen consumption
Postactivation potentiation
Psychological effects and increased preparedness

Source: (Bishop, 2003a)

2.4.2 Optimising Sprint Cycling Performance

Sprint performance requires the ability to accelerate, achieve a high maximum velocity and be able to sustain maximal velocity under conditions of fatigue (Ross, et al., 2001). Sprint ability is, therefore, characterised: in neuromuscular performance by fast activation and coordination of muscle fibres; in metabolic performance by the ability to withstand fatiguing effects of intensive anaerobic ATP production; and in anthropometry by volume and quality of muscle mass with respect to the size of the rider (Bowman & Brown, 2012; Craig & Norton, 2001).

Power output demands for sprint cyclists are dictated by a number of variables. These include rider size and position, bike design, bike-rider speed, rolling resistance, air resistance and demands of the specific event (Martin et al., 2007). The maximum power a rider can produce will depend on such factors as pedalling rate, muscle size and fibre-type distribution, riding position and degree of fatigue (Faria et al., 2005a). It is commonly accepted that power is primarily produced at the crank by contribution of muscles spanning the hip, knee and ankle, whereas McDaniel et al. (2005) suggested that in sprint cycling as much as 9% of the total contribution may be derived from transmission across the hip - in effect the core and upper body musculature. Further, Davidson et al. (2005) have determined that the additional power delivered in a standing start is achieved by increased contribution of upper body, while joint power contribution of the hip, knee and ankle remains unchanged. In such cases, to maximise potentiation of relevant neuromuscular pathways, the CC stimulus will require consideration of upper and lower limb contributions.

Additional constraints on the ability to generate power are imposed by the bike itself. The use of a fixed, single gear requires a trade-off between overcoming inertia in accelerating from standing start or low speed and the maximum leg speed achieved at peak velocity later in the sprint. Bike set-up, including rider position, choice of gear and crank length will, therefore, dictate performance along the force-length-velocity relation of contributing muscles (Martin, et al., 2007; Martin & Spirduso, 2001). In the 200 m event, where world class times are of the order of 10 seconds, riders will generate peak torques of over 300 Nm at the outset, achieving peak velocity of around 65 km/h and cadences of 150 rpm by the finish (Craig & Norton, 2001; Schumacher et al., 2001). With muscle shortening velocity determined by pedal speed, muscle power will increase off the line, peak and then decline as pedal speed reaches maximum (Martin, et al., 2007). Pedal rate, or cadence, will, additionally, influence excitation-relaxation kinetics (Neptune & Kautz, 2001), while pedal technique and the ability to effectively direct force round the pedal stroke will influence the transfer of muscular force to forward motion of the bike-rider system (Abbiss et al., 2009; Hug et al., 2008). The interaction of these two factors will consequently determine whether peak force will be produced in the optimal (80-110°) sector of the crank for generating external power (Gregor, 2000). In fact, electromechanical delay (EMD) and pedal stroke variability show increasingly negative effects on power production at higher cadences (Ettema et al., 2009).

Over the course of sprint events, the rider will use both standing and seated riding positions and will be required to achieve maximal performance over an extensive range of the force-velocity-power (FVP) relationship (Craig & Norton, 2001). Optimising conditions for sprint cycling performance, therefore, not only requires the increase of temperature and acidosis levels within appropriate range, but, in addition, should facilitate maximum motor unit recruitment, maximum motor unit discharge rates, fastest nerve conduction and temporal sequencing of muscle activation, maximum rate and efficiency of excitation-contraction coupling and cross-bridge recycling, while positively affecting the hormonal milieu and avoiding any degree of metabolic fatigue (Bishop, 2003b; Cormie, et al., 2011; Madon, 2007; Tomaras & MacIntosh, 2011; Wittekind & Beneke, 2011). In the tightly-constrained bike-rider system the efficacy of potentiation is undoubtedly observed in supporting potential benefits to psychomotor function, as well as both central and peripheral components of the neuromuscular chain of command.

Finally, it is essential to acknowledge that cycling power is generated by predominantly concentric muscle action. Potentiation studies have had some success in cycling outcomes (Jo, et al., 2010; Lawrence, et al., 2010; J. C. Smith, et al., 2001; Thatcher, et al., 2012), and, in such cases, potentiation cannot be a simple augmentation of the stretch reflex or stretch-shortening cycle (SSC) action, as has been suggested (Cabrera, et al., 2009). In fact, prior consideration of PTP studies has revealed the greater potential for response in concentric contractions and cycling presents an ideal movement pattern to validate this finding in whole body performance. Although Bishop (2003b) suggests that temperature related reduction in muscle and joint stiffness would benefit explosive exercise, Watsford et al. (2010) recently showed that an *increased* musculoarticular (MA) stiffness was beneficial to sprint cycling. In support, Ditroilo et al. (2011) have confirmed that a decline in MA stiffness with fatigue significantly impairs performance in a 6-second cycle sprint. The lack of SSC component in the cycling action may impose somewhat different requirements of MTU compliance (Stafilidis & Arampatzis, 2007). In such a case the structural and architectural impacts of preload CC could represent an auxiliary benefit of PAP to sprint cycling performance.

The merit of incorporating a CC protocol into a sprint cycling warm-up is evident and, in fact, could provide a means to surmount the compromises required by existing preparatory strategies. Definition of an appropriate protocol may be made through appraisal of existing performance studies.

2.5 ACUTE EFFECTS OF POST-ACTIVATION POTENTIATION ON PERFORMANCE

The integration of a PAP protocol into the pre-exercise warm-up is certainly advocated, *if* conditions upholding an overall net potentiation can be achieved. However, despite an overwhelming body of research, *in vivo* studies of PAP continue to struggle, in a trial and error approach, to satisfy protocol design (Docherty & Hodgson, 2007). Following the test-CC-retest methodology, such studies examine ballistic movement pre- and post- application of an isometric or dynamic loading protocol designed to evoke PAP. The methodology has equally been applied to induce chronic neuromuscular adaptations. In so-called ‘Complex Training’, either execution of a biomechanically similar strength exercise prior to a power exercise, or alternating paired power and strength (Contrast Training), is used to affect a potentiated increase in training stimulus (Ebben, 2002). In an attempt to consolidate appropriate design recommendations, this review will be constrained to studies where a high resistance or high power exercise is applied as an acute performance stimulus. It is noted that a number of other types of stimuli have been applied in order to evoke PAP in an acute performance setting (for example Batista et al. (2007), Boullosa and Tuimil (2009), Boullosa et al. (2011) and Cochrane et al. (2010)).

2.5.1 Evidence of Potentiation in a Performance Setting

Mechanisms that may improve acute performance in response to prior exercise are multifaceted; the well-established effects of temperature are most commonly cited as the primary benefit conferred (Bishop, 2003a). Successful PAP performance studies have, therefore, been inherently criticised for failing to determine if potentiation was indeed responsible (rather than alternative mechanisms such as those proposed in Table 2.1). Relatively few studies have reconciled performance improvement with evidence of either TP or RP. These studies are summarised in Table 2.2.

As previously acknowledged, evidence of potentiation is most aptly demonstrated in twitch or H-reflex response. The studies of Gullich and Schmidtbleicher (1996), Hodgson (2005) and Iglesias-Soler et al. (2011) each examined H-reflex alongside performance in explosive plantar flexion, producing contrasting results. Where Gullich and Schmidtbleicher found a correlation in the time courses of improvements in each, Iglesias-Soler et al. found performance improvement without concomitant change in H-reflex. Hodgson additionally tested twitch properties and found an increase in post-CC peak twitch torque, without change in either performance or H-reflex. However, the Gullich and Schmidtbleicher study additionally documented the increased propensity for success in highly-trained athletes and, as such, the Hodgson and Iglesias-Soler et al. results can be distinguished by their use of recreationally trained participants. Content of the CC protocols further demarcate outcomes. Comparing 7- and 10-second MVC's, the Iglesias-Soler et al. study found that the longer contraction duration was required to produce improvement and, in such a case, Hodgson's use of a 5-second MVC might not have provided adequate stimulus. While Hodgson utilised 2 additional repetitions of the CC, the Gullich and Schmidtbleicher study advocates a *5 repetition* protocol. Such comparisons highlight that density of the protocol and total time under tension must additionally be considered in strategy design.

Besides Hodgson, TP has been confirmed in a performance setting by a number of other authors. Folland et al.'s (2008) protocol of 10-second MVC knee extension, previously evidencing TP without concomitant performance improvement, affected similar outcomes in the study of Gossen and Sale (2000). Conversely, Mitchell and Sale (2011), Miyamoto et al. (2011) and Requena et al. (2011) established positive relationships between TP and performance. Mitchell and Sale recorded twitch potentiation in the quadriceps femoris 4 minutes after a 5RM back squat before subsequently repeating the trial and finding 2.9% improvement in jump height at the same time point. Testing a 10-second knee extensor MVC in professional soccer players, Requena et al. established a significant positive and negative correlation between improvement in twitch response and performance in squat jump (SJ) and CMJ height, and 15 m sprint time, respectively. Finally, Miyamoto et al. concurrently tested twitch and concentric peak torque of the triceps surae each minute following a 6-second MVC of the plantar flexors, finding the former potentiated between 0 and 5 minutes and the latter between 1 and 3 minutes. Observing an immediate post-CC depression in electromyography (EMG) response of the medial gastrocnemius without changes in M-wave amplitude, results of this study further implicate the presence of central fatigue directly following the contraction. The Miyamoto et al. study, then, perfectly describes the characteristic trade-off in fatigue and potentiation in creating a window of opportunity for performance increase.

Table 2.2 Summary of Literature Providing Evidence of Potentiation in a Performance Setting.

AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Cabrera, et al., 2009)	12M REC	BP	BPT	5R	55,70,86%1RM RD = 4min	ave/pkP EMG	↓ ave/pkP EMG↔
(Esformes, et al., 2011)	10M ATH	BP	BPT	7s 3R RD = 12min	MVC 3RM	pkP, distance pkFo/RFD EMG	↑ pkP w MVC other measures↔
(Fletcher, 2012)	16M ATH	Dyn Ex Stretches BS	CMJ SJ DJ	1x3R,1x3R 1x2R/2min RD = 4min	30,70,90%1RM	jump height EMG	↑ after each CC 4%↑ after BS
(Folland, et al., 2008)	8M REC	KnEx	KnEx	10s RD = 5min	MVC	pkTT, pkFo/RFD H-reflex	↑ pkTT, H-reflex other measures↔
(French, et al., 2003)	10M/4F ATH	KnEx	CMJ DJ KnEx 5s C-sprint	3x3,5s/3min RD = 0	MVC	jump height GRF KnEx pkT cycle pkP, ttpkP	↑JH, pkT w 3s 5s MVC ↔ C-sprint ↔ trend ↑EMG EMG
(Gossen & Sale, 2000)	6M/4F UN	KnEx	KnEx	10s RD=15-60s	MVC	pkTT EMG KnEx pkT, pkV	↑ pkTT KnEx ↔
(Gullich & Schmidtbleicher, 1996)	7UN 10ATH/E	PtFlx MVC	PtFlx	5x5s/1min RD=5s-13min	MVC	pkFo/RFD H-reflex	↑RFD 4-13min ↑H-reflex 4-11min Muscle group fx
(M. Hodgson, 2005)	13M REC	PtFlx MVC	PtFlx	3x5s/1min RD=0-11min	MVC	twitch torque H-reflex RFD	↑TT only

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AUTHOR	**Participants**	**CC**	**PERF EX**	**Protocol**	**Load**	**Measures**	**Outcome**
(Iglesias-Soler, et al., 2011)	14M REC	Soleus MVC	PtFlx	7,10s RD=5s,4,10min	10,100%MVC	pkP H-reflex	↑pkP w 100%,10s H-reflex ↔
(P. Jones & Lees, 2003)	8M REC	BS	CMJ DJ	5R RD=3,10,20min	85%1RM	jump height performance phase EMG	↔
(Mitchell & Sale, 2011)	11M ATH	BS	CMJ	5R RD = 4min	5RM	pkTT jump height	↑ pkTT & JH
(Miyamoto, et al., 2012)	13M UN	KnEx	KnEx	3,5,10s RD=0,1,3,5min	MVC	pkTT pkT EMG	↑ w 5s only
(Miyamoto, et al., 2011)	9M REC	PtFlx MVC	PtFlx	3x6s RD=0-5min	MVC	pkTT pkT EMG	↑ pkTT 0-5min ↑ pkT 1-3min ↓EMG immed post
(Sotiropoulos et al., 2010)	26M ATH	HS	VJ	2x5R/3min RD = 3min	25&35%1RM 45&65%1RM	pkP jump height EMG	↑both load conditions
(Requena, et al., 2011)	14M E	KnEx	15m Sprint CMJ SJ	10s RD = 5min	MVC	pkTT/RTD sprint time jump height	↑pkTT & RTD correlation to sprint & JH

ATH=athlete; ave=average; BP=bench press; BPT=bench press throw; BS=back squat; C-sprint=cycle sprint; CC=conditioning contraction; CMJ=countermovement jump; DJ=drop jump; Dyn Ex=dynamic exercises; E=elite; EMG=electromyography; F=female; Fo=force; fx=effects outcome; GRF=ground reaction force; HS=half squat; JH=jump height; KnEx=knee extension; M=male; MVC=maximal voluntary contraction; P=power; Perf Ex=performance exercise; pk=peak; PtFlx=plantar flexion; R=repetitions; RD=recovery duration; REC=recreationally trained; RFD=rate of force development; RM=repetition maximum; RTD=rate of torque development; SJ=squat jump; T=torque; TT=twitch torque; ttpk=time to peak; UN=untrained; V=velocity; VJ=vertical jump; w=with; ↑indicates increase; ↓ indicates decrease; ↔ indicates no difference.

Further studies have recorded EMG activity as a means of interpreting changes in muscle recruitment following CC stimulus. Esformes et al. (2011) found no change in normalised aEMG (average EMG activity 0.5 seconds before and after peak EMG activity is observed) of the pectoralis major and tricep brachii following a successful CC strategy affecting improvements in BPT performance. In contrast, French et al. (2003), examining PAP of the knee extensors, found a trend for increased EMG activity that additionally reflected the specific CC protocol applied. Demonstrating improved performance in CMJ and knee extension (but notably not 5-second cycle sprint) following 3 repetitions of a 3-second (but not 5-second) MVC, French et al. concluded that activation of a greater number of MU could, in part, be responsible for outcomes. Again differences in protocol were evident, with the Esformes et al. study applying only a single MVC and allowing a more substantial recovery before retesting. In accordance with French et al., Sotiropoulis et al. (2010) found that increases in CMJ height and mechanical power following preload squats were accompanied by an increase in EMG activity of the knee extensors muscles. Fletcher (2012) similarly included analysis of EMG activity in key muscle groups of the lower limb during assessment of jump performance. Examining the effects of a sequential warm-up strategy of cycling, dynamic stretches and heavy back squats, the study demonstrated a progressive increase in jump height following each component. The squat component was observed to add an average of 4% improvement across different types of jumps when compared to pre-squat performance. Increased muscle activation, exemplified by the concomitant increase in aEMG, led authors to conclude that mechanisms of PAP most certainly contributed to the outcome.

In contrast, two studies found neither performance improvement nor evidence of potentiation. Cabrera et al. (2009) compared the effects of CC intensity applying 5 repetitions of a 50, 70 or 86% 1RM bench press as preload to BPT performance. The absence of any significant change in EMG data led the authors to conclude that the potentiation may have simply negated fatigue. Nevertheless, decline in performance power post-CC suggests at least peripheral mechanisms of fatigue were over-riding. The relatively smaller muscle groups of the upper body, and relatively short, 4-minute, recovery time, also suggests that the volume-recovery combination had simply not presented enough time for fatigue to decay. Jones and Lees (2003) used a 5-repetition protocol with 85% 1RM back squat ahead of two distinct jump performances. The only significant result was an increase in EMG activity of the biceps femoris observed in the propulsive phase of a drop jump (DJ). The protocols in each of these studies are similar to that of the successful study of Mitchell and Sale. However, here again, the recreational training status of participants may have contributed to the predominance of fatigue.

2.5.2 Performance Outcomes

The optimal stimulus for potentiation of a goal movement is, most likely, a preceding (near-) maximal contraction of the same movement pattern (Tillin & Bishop, 2009). In single joint action the CC exercise is somewhat instinctive; achieving the prerequisite biomechanical similarity in whole-body performance is more involved. Since the potentiation strategy is inextricably linked to the outcome exercise pattern concerned, subsequent review will be made in the context of those performance outcomes.

2.5.2.1 Jumping

The intuitive pairing of squat-based patterns with jump performance has seen a profusion of studies examining variations of jump tasks as the performance measure. Studies of jump performance are summarised in Tables 2.3 to 2.6, delineated firstly by the type of CC applied and secondly by isolating studies where comparison of different CC modes or performance exercises is made.

Table 2.3 Summary of Literature Examining Jump Performance Post Execution of a Resistance Exercise Pattern as Conditioning Activity.

AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Batista et al., 2011)	23M E/REC/UN	LP	CMJ	1x3s/3min 3x3s/3min RD=4min	MVC	jump height take-off V	↔
(Berning, et al., 2010)	13REC/8 UN	Fl squat	CMJ	3s RD = 4,5min	150% 1RM	jump height	↑ REC only
(Boullosa, et al., 2012)	12M REC	HS	CMJ	5R 5R clustered@30sec RD=1,3,6,9,12min	5RM	pkP,pkFo vert displ leg stiffness Ft measures	↑ independent of RD pkP > 1 min w cluster pkP > 9min w standard set
(Chaouachi et al., 2011)	12M E	HS	CMJ	10,5,5,3,3,1R RD=1,3,5,10,15min	70,70,85,85 90, 90% 1RM	jump height pkP, pkFo,pkV	5x70 most consistent RD varies w measures & participant
(Chiu, et al., 2003)	7ATH/17REC (M/F)	BS	JS	5x1R/2min RD = 5,18.5min	90% 1RM	jump height ave/pkP ave/pkFo	no group fx ↑ATH @ 5min ↑ REC @ 18.5min
(Comyns et al., 2006)	9M/9F REC	BS	SL CMJ	5R RD = 30s,2,4,6min	5 RM	jump height GRF flight time reactive strength index	individualised RD
(Comyns, et al., 2007)	12M E	BS	SL DJ	3R RD = 4,10min	65/80/93% 1RM	flight time GRF leg stiffness	↑ time & GRF all conditions ↑stiffness w heavy load
(Crum et al., 2012)	20M REC	QS	CMJ	3x1R/30s RD=30s,3,4,10,15min	50,65% 1RM	vert displ pkP,pkF,RFD	↔

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Dinsdale, et al., 2009)	6M ATH	BS	CMJ	1,3R 5R RD=1,5,9,13min	90% 1RM 87.5% 1RM	jump height BLa	↔ JH ↑ BLa
(Dinsdale & Bissas)	12M ATH	HC	VJ	3R RD=0-6min	90% 1RM	jump height pkP	↓ 0,2,3min ↔ 1,4,5,6min
(El Hage et al., 2011)	17M REC	BHS	CMJ	3R 1R RD = 2,4min	85% 1RM MVC	jump height	↓
(Gilbert & Lees, 2005)	15M ATH	BS	CMJ KnEx	5x1R/5min RD =1-61min	1RM Pmax	jump height pkFo/RFD	↑ JH both conditions ↑ RFD w time CC load fx RD profile
(Gourgoulis, et al., 2003)	20M UN	HS	CMJ	5x2R each load RD = 0	20,40,60,80, 90% 1RM	jump height	↑ 2.39% 1RM fx results
(Hanson et al., 2007)	24M/6F REC	SMSq	CMJ	8R 4R RD = 4min	40% 1RM 80% 1RM	impulse GRF contact time	↔
(Hoffman et al., 2007)	64M ATH	BS	CMJ	1RM test RD = 5min	1RM	jump height pkP	↑ both measures (JH 3%)
(Jensen & Ebben, 2003)	21M ATH	BS	CMJ	5R RD=10s,1-4min	5RM	jump height GRF	↔
(Kilduff et al., 2008)	20M E	BS	CMJ	3x3R RD =15s,4,8,12,16,20,24min	87% 1RM	pkP,pkRFD	↑ @ 8min jump height
(Khamoui et al., 2009)	16M REC	BS	VJ	2,3,4,5R RD = 5min	85% 1RM	jump height GRF take-off V	↔

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Lowery et al., 2012)	13M REC	BS	VJ	5R 4R 3R RD=0,2,4,8,12min	56% 1RM 70% 1RM 93% 1RM	jump height pkP	↑ higher loads ↑ time course w load
(Mangus et al., 2006)	10M REC	HS QS	VJ	1R/2min RD=3min	90% 1RM	jump height GRF	↔
(Mitchell & Sale, 2011)	11M ATH	BS	CMJ	5R RD = 4min	5RM	pkTT,EMG jump height	↑ pkTT & JH
(Moir, et al., 2011)	11F ATH	BS	CMJ	3R 12R RD = 2min	90% 1RM 37% 1RM	jump height vert stiffness	↑ stiffness w heavy load
(Nibali et al., 2011)	11M ATH	BS	CMJ	5R RD=30s,2,4,6,8,10,12min	5RM	Ft, pkP displacement	↑ pkP individualised RD
(Rixon, et al., 2007)	15M/15F REC/UN	Sq	CMJ	3x3s/2min 3R RD = 3min	MVC 90% 1RM	jump height pkP	Isometric > Dynamic M > F REC > UN
(Ruben et al., 2010)	12M ATH	BS	HorizHJ	5R,3R,3R/2min RD = 5min	30% 1RM,70% 1RM, 90%1RM	ave/pkP ave/pkV ave/pkFo	↑ ave F ↑ pkP strength fx
(Schneiker et al., 2006)	9M ATH	HS	JS	6R CT RD=4min	6RM 30% 1RM	ave/pkP	↔ trend for ↑
(Sotiropoulos, et al., 2010)	26M ATH	HS	VJ	2x5R/3min RD = 3min	25 & 35% 1RM 45 & 65% 1RM	pkP jump height EMG	↑ JH & P bth conditions ↑ EMG

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Witmer et al., 2012)	12M/12F REC	BS	CMJ	3R RD = 3min x 10R	70% 1RM	jump height vert stiffness	↔ no gender fx
(Young, et al., 1998)	10	BS	CMJ	5R RD = 4min	5RM	jump height	↑ w squats (2.8%) correlation to 5RM

ATH=athlete; ave=average; BHS=back half squat; BLa=blood lactate; BHS=back half squat; BS=back squat; CC=conditioning contraction; CMJ=countermovement jump; CT=complex training sets; displ=displacement; DJ=drop jump; E=elite; EMG=electromyography; F=female; FI=functional isometric; Fo=force; Ft=force-time; fx=effects outcome; GRF=ground reaction force; HC=hang clean; HorizHJ=horizontal hurdle jumps; HS=half squat; JH=jump height; JS=jump squat; KnEx=knee extension; LP=leg press; M=male; MVC=maximal voluntary contraction; P=power; power; Perf Ex=performance exercise; pk=peak; Pmax=load that achieved maximum; QS=quarter squat; R=repetitions; RD=recovery duration; REC=recreationally trained; RFD=rate of force development; RM=repetition maximum; SL=single leg; SMsq=smith machine squat; Sq=squats; TT=twitch torque; UN=untrained; V=velocity; vert=vertical; VJ=vertical jump; w=with; ↑indicates increase; ↓ indicates decrease;
↔ indicates no difference; > indicates greater outcomes.

Table 2.4 Summary of Literature Examining Jump Performance Post Execution of a Loaded Jump Pattern as Conditioning Activity.

AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Berning et al., 2008)	8M/6F REC	Ld-J	VJ	30s cont RD = 3,4,5min	30% BW	power	↓ @ 3min ↑ @ 4,5min
(Chattong et al., 2010)	20M REC	Ld-VJ	VJ	5R RD = 2min	5,10,15,20%BW	jump height	↑ in all conditions
(Deneke et al.)	10F ATH	Ld-CMJ	SBVJ AVJ	10R RD = 4min	20% BW	jump height	↑ in AVJ

ATH=athlete; AVJ=approach vertical jump; BW=body weight; CC=conditioning contraction; cont=continuous jumping; F=female; Ld-CMJ=loaded countermovement jump; Ld-J=loaded jump; Ld-VJ=loaded vertical jump; M=male; Perf Ex=performance exercise; R=repetitions; RD=recovery duration; REC=recreationally trained; SBVJ=standing block vertical jump; VJ=vertical jump; ↑indicates increase; ↓ indicates decrease

Table 2.5 Summary of Literature Comparing Different Modes of Conditioning Activity Prior to Jump Performance.

AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Andrews et al., 2011)	19F ATH	CMJ	CMJ	3x3R CT/3min		Vert displ	↓ least w HC
		BS		RD = 3min	75%1RM		
		HC			60%1RM		
(Burkett, et al., 2005)	29M ATH	J	VJ	5R		jump height	loaded > unloaded
		Ld-J			10%BW		
		Stretches					
(Clevidence, 2008)	10M REC	JS	CMJ	5R	Pmax	jump height	↑ w JS
		BS		RD = 5,15min	60%1RM	ave/pkP	5min best RD
(Esformes et al., 2010)	13M ATH	HS	CMJ	3R	3RM	vert displ	↑ w squats
		PLYOS		24 contacts		pkP, pkFo/RFD	↔ w plyo
				RD=5min			
(Fletcher, 2012)	16M ATH	DynEx	CMJ	1x3R,1x3R	30,70,90%1RM	jump height	↑ JH after each CC
		Stretches	SJ	1x2R/2min		EMG	> after BS
		BS	DJ	RD = 4min			
(Gonzalez-Rave, et al., 2009)	24M UN	Sq	SJ	3x4R(w test btwn)/3min	90% 1RM	jump height	↔
			CMJ			GRF	
		Stretches		3x15s			
				RD=3min			
(Koch et al., 2003) (abs)	32M/F	Sq	SBJ	“low volume”	“high % 1RM”		↔
		Speed-Sq		RD = 0,15min	“low % 1RM”		
		Stretches					
(McCann & Flanagan, 2010)	8M/8F ATH	BS	VJ	5R	5RM	jump height	↑ 5.7% if individualised
		HC		RD = 4,5min		GRF	↔M/F
		J					

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Radcliffe & Radcliffe, 1996)	24M/11F ATH	BS	Horizontal CMJ	4x4R	75-85% 1RM	distance	↑ in M w PS only
		PS		RD = 3min	75-85%1RM		↔ in F
		Ld-J			15-20%BW		
(Saez Saez de Villarreal, et al., 2007)	12M ATH	Ld-J	CMJ	3x5R/1min	optimised	jump height	↑ w high load & VB specific
		Sq	DJ	2x4R,2x2R/1min	80,85% 1RM	pkP	↑@6hrs w high load
				2x4R,2x2R,2x1R	80,90,95% 1RM		
				3x5R/1min	30%1RM		
		DJ		3x5R/1min			
		VB specific		RD=5min, 6hrs			
(Smilios et al., 2005)	10M ATH	HS	SJ	3x5R/3min	30,60% 1RM	jump height	↑ CMJ both JS loads
		JS	CMJ	(test @ 1min)			↑ CMJ heavy HS load only
				RD = 5,10min			SJ↔
(Turki, et al., 2011)	20M ATH	DL	CMJ	3x3R/4min	3RM	jump height	↑ w Stretches & DL
		BS		3x3s	MVC	pkP/V/Fo	DL no additional benefit
		TJ		3x3R			RD individualised
		DJ		3R			
		Stretches		RD=15s,4,8,12,16,20min			
(Weber et al., 2008)	12M ATH	BS	SJ x 7	5R	85% 1RM	jump height	↑ over 7R w BS only
		SJ		RD = 3min		GRF	
(Winchell et al., 2009)	7M/F REC	CMJ	CMJ	10R		jump height	↔
		Ld-CMJ		RD = 4min	20,40% BW		

ATH=athlete; ave=average; BS=back squat; BW=body weight; CC=conditioning contraction; CMJ=countermovement jump; CT=complex training sets; DJ=drop jump; Dyn Ex=dynamic exercises; EMG=electromyography; F=female; Fo=force; GRF=ground reaction force; HC=hang clean; HS=half squat; J=jump; JH=jump height; JS=jump squat; Ld-CMJ=loaded countermovement jump; Ld-J=loaded jump; M=male; MVC=maximal voluntary contraction; P=power; Perf Ex=performance exercise; pk=peak; Plyos=plyometric exercises; Pmax=load that achieved maximum power;PS=power snatch; QS=quarter squat; R=repetitions; RD=recovery duration; REC=recreationally trained; RFD=rate of force development; RM=repetition maximum; SBJ=standing broad jump; SJ=squat jump; Sq=squats; TJ=tuck jump; UN=untrained; V=velocity; VB=volleyball; vert displ=vertical displacement; VJ=vertical jump; w=with; ↑indicates increase; ↓ indicates decrease; ↔ indicates no difference; > indicates greater outcomes.

Table 2.6 Summary of Literature Comparing Different Modes of Jump Performance Post Execution of a Conditioning Activity .

AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Deneke, et al.)	10F ATH	Ld-CMJ	SBVJ AVJ	10R RD = 4min	20% BW	jump height	↑ in AVJ
(Fletcher, 2012)	16M ATH	Dyn Ex Stretches BS	CMJ SJ DJ	1x3R,1x3R, 1x2R/2min RD = 4min	30,70,90% 1RM	jump height EMG	progressive↑ thro w-up > after BS
(Gonzalez-Rave, et al., 2009)	24M UN	Sq Stretches	SJ CMJ	3x3R/3min (w test btwn) RD = 3 min	85% 1RM	jump height GRF	↔
(Gullich & Schmidtbleicher, 1996)	36 E/ATH/UN	BP	BPT	1,2,3x1,3,5s/ 0,1,5min, RD=3-5min	90, 100, >100%	pkFo/RFD jump height	↑ RFD, JH CC fx
		LP	VJ/DJ	3x5s/1,5min RD=1-5min	MVC		
(P. Jones & Lees, 2003)	8M REC	BS	CMJ DJ	5R	85% 1RM	jump height EMG	↔
(Kovacevic et al., 2010)	9F E	Semi-Sq	VJ LJ	1R/6s RD=60, 90sec	MVC	jump height jump distance	↑ vertical only @ 60, 90sec

Continued next page

AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Saez Saez de Villarreal, et al., 2007)	12M ATH	Ld-J	CMJ	3x5R/1min	optimised	jump height	↑ w high load & VB specific
		Sq	DJ	2x4R,2x2R/1min	80,85% 1RM	pkP	↑@6hrs w high load
				2x4R,2x2R,2x1R	80,90,95% 1RM		
				3x5R/1min	30%1RM		
		DJ		3x5R/1min			
		VB specific		RD=5min, 6hrs			
(Scott & Docherty, 2004)	19M REC	BS	VJ	5R	5RM	jump height	↔
			HorizJ	RD = 5min		jump distance	no repeat exposure fx
(Smilios, et al., 2005)	10M ATH	HS	SJ	3x5R/3min	30,60% 1RM	jump height	↑ CMJ both JS loads
		JS	CMJ	(test @ 1min)			↑ CMJ heavy HS load only
				RD = 5,10min			SJ↔

ATH=athlete; AVJ=approach vertical jump; BP=bench press; BPT=bench press throw; BS=back squat; BW=body weight; ; CC=conditioning contraction; CMJ=countermovement jump; DJ=drop jump; Dyn Ex=dynamic exercises; E=elite; EMG=electromyography; F=female; Fo=force; fx=effects outcome; GRF=ground reaction force; HorizJ=horizontal jump; HS=half squat; JH=jump height; JS=jump squat; Ld-CMJ-loaded countermovement jump; Ld-J=loaded jump; LJ=long jump; LP=leg press; M=male; MVC=maximal voluntary contraction; P=power; Perf Ex=performance exercise; pk=peak; PtFlx=plantar flexion; R=repetitions; RD=recovery duration; REC=recreationally trained; RFD=rate of force development; RM=repetition maximum; SBVJ=standing block vertical jump; SJ=squat jump; Sq=squats; UN=untrained; VJ=vertical jump; VB=volleyball; w=with; ↑indicates increase; ↔ indicates no difference; > indicates greater outcomes.

Table 2.3 presents those studies where a resistance exercise pattern was used as CC. Examining those studies utilising isometric CC, results are divided: Berning et al. (2010) and Rixon et al. (2007) found improvements in jump performance following a squat pattern; Batista et al. (2011) found no change and El Hage et al. (2011) found performance declined. The Berning et al. and Rixon et al. studies acknowledge the influence of training status, agreeing that participants of a higher training status showed a higher proclivity for success. The Batista et al. study, however, similarly compared training status, with no apparent difference observed. In utilising the leg press exercise as CC, the insignificant outcomes in this study might simply be indicative of the lower degree of specificity. Certainly, the upright posture and, hence, increased spinal loading in the squat pattern, will add to the nervous system excitation in the former trials. Intensity of the MVC is critical and the capacity to achieve an absolute maximal contraction is considered a distinguishing factor of training status (Astrand et al., 2003). Utilising functional isometric squats, Berning et al. presented a supra-maximal loading (150% 1RM) which may, therefore, have ensured the highest level of recruitment. Effects of MVC duration is apparent and, again, delineation can be made in the repetitions and density of the CC protocol - the Rixon et al. trial applied multiple repetitions and provided a 2-minute recovery between contractions.

The Rixon et al. and El Hage et al. studies provide further interest in comparing isometric and dynamic CC modes of contraction. Dynamic preloading of 3 repetitions of 90% (Rixon et al.) and 85% (El Hage et al.) 1RM squats were similarly unsuccessful and clearly, for Rixon et al., the isometric protocol had the better results. Yet, results of other studies using single set dynamic CC have been favourable. Mitchell and Sale (2011), Nibali et al. (2011) and Young et al. (1998), each found improvement executing 5 repetitions of back squats at a load of 5RM (equivalent to 85-87% 1RM) suggesting greater volume may be required. However, Comyns et al. (2007), Lowery et al. (2012) and Moir et al. (2011) successfully potentiated performance outcome with 3RM back squat repetitions; here, though, the participants were of much higher training status (being trained athletes).

Comparing various load-repetition combinations and the time course of effect, Lowery et al. further acknowledges that higher loads extend the time window in which PAP is observed. Broadening the analysis, Chaouachi et al. (2011) determined that optimal load-repetition-recovery combinations were highly individualised, even in elite athletes: though trial results suggested 5 repetitions at 70% 1RM were most consistent. The Comyns et al. trial compared 3 repetitions at low (65% 1RM), moderate (80% 1RM) and high (93% 1RM) loads and found that, in elite athletes, all intensities were sufficiently beneficial. Uniquely examining single leg jumps, the study recorded increasing effects on leg stiffness at higher intensities suggesting that additional gain was afforded in this condition. In a comparison of two different densities of 5 repetition-5RM preload, Boullosa et al. (2012) found equal success but at different recovery times. A 'cluster-training' configuration, which allowed 30 seconds rest between repetitions, peaked performance almost immediately, where a standard configuration peaked at 9 minutes post-CC, inferring influence of CC density on the decay-time of fatigue.

Contrasting results in single-set protocols can likely be elucidated by protocol factors including: low intensity (Witmer, et al., 2012); low training status (Khamoui, et al., 2009); individualisation of the time course of response (Jensen & Ebben, 2003) and inappropriate CC exercise (Batista, et al., 2011; Dinsdale & Bissas, 2010; Hanson, et al., 2007). With respect to the latter, as with Batista et al.'s use of leg press, Hanson et al.'s Smith Machine squats probably did not induce sufficient excitation; Dinsdale and Bissas' use of a hang clean, though satisfying load-velocity demands as a suitable high power stimulus, may not, in this instance, have provided adequate kinematic similarity to the performance exercise.

Outcomes of multiple set protocols are far more consistent. Gourgoulis et al. (2003) succeeded in potentiating CMJ by an average of 2.39% in non-athletes, applying a 5 set protocol of half squats with 2 repetitions performed at each of 20, 40, 60, 80 and 90% 1RM. Dividing the group by 1RM strength, the stronger participants were found to have achieved a mean increase of 4.01%, further corroborating the influence of training. Rubin et al. (2010), similarly, used an ascending protocol, here reducing the repetitions per set as load increased and found consistent results in horizontal hurdle jumps. The study additionally confirmed the correlation to strength, with individuals who could squat greater than two times their body mass demonstrating the greatest potentiation. Where the former studies had retested performance at a single point following CC, Kilduff et al. (2008) extended analysis by repeatedly examining performance over a 24-minute period following 3x3 (set x repetition) back squat with 87% 1RM load. The study confirmed the potentiation time course as demonstrating an initial performance depression followed thereafter by performance increase, peaking at 8 minutes with an improvement in jump height of 4.9%. Further, correlation between 3RM strength and magnitude of potentiation at the 8 minute time point was established. Gilbert and Lee's (2005) use of a 5x1 protocol reinforced previous findings in 1RM load conditions by establishing significant increase in both jump height and rate of force development between 15 and 20 minutes post preload - a later time to peak here consistent with the lower training status of participants. On the other hand, when using a load maximising individual power, the potentiation of jump and RFD appeared almost immediately at 2 minutes, thereafter declining. Although it cannot be established if the 2 loading schemes affected distinct mechanisms of potentiation, the results are certainly suggestive of substantially different responses. Finally, Chiu et al. (2003) tested 2 modes of jump squats at 5 and 18.5 minutes following a 90% 1RM squat adopting the same 5x1 protocol. Where group results were inconsistent in time and magnitude of response, when separated into ‘trained’ and ‘recreational’ athletes, the trained group observed consistently improved performance at 5 minutes. The relationship between training status, fatigue decay and PAP response is further substantiated.

Only one study using multiple sets failed to find positive gain. Crum et al.'s (2012) use of low loads (50 and 65% 1RM), a single repetition per set and quarter squat movement pattern appear to have provided little stimulus for PAP. Equally, in comparing half squat and quarter squat patterns, Mangus et al. (2006) observed no change. The restricted range of motion in the squat patterns could have contributed through factors such as altered recruitment, mechanics, reflex response and effects on the series elastic components. Once again the protocol is deficient with a single 90% 1RM repetition as CC following execution of warm-up sets.

Examining the full summary of jump studies, it is evident that the majority of trials involved testing unloaded countermovement vertical jumps. Only two studies assessed loaded jump performance. The Chui et al. (2003) study is unique in assessing three different intensities of jumps squats (30, 50 and 70% 1RM), doing so in 2 modes – rebound and concentric only. In spite of differences in contribution (or otherwise) of stretch-shortening cycle activity, similar statistical results in rebound and concentric conditions implies the equivalent contribution of PAP to each performance. In Schneiker et al.'s (2006) testing of a 30% 1RM jump squat, improvements in peak and average power over two successive repeats of the preload-exercise pairing failed to reach significance. Although the authors explicate outcomes by suggesting PAP may benefit low- but not high-load power, the single set CC protocol might simply have been marginally insufficient.

Table 2.5 summarises studies comparing different modes of CC. A number of studies examined the effects of CC on unloaded concentric-only SJ with results showing similar tendencies to previous jump studies. Weber et al. (2008) found improvement in repeat SJ efforts using a single-set high-load back squat as CC, while SJ themselves as CC failed to improve subsequent test jumps. The aforementioned warm-up study of Fletcher (2012) found improvements in each of CMJ, DJ and SJ after the high load squat component of the warm-up - though the CMJ and DJ showed significantly higher response than that of SJ. Gonzalez-Rave et al. (2009) mimicked a complex training session in a repeated protocol design similar to that of Schneiker et al.'s, testing 3 repeats of 3 distinct preload-CMJ or SJ combinations. The study found no difference between preload conditions, but did observe distinct patterns in overall response of CMJ and SJ across repeat sets. Squat jump responded as in the Schneiker et al. study, peaking after set 1 and declining after subsequent sets, where CMJ declined initially increasing after sets 2 and 3. Smilios et al. (2005) compared the effects of 30% and 60% 1RM loads (with equivalent set-repetition combinations) in both jump squats and back squat and demonstrated potentiating effects on CMJ at both loads in response to the power exercise, but heavier load only in the strength exercise. No significant change was found in testing SJ. Together these studies suggest that, although differences do present in concentric only activities, it is unlikely a consequence of the lack of SSC contribution alone. Instead, the combination of CC variables may simply require a distinct optimisation.

The Smilios et al. study illustrates the ability of a biomechanically similar power exercise to potentiate with lower relative loads, where the lower movement velocity in strength exercise necessitates a higher loading. In agreement, Clevidence (2008) compared a jump squat loaded to achieve maximum power, with a 60% 1RM back squat, finding that only the former achieved significant potentiation at 5 minute post-CC. Andrews et al. (2011), McCann and Flanagan (2010), and Radcliffe and Radcliffe (1996) each compared the use of a heavy resistance exercise (back squat) with an Olympic lift as CC. Over 3 repeats pairing either back squats or hang cleans with performance CMJ, Andrews et al. found no acute improvement in CMJ following the preload intervention. However, results showed that hang cleans best maintained performance in the fatiguing repeat conditions of the trial. Comparing back squats, power snatch, loaded and unloaded jumps as CC, Radcliffe and Radcliffe, likewise, determined the power exercise as the best outcome, observing significantly greater distance in horizontal CMJ of male (though not female) participants in this condition. McCann and Flanagan tested vertical jumps at two different recovery times following each of back squats and hang cleans as CC and conceded that optimal strategy for PAP was highly individual such that no overall best strategy could be recommended. Comparing mean 'best outcome' versus control condition demonstrated a 5.7% increase in vertical jump height following an individualised protocol.

A few studies have attempted to use the jumps themselves as PAP stimulus (Table 2.4). Satisfying the load-velocity demand for CC, Berning et al. (2008), Chattong et al. (2010) and Deneke et al. (2010) each achieved positive outcome by adding a weighted vest to the jump condition, thereby maintaining biomechanical specificity while appropriately increasing the intensity of effort. Further studies compared loaded and unloaded jumps with other interventions such as heavy resistance exercise and stretching (Table 2.6). Results of Burkett et al. (2005), Esformes et al. (2010) and Saez Saez de Villarreall et al. (2007) individually corroborate the intensity dependent relation of CC in achieving performance gain under higher load conditions. The de Villarreal et al. study must be further distinguished in providing evidence of a much longer time frame of effect. Repeating testing at 6 hours, the authors found the performance measure still in excess of those pre-CC in high load conditions. In contrast to these outcomes, Turki et al. (2011) compared dynamic deadlifts, isometric back squats, tuck jumps (TJ), DJ and stretches as warm-up interventions and found significant increases in vertical jump height, peak power, velocity and force, in only the deadlift and stretch conditions. Closer inspection determined that, in fact, the deadlift did not further augment the benefits afforded by stretching alone. In testing athletes, it would have been expected that both the 3x3RM deadlift and 3x3-second isometric back squat protocol would have been successful. Thus, it can be suggested, that the methodological impact of conducting stretching ahead of the loaded conditions counteracted their potentiating effects. PAP has previously shown to be blunted by stretching (Cè et al., 2009; Parry, et al., 2008; Sale, 2002), though current discourse on the effects of stretching on strength and power performance observes contrasting opinions (Behm & Chaouachi, 2011; McHugh & Cosgrave, 2010).

Finally, it is apparent that results in horizontal jump conditions are similar to those in the vertical plane, showing success (Radcliffe and Radcliffe (1996), Table 2.5; Ruben et al. (2010), Table 2.3) and failure (Kovacevik et al. (2010), Scott and Docherty (2004), Table 2.6) that may be distinguished by protocol and participant factors. Successful protocols used vertically loaded CC exercises equally achieving improved performance in the horizontal plane. Potentiation of the relevant neuromuscular pathways appears sufficiently beneficial despite the impulse being applied in a different direction. There is one exception: Kovacevic et al.'s comparison of high and long jumps preceded by isometric semi-squats, benefitted height but not distance, leading the author to conclude that biomechanical specificity was not achieved horizontally. Interpretation of this conclusion requires assessment of the methodology used and, unfortunately, no explanation was provided as to jump technique and whether controlled conditions were applied in execution. Nevertheless, the limited range applied to the CC pattern is questionable.

2.5.2.2 Upper Body Power

Where ballistic performance of the lower limb is commonly tested in squat-jump combination, the instinctive pairing of bench press (BP)-bench press throw (BPT) has been utilised in a number of protocols examining PAP of upper body power (Table 2.7). Muscle groups of the upper body present some distinctions compared to those of the lower limb, including relative size and functional requirements, and it is apparent that some differences exist in PAP response.

Comparing the squat-jump and BP-BPT combinations, Kilduff et al. (2007) presented 3 repetitions of a 3RM (approximately 90% 1RM) load as CC in each condition and measured performance over a recovery time course of 20 minutes. The 3RM protocol has, elsewhere, been successful in trained participants. The professional rugby players of the Kilduff et al. study yielded similar benefit, increasing peak power by 8% and 5.3% at the 12-minute point in the lower and upper limb, respectively. An initial depression, then potentiation between 8 and 12 minutes, was similar in each.

Table 2.7 Summary of Literature Examining Upper Body Power Performance Post Execution of a Conditioning Activity.

AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Baker, 2003)	16M ATH	BP	BPT	6R RD=3min	65% 1RM	pkP	↑ 4.5%
(Baker & Newton, 2005)	24M ATH	Bpull	BPT	8R RD=3min	50% BP 1RM	pkP	↑ 4.7%
(Bellar et al., 2012)	17 E	O-W throw	H-T throw	5R RD=3min	1.35kg O-W 2.27kg O-W	distance	↑ w both CC
(Brandenburg, 2005)	8M REC	BP	BPT	5R RD=4min	50/75/100% 5RM	aveP per phase	↔
(Cabrera, et al., 2009)	12M REC	BP	BPT	5R RD=4min	55/70/86% 1RM	ave/pkP EMG	↓ ave/pkP
(Ferreira et al., 2012)	11M REC	BP	BP	1R RD=1,3,5,7min	1RM	ave/pkP	↑ @ 7min
(El Hage et al., 2012)	10M REC	BP	BP	3R 4R RD=0,2,4,8min	80% 1RM 20% 1RM	pkP	↑ w light load
(Esformes, et al., 2011)	10M ATH	BP	BPT	7s 3R RD = 12min	MVC 3RM	pkP, distance pkFo/RFD EMG	↑ pkP w MVC other measures ↔
(Faigenbaum, et al., 2006)	18F ATH	Ld-dyn ex stretches	VJ LJ MB toss 10yd sprint	9 exercises 5 stretches RD = n/s	2, 6% BW	jump height jump distance toss distance sprint time	↑ VJ, LJ w Ld-dyn ex other measures ↔

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AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Farup & Sorensen, 2010)	8M ATH	BP	isom BP BPT	5x1R/5min RD=1-21min	1RM	pk isomFo/RFD pkP	↓ RFD pkP↔
(Gullich & Schmidtbleicher, 1996)	36 E/ATH/UN	BP	BPT	1,2,3x1,3,5s/ 0,1,5min, RD=3-5min	90, 100, >100%	pkFo/RFD jump height	↑ RFD, JH CC fx muscle group fx
		LP	VJ/DJ	3x5s/1,5min RD=1-5min	MVC		
(Hrysomallis & Kidgell, 2001)	n/s	BP	Expl PU	5R	5RM	impulse pk RFD	↔
(Judge, Bellar, & Judge, 2010)	10M/F ATH	O-W throw	H-T throw	5R RD = 3min	1.35kg O-W 2.27kg O-W	ave/pk distance	↑w both conditions light>heavy
(Judge, Bellar, & Glickman, 2010)	6F ATH	MB throw	Shot put	1R RD = n/s	8,18.2kg	distance	↔ trend for ↓
(Kilduff, et al., 2007)	23M E	BS BP	CMJ BPT	3R RD=15s,4,8,12,16,20min	3RM	pkP	↓ @ 15s ↑ 5.3&8%@12min ↑BPT only 16min ↔ @ 20min
(Markovic et al., 2008)	23M REC	BP	MB throw	3x3R/3min RD = 3min	3RM	pk ball speed	↑ w 4kg ball
(Matthews et al., 2009)	12M ATH	BP MB pass	BB push-pass	5R RD = 4min	85% 1RM 2.3kg	flight time	↓ w BP only
(Read et al., 2012)	16M ATH	CMJ	Golf swing	3R RD=1min		club head speed	↑
(Terzis et al., 2009)	16M/8F REC	DJ	Sq-throw	5R RD = 20s		distance muscle biopsy 6RM LP strength	↑ distance M only correlation w typeII fibres LP strength relation

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Tsolakis et al., 2011)	13M/10F E	BP Plyos PU LP TJ	CMJ BPT	3x3s/15s 3x5R RD=0,4,8,12min	MVC	pkP	↓ pkP CMJ w RD in MV ↔ other conditions -‘ve correlation w strength
(West et al., 2012)	20M E	BP	BPT	3x3R RD = 8min	87% 1RM 30% 1RM	pkP	↑ both conditions
(Wilson et al., 2012)	16M ATH	Ld-bat swing	Bat swings	5R RD = M RD=1,2,4,8min		pk bat V, accel pk/ttpk accel	↔

Accel=acceleration; ATH=athlete; ave=average; BB=basketball; BP=bench press; BPT=bench press throw; Bpull=bench pull; BS=back squat; BW=body weight; CC=conditioning contraction; CMJ=countermovement jump; DJ=drop jump; Dyn Ex=dynamic exercises; E=elite; EMG=electromyography; Expl=explosive; F=female; Fo=force; fx=effects outcome; H-T=heel turn; isom=isometric; JH=jump height; Ld-bat swing=loaded bat swing; Ld-dyn ex=loaded dynamic exercise; LJ=long jump; LP=leg press; M=male; MB=medicine ball; MVC=maximal voluntary contraction; n/s = not specified; O-W=over-weight; P=power; Perf Ex=performance exercise; pk=peak; Plyos=plyometric exercises; PtFlx=plantar flexion; PU=push ups; R=repetitions; RD=recovery duration; REC=recreationally trained; RFD=rate of force development; RM=repetition maximum; Sq-throw=squat throw; TJ=tuck jump; ttpk=time to peak; UN=untrained; V=velocity; VJ=vertical jump; w=with; ↑indicates increase; ↓ indicates decrease; ↔ indicates no difference; > indicates greater outcomes.

However, lower limb returned to baseline by 16 minute where upper remained significantly higher. The single set protocol was, certainly, a relatively low volume stimulus compared to other successful squat-based protocols and, it may be, that the upper body responds better with less preload. In agreement, Farup and Sorensen (2010) retested the successful squat-jump protocol of Gilbert and Lees using BP-BPT, finding no benefit to peak power and a reduction in rate of force development, suggesting the protocol was too severe. Brandenberg (2005) and Cabrera et al. (2009) each tested 5 repetitions of BP over a range of intensities and found no positive effect. Both studies retested at 4 minutes, a time point at which Kilduff et al. similarly found no benefit and perhaps a longer recovery would have revealed a positive outcome. The recreational training status of participants advocates that a period longer than that of Kilduff et al. was likely necessary. Nevertheless, Baker (2003) observed a 4.5% improvement in peak BPT power at 3 minutes following a 6 repetition protocol in athletes. Here, relative loading of 65% 1RM is a somewhat moderate load for athletes in this volume of lift, which may, again, corroborate lighter preloading requirements of upper body musculature.

In contrast, Gullich and Schmidtbleicher (1996) reported the need for maximal recruitment in achieving PAP by comparing near-maximal 1x3 (90% 1RM load), maximal 1x1 and 3x1 (100% 1RM load), quasi-isometric 2x1 (>100% load) and isometric 5x5-seconds (>100% load in fixed hold position). Additionally varying the time between repetitions (density) and post-CC recovery time, the study found improvements in rate of force development in all but the sub-maximal condition, with superior outcomes in moderate volume (1-3 contractions) and low density (5 minute rest between contractions) strategies. The Gullich and Schmidtbleicher study, though, predominantly focuses interest on the neural mechanisms of PAP and presents few sub-maximal volume comparisons that may have provided an alternative outcome. Nonetheless, Esformes et al. (2011) also found an isometric CC to be the most successful, with peak power significantly higher at 12 minutes post-CC following a 7-second MVC, where a dynamic 3RM BP failed. Again, an alternative dynamic loading may have produced more favourable results in this condition.

Comparisons have also been made between high resistance and power patterns in potentiating BPT. West et al. (2012) assessed BPT power following 3 sets of 3 repetitions BP conducted as either a heavy resistance (80% 1RM) or ballistic (30% 1RM) exercise. Peak power tested at 8 minutes was significantly, and comparatively, elevated when compared to pre-CC condition suggesting that both high load and high power stimuli are equally effective. In spite of the elite status of participants, Tsolakis et al. (2011) failed to show any benefit of either an isometric or plyometric CC on subsequent BPT performance. Equivalent comparisons of lower body ballistic performance were similarly unsuccessful. It has previously been acknowledged in jump assessment that, even with power exercises, loading is critical. In such cases, the Tsolakis protocol appears to have presented little stimulus in either condition. The isometric strategy of 3 repetitions of a 3-second MVC mirrored that of the successful Rixon et al. protocol in jump performance. However, here the substantially higher CC density (15-second versus 2-minute rest between contractions) may have been detrimental – indeed in this trial countermovement jump performance actually declined following CC.

The pairing of bench press with alternative ballistic upper body exercises has been examined with contrasting results. Hrysomallis and Kidgell (2001) failed to potentiate explosive push-ups following 5 repetitions at 5RM load, while Markovic et al. (2008) succeeded in improving performance in a medicine ball (MB) throw using a strategy of 3x3 at 3RM load. The Markovic et al. study specified the influence of performance load on outcome with contrasting effects using heavy and light weight MB: only the heavier of the two showed a significant difference in peak ball speed. El Hage et al. (2012) and Ferreira et al. (2012) each used BP as a CC stimulus for subsequent low-load power performance of BP. While Ferreira et al. found a 1RM BP improved BP 50% 1RM power at 7 minutes post-CC, El Hage et al. compared 2 load-volume combinations and found a lighter, higher volume combination more successful in potentiating 40% 1RM BP power at 2 and 8 minutes.

Comparisons of resistance and power CC have also been conducted in other ballistic exercise settings. Matthews et al. (2009) assessed the outcome of 5 repetitions of either 85% 1RM BP or 2.3 kg MB pass on subsequent basketball push-pass. Performance was assessed as flight time over a fixed distance and, although a trend was observed in the MB condition, only the BP showed a significant reduction in time. At first view, it appears this result contradicts the performance load finding of Markovic - but the basketball itself represented a weight slightly higher than the unsuccessful condition of the Markovic et al. study. The CC itself was, additionally, lighter, with higher repetitions in a single (rather than multiple) set protocol.

The use of an overweight projectile as CC ahead of a ballistic throw is an intuitive load-exercise pairing in upper body performance. Bellar et al. (2012) compared two load conditions of overweight implement as preload for a heel-turn throw in collegiate and elite athletes and improved throw distance equally in each case. The results corroborate positive outcomes of previous study by the same research team (Judge, Bellar, & Judge, 2010); in this case, results showed a higher magnitude of improvement with the lighter of the 2 overload conditions, an outcome likely relating to the lower training status and relative strength of the participants. Contrasting results were found by the team in assessing shot-put throw (4 kg shot) preceded by either an 8 kg or 18 kg MB throw as CC (Judge, Bellar, & Glickman, 2010). Here performance, given by distance of the throw, declined. The research is only presented in abstract form and the protocol appears to have been simply a single weighted throw added to the warm-up. This is unlikely to have evoked PAP: rather, as observed, simply fatigue the arm. Wilson et al. (2012) used a similar approach seeking to increase the peak velocity and acceleration of baseball bat swing. Trial conditions compared a number of overweight bats without effect. An earlier baseball study of Reyes and Dolny (2009) had, similarly, found no potentiating effect. Since weight is added to the distal end of the bat, consideration should be given that the load may have adversely affected swing mechanics and, hence, coordination.

Though energy transfer to a thrown implement is ultimately delivered by the musculature of the upper limb, upper body ballistic power requires the functional integration of the whole body. A few studies have examined the effects of a lower body CC on upper body performance. Faigenbaum et al. (2006) failed to potentiate MB toss through a loaded (though unspecific) dynamic exercise protocol, while Terzis et al. (2009) observed that 5 repetitions of a drop jump CC intervention improved subsequent performance of squat underhand front shot throw in male, but not female, participants. This is easily attributable to a potentiated contribution of the squat pattern in generating initial momentum for the throw. However, the study offers greater insight in finding a positive correlation between magnitude of improvement and the percentage of type II fibre, as determined by muscle biopsy following completion of the trial. A weaker relation with 6RM leg press strength was also observed. The recent study of Read et al. (2012) is more interesting in achieving a significant improvement in golf club head speed following the inclusion of 3 repetitions of CMJ in the golf-specific warm-up. Analysis of the golf swing reveals a complex functional movement requiring coordination of leg, core and arm action. In such cases, while the CC offers little kinematic specificity, potentiated improvement in power and synchronised performance of the core and lower limb musculature may have enhanced the sequencing of the action from the ground up (C. J. Smith et al., 2011).

2.5.2.3 Sprinting

The majority of studies assessing PAP in jump performance have observed benefit in conducting a loaded resistance or power squat-variation ahead of the exercise. Further, these vertically loaded squat patterns appear to have positive carry-over to horizontal jumping. Performance in squat jump and countermovement jump has been determined as an appropriate predictor of 100 m sprinting (Smirniotou et al., 2008), while jump-squat power is related to sprint acceleration (G. Sleivert & Taingahue, 2004). It is reasonable to predict that similar potentiation schemes may assist sprinting.

Table 2.8 Summary of Literature Examining Sprint Performance Post Execution of a Conditioning Activity.

AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Antonopoulos, et al., 2012)	14M ATH	HS	30m sprint	10x1R/3min RD=3,6,9,12min	90% 1RM	10/20/30m split time	↓ 10m @ 6min ↓ 20/30m @ 12min
(Berning et al., 2009)	5M REC	Fl squat	40yd sprint	3s RD = 4min	150% 1RM	sprint time	↓ time
(Bevan et al., 2010)	16M E	BS	10m sprint	3R RD=4,8,12,16min	91% 1RM	5,10m split time	↓ w individualised RD
(Bomfim Lima et al., 2011)	10M E	DJ	CMJ 50m sprint	2x5R/3min RD =5,10,15min		jump height sprint time	↑ JH @ 15min(6%) ↓ time @ 10,15 min (2.4,2.7%)
(Chatzopoulos et al., 2007)	15M ATH-REC	BS	30m sprint	10x1R/3min RD = 3,5min	90% 1RM	10,30m splits 0-10,0-30m speed	↑ performance @ 5min
(Comyns, et al., 2010)	11M E	BS	30m sprint	3R RD=4min	3RM	10m split time ave/pkV per phase	↔ first trial ↑ 20m,30m V w repeats
(Creekmur, 2010)	10M ATH	Ld-CMJ	40m sprint	2x8R/3min RD = 5min	n/s	20,40m splits	↓ split times (1.15,1.24%)
(Crewther, et al., 2011)	9M E	BS	CMJ Sled push 10m sprint	3R RD=15s,4,8,12,16min	3RM	jump height 5,10m sprint time 3m push time Salivary hormones	↑ JH only > w individualisation of RD
(Faigenbaum, et al., 2006)	18F ATH	Ld-dyn ex stretches	VJ LJ MB toss 10yd sprint	9 exercises 5 stretches RD = n/s	2,6% BW	jump height, dist jump distance toss distance sprint time	↑ VJ, LJ w L-dyn ex other measures ↔

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Linder et al., 2010)	12F REC	BS	100m sprint	4R RD=9min	4RM	sprint time	↓ time
(McBride, et al., 2005)	15M ATH	Squat Ld-CMJ	40m sprint	3R RD=3min	90% 1RM 30% 1RM	10,30,40m split time	↓ 40m w squat only split times ↔
(Matthews, et al., 2004)	20M E	BS	20m sprint	5R RD=5min	5RM	sprint time	↓ time (3.3%)
(Needham, et al., 2009)	20M E	Static Stretches Dyn Stretches FS	CMJ 20m sprint	+8R RD=3,6min	+20% BW	jump height pkP 10,20m split time	↑ JH w FS split time ↔ dyn stretches split time ↔ FS
(Okuno, et al., 2013)	12M E	HS	RSA	1x5R/1x3R/5x1R /2min RD = 5min	50%/70%/90% 1RM	pk sprint time ave sprint time	↓ pk & ave time
(Rahimi, 2007)	12M E	BS	40m sprint	2x4R/2min RD = 4min	60% 1RM 70% 1RM 85% 1RM	pk speed	↑ all conditions > w heavier load
(Requena, et al., 2011)	14M E	KnEx	15m sprint CMJ SJ	10s RD = 5min	MVC	pkTT/RTD sprint time jump height EMG	↑ pkTT & RTD correlation to time & JH
(Till & Cooke, 2009)	12M E	DL TJ isom KnEx	VJ 20m sprint	5R 5R 3x3s/15s RD=4,5,6min	5RM	10,20m split time jump height	↔ individualisation response

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Yetter & Moir, 2008)	10M REC	BS FS	40m sprint	5R/4R/3R/2min RD = 4min	30/50/70% 1RM	ave speed 10m split time	BS>Control 10-20m BS>FS 30-40m
(Zois, et al., 2011)	10M REC	SmSiGame LP Team sport	CMJ Reaction exercise 20m sprint (RSA)	5R RD = n/s	5RM	jump height sprint time reactive ability BLa, HR, PRE	↑ JH w SmSiGame & LP ↓ time w LP ↑ reaction w LP

ATH=athlete; ave=average; BLa=blood lactate; BS=back squat; BW=body weight; CC=conditioning contraction; CMJ=countermovement jump; DL=deadlift; DJ=drop jump; Dyn=dynamic; E=elite; EMG=electromyography; F=female; FI=functional isometric; FS=front squat; HR=heart rate; HS=half squat; isom=isometric; JH=jump height; KnEx=knee extension; Ld-CMJ=loaded countermovement jump; Ld-dyn ex=loaded dynamic exercises; LP=leg press; M=male; MB=medicine ball; MVC=maximal voluntary contraction; n/s=not specified; P=power; Perf Ex=performance exercise; pk=peak; PRE=perceived rate of exertion; R=repetitions; RD=recovery duration; REC=recreationally trained; RM=repetition maximum; RSA=repeated sprint ability; RTD=rate of torque development; SJ=squat jump; SmSiGame=small sided game; TJ=tuck jump; TT=twitch torque; V=velocity; VJ=vertical jump; w=with; ↑indicates increase; ↓ indicates decrease; ↔ indicates no difference; > indicates greater outcomes.

It may be expected that benefit of PAP would be restricted to single-action explosive efforts. However, a number of studies have used back squat as a potentiating stimulus and found improvements in sprint time or velocity in sprints conducted over a range of distances (Table 2.8). In the longest distance study, Linder et al. (2010) tested recreationally trained women in 100 m sprinting and found that 4 repetitions of 4RM (87-88% 1RM) back squat significantly improved sprint time by 0.19 seconds. In moderate distance trials a number of studies show consistent results. Rahimi (2007) successfully improved 40 m sprint performance applying 2 sets of 4 repetitions of back squats at different loads, additionally noting the positive relation between peak speed and CC load. McBride et al. (2005) demonstrated improvements in 40 m time using a high intensity back squat set of 3 repetitions at 90% 1RM, while, in comparison, a further condition using 30% 1RM loaded CMJ as preload was unsuccessful. The authors concluded that a heavy lifting protocol is required. However, Creekmur (2010) used the same power exercise and improved 40 m sprint time using a higher volume protocol (2 sets of 8 repetitions). While Yetter and Moir (2008) equally improved 40 m sprint performance using a high resistance back squat CC, differences between the Yetter and Moir, and McBride et al. results are revealed in the distinct response over intermediate split times. McBride et al. failed to show any significant change at the 10 m and 30 m splits where the Yetter and Moir study found significant improvement between 10 and 20 m. Furthermore, the magnitude of response was much greater over the 40 m distance in the Yetter and Moir study, showing a markedly higher 2.3% compared to 0.9% improvement in the McBride et al. trial despite similar participant samples. The volume of the Yetter and Moir protocol was again higher, using ascending load across multiple sets peaking at a substantially lower intensity than that of McBride et al. With sprint outcomes it is possible that the intensity-volume relation not only affects the success, or otherwise, of the preload itself, but also the phase of the sprint in which benefit is observed.

Interestingly, although the Yetter and Moir trial found significant improvements in speed over the first 20 m, no difference was observed between 20 and 30 m. Comyns et al. (2010) retested the

McBride et al. protocol over a single 30 m distance and initially agreed that there was no benefit: in fact, findings reflected a deterioration of performance following the CC. However, 3 subsequent repeats of the trial day found that performance gradually improved, measures equalling pre-CC results after session 2 and marginally increasing above pre-CC in sessions 3 and 4. This led the authors to conclude that participants could learn to utilise PAP through repeat exposure. Further reflection can be made with respect to the fixed, 3 or 4 minute, recovery periods of the Comyns et al., McBride et al., and Yetter and Moir trials. Chatzopoulos et al. (2007) applied a high intensity, high volume but low density strategy (10 sets of 1 repetition back squats at 90% 1RM) and tested 30 m sprint with 10 m splits at recovery times of 3 and 5 minutes. Significant improvements in both 10 and 30 m times were found at 5 minutes, but not 3 minutes post-CC. Repeating the same CC protocol and measuring 10, 20 and 30 m splits over multiple recovery times, Antonopoulos et al. (2012) confirmed the post-activation depression (PAD) at 3 minutes but observed a significant PAP in 10 m split at 6 minutes and in 20 m and 30 m splits at 12 minutes. Just as the intensity-volume relation distinctly affects sprint phases, it appears recovery time is, similarly, somewhat discrete.

The Creekmur study, which assessed performance over shorter distances, found significant improvement over the 20 m split, while Matthews et al. (2004) equally found benefit of 5 repetitions of 5RM back squat over the same (single) distance. Needham et al. (2009) compared the addition of dynamic stretching and a loaded squat protocol to warm-up prior to execution of 20 m sprint and vertical jump. Although the squat protocol produced a significantly higher jump, results of 10 m and 20 m splits were significantly better than the control warm-up, but indistinct from the dynamic stretching condition. Here, however, the CC used was a *front* squat pattern. The Yetter and Moir study repeated their testing of 40 m sprint using the front squat and found contrasting results. The average velocity over 10-20 m and 30-40 m distances was significantly higher in the back squat condition versus control. While no difference was observed between back and front squat between 10 and 20 m, over the 30-40 m phase of the sprint the back squat was additionally significantly higher than the front squat condition. These outcomes could possibly be due to differences in the biomechanics of front and back squat execution. Comparing the two exercises, Gullett et al. (2008) found no difference in muscle recruitment of each. However, differences in the position of the bar centre of mass *do* affect torso position and, consequently, knee and hip extensor moments in each condition (Russell & Phillips, 1989). Nevertheless, the mechanics of the front squat results in a propensity for lower lifting capacity and the comparatively lower absolute load documented in the front squat trial, could equally distinguish the results.

Analysis of sprint performance delineates four phases of performance as initial acceleration, transition, attainment of peak velocity and maintenance of peak velocity (Cunha, 2005). A number of authors agree that the 0-10 m distance is a pure acceleration phase, having distinctive differences in muscle activation and kinematic profile as compared to the subsequent maximal velocity phases (Delecluse, 1997; Hrysomallis, 2012; McFarlane, 1993). With respect to this phase of the sprint, results appear to be inconsistent. In addition to the lack of improvement found over the 10 m distance in trials of Comyns et al., McBride et al. and Yetter and Moir, Crewther et al. (2011) determined that a single set of 3RM back squat provided no benefit to either 5 and 10 m sprint; a 3 m loaded horizontal sled push was similarly unsuccessful. However, potentiation of CMJ *was* observed during the same trial, leading the authors to cite biomechanical specificity as the obvious distinction. In contrast, Antonopoulos et al. (2012) and Chatzopoulos et al. (2007) found performance improvement at the 10 m split, while Bevan et al. (2010) examined 5 and 10 m sprint performance following the same CC protocol as Crewther et al. and concluded it to be beneficial. Although the Bevan et al. study produced no group significance, comparison across retest time points up to 16 minutes post-CC highlighted that positive outcomes were present on an individualised basis. However, Crewther et al. similarly examined multiple recovery times and, indeed, examined individualised CMJ results. Most variables of the trials are equivalent, making it difficult to interpret their contrasting outcomes. Participants of both studies were rugby players though the Crewther et al. study reported sub-elite status compared with the elite players in Bevan et al.'s study. While strength characteristics are similar, the difference in status is reflected in a 5-year difference in average chronological age between the studies. This may also distinguish training age. Further, considering the distinct training phases in which the trials were conducted (post-power in-season in Bevan et al. and off-season in Crewther et al.), the participants of the Bevan et al. trial would have been in a more highly trained condition. Statistical power was, in addition, much higher in the Bevan et al. study. Nonetheless, it would appear that, while performance in peak velocity phases is responsive to PAP, the acceleratory phase is less consistently so.

Whereas dynamic squat patterns have been more prevalent, a few studies have examined sprint in response to other CC exercises. Berning et al. (2009) utilised the functional isometric squat, successfully applied in CMJ performance, and found a single 3-second maximal contraction was sufficient to improve 40 yard (approximately 36.6 m) sprint time. Comparing a number of warm-up strategies including 5 repetitions of high resistance (5RM) deadlift, Till and Cooke (2009) failed to potentiate either 20 m sprint or VJ performance. The trial protocol and participants' training status are equivalent to that in the successful Matthews et al. study using back squat, suggesting that differences in loading profile of the CC exercise may have bearing on outcome. However, Zois et al. (2011) compared soccer warm-up strategies and found significant benefit in 20 m sprint performance using the same intensity-volume combination in a preload leg press - an exercise with seemingly less biomechanical specificity to sprinting. Maintaining significance over the course of 15 repeated sprint efforts, the Zois et al. study suggests sustained benefits of a high resistance warm-up. The finding is confirmed by Okuno et al. (2013) who tested 6x30 m shuttle sprints (with turnaround at 15 m) following an ascending intensity 3-set squat protocol and demonstrated significant reductions in best and mean sprint times across the 6 repetitions. Though the sprint test was embedded in an intermittent exercise circuit, the study provisionally confers the potential benefit of PAP over repeated execution of explosive activities.

Table 2.9 Summary of Literature Examining Sports Performance Post Execution of a Conditioning Activity.

AUTHOR	**Participants**	**CC**	**Perf Ex**	**Protocol**	**Load**	**Measures**	**Outcome**
(Feros, et al., 2012)	9M/1F E	Isom row	1000m row	5x5s/15s RD = 4min	2s subMVC, 3s MVC	100m splits aveP stroke rate	↓ time (1.9%) ↑ aveP (6.6%) ↑ SR (5.2%) first 500m
(French, et al., 2003)	10M/4F ATH	KnEx	CMJ DJ KnEx 5s C-sprint	3x3,5s/3min RD = 0	MVC	jump height GRF KnEx pkT cycle pkP, ttpkP	↑JH, pkT w 3s 5s MVC ↔ C-sprint ↔ trend ↑EMG EMG
(Hancock, 2004)	15M/15F ATH	Ld-swim	100m S-sprint	4x10m/1min RD = 6min	individualised	50m split time BLa	↓ time
(Jo, et al., 2010)	12M REC	BS	30s wingate	5R RD=5,10,15,20min	85% 1RM	abs ave/pkP rel ave/pkP Fatigue Index	↑ power w individualised RD correlation 1RM to RD
(Kilduff, et al., 2011)	7M/2F E	BS	CMJ 15m S-sprint	3R RD=15s,4,8,12,16min	87% 1RM	jump height pkP 15m time Start pkVFo/HFo	↑ JH @8min ↑ pkVFo & HFo 15m time ↔
(Lawrence, et al.)	7M/3F REC	Ld-cycle	10s C-sprint	8-10s RD = 4min	max	abs/rel pkP Fatigue Index	↑ abs/rel pkP
(Matthews et al., 2010)	11M ATH	Ld-sprint	25m ice sprint	10s RD = 4min	individualised	sprint time	↓ time (2.6%)

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AUTHOR	Participants	CC	Perf Ex	Protocol	Load	Measures	Outcome
(Miarka, et al., 2011)	8M ATH	Plyos Sq	Judo test CT	10x3R/30s 3x1R/2min RD = 3min	95% 1RM 3x2+5R/2min	num of throws HR 90% 1RM	plyos ↑ throws CT ↑ test index test index
(Parry, et al., 2008)	7M ATH	BS	30s wingate	5x1R/2min RD = 20min	30% 1RM 90% 1RM	ave/pk/end P fatigue index	↔
(J. C. Smith, et al., 2001)	9M REC	BS	10s C-sprint	10x1R/2min RD = 5,20min	90% 1RM	ave/pkP	↑ P @ 5min
(Thatcher, et al., 2012)	10M REC	DL	30s wingate	5R RD=5,10,20,30min	85% 1RM	pkP aveP per phase Fatigue Index gas analysis BLa	↑ aveP to 5,10s @ 10min ↑pkP @ 10 min

Abs=absolute; ATH=athlete; ave=average; BLa=blood lactate; BS=back squat; C-sprint=cycle sprint; CC=conditioning contraction; CMJ=countermovement jump; CT=complex training sets; DJ=drop jump; DL=deadlift; E=elite; EMG=electromyography; F=female; Fo=force; GRF=ground reaction force; HFo=horizontal force component; HR=heart rate; Isom row=isometric pull on rower erg; JH=jump height; KnEx=knee extension; Ld-cycle=loaded cycle; Ld-sprint=loaded (resisted) sprint; Ld-swim=loaded (resisted) swim; M=male; MVC=maximal voluntary contraction; P=power; Perf Ex=performance exercise; pk=peak; Plyos=plyometric exercises; R=repetitions; RD=recovery duration; REC=recreationally trained; rel=relative; RM=repetition maximum; S-sprint=swim sprint; SR=stroke rate; Sq=squats; T=torque; ttpk=time to peak; V=velocity; VFo=vertical force component; ↑indicates increase; ↓ indicates decrease; ↔ indicates no difference.

2.5.2.4 Other Sports

Achieving a CC matched to movement kinematics in sports where movement complexity or environmental factors impact performance, is a more challenging task. A few studies have attempted to influence performance gain in these sports through identifying and potentiating key components of the overall movement. Further studies have achieved an appropriate CC condition by applying resistance to the performance movement itself. A summary of these studies is provided in Table 2.9.

Isolating a movement phase or muscle group central to performance may assist in determining an effective PAP strategy. In swimming, Kilduff et al. (2011) attempted to benefit sprint time by focussing on start performance off the blocks. Three repetitions of 87% 1RM back squat were added to the warm-up and assessment was made over the start to 15 m distance under 50 m race conditions; post-CC recovery time for the trial was optimised by prior assessment of CMJ potentiation following the same CC protocol. Improvements in performance kinetics were observed with significantly higher peak vertical and horizontal components of starting block reaction force. However, athletes appeared unable to capitalise on benefits: time to 15 m was unaltered. In cycling, French et al. (2003) failed to potentiate a 5-second maximal sprint through isometric MVC of the knee extensors. Improvements in parallel tests of jump performance and dynamic knee extensions and a concomitant increase in EMG activity of the knee extensors, suggest mechanisms of PAP were present. However, no change was observed in peak power or time to peak power in the cycling test. Studies in sub-maximal conditions agree that flexion of the knee provides the dominant contribution to cycling action, representing 45-54% of net joint power (Horscroft et al., 2005; Pettitt et al., 2002). In contrast, McDaniels et al. (2005) determined that the distinct task specificity of maximal sprinting imposes the requirement for a more prominent hip contribution in order to maximise the power production capacity of the joints. In fact relative hip contribution has been shown to increase from 26% to a more considerable 41% at higher cadences during maximal sprints (Pettitt, et al., 2002).

The ankle joint and upper-body musculature also contribute and relative contributions are further dependent on power output and cadence (Martin et al., 2002; Sanderson et al., 2008). In such cases, it is unlikely that potentiation of the knee extensors alone would have provided enough stimulus for overall performance improvement. Further, the relatively low load used for the ergometer test conditions would not have facilitated maximal power output during the sprint. Although the author states this as acceptable in a comparative trial, it does not present optimal conditions for observance of PAP.

Three studies examined performance in a 30-second cycle sprint following a loaded squat-based movement pattern as PAP stimulus - more appropriately exciting the musculature of the three contributing joints and torso. Conducting the trials following the commonly used Wingate protocol, the studies produced disparate outcomes. Jo et al. (2010) applied 5 repetitions of an 85% 1RM back squat and found that improvements in peak power were only realised when comparing individualised recovery times. Correlation of 1RM strength to recovery duration further confirmed that PAP was observed earlier in stronger participants, where weaker participants required more time presumably allowing decay of a presiding net fatigue. Parry et al. (2008) utilised a strategy of 5x1 back squats comparing loads of 90% 1RM and 30% 1RM and found no improvement in either condition. In this case, a single recovery time of 20 minutes was applied before retesting and few studies have observed a potentiation over such a long time frame. Thatcher et al. (2012), instead, tested Wingate performance at multiple recovery times following execution of a deadlift. Applying 5 repetitions at 85% 1RM load, a significant 9% improvement in peak power was observed 10-minutes post-CC. Expanding the analysis further, Thatcher et al. assessed mean power over discrete time periods of the test finding significant improvement in the index over the first 5 and 10 seconds only - again at the 10 minute mark. The authors conclude that PAP response might only be consistent in sprints of 10 seconds or less.

Thatcher et al.'s conjecture is partly supported by other studies. Though French et al. (2003) failed to induce performance gain in a 5-second sprint, two studies of 10-second sprints have been successful. Smith et al. (2001) preloaded the sprint with a high volume, high intensity, but low density protocol of 10x1 back squats at 90% 1RM. Average power was significantly higher when the trial was retested at 5 minutes post-CC, while a trend was observed for similar improvement in peak power. Lack of significant improvement in either parameter at 20-minutes post-CC adds credibility to the suggestion that recovery time was too long in the Parry et al. trial. Whiteford et al. (2011) and Lawrence et al. (2010) have each published results of the same study, inventively using the resistance of the test ergometer itself as a heavy preload stimulus. With the bike loaded to apply maximum resistance, participants conducted a pre-trial sprint. Concurrently, the researchers applied additional manual pressure to the flywheel, eliciting complete fatigue within 8-10 seconds. Following a 4-minute recovery, the 10-second test sprint was then conducted with an ergometer loading equivalent to 7.5% of the participant's body mass. Power values in the preload condition were significantly higher than that of the control trial.

Loading of the performance movement itself presents an effective CC strategy that has been successfully applied in a number of other sporting disciplines. Feros et al. (2012) utilised an ergometer as preload and tested measure in rowing performance. Trials of elite rowers used 5 repetitions of a 5-second isometric pull in a fixed position on the rowing ergometer and found a significantly improved performance with 1.9% improvement in time, 6.6% in mean power and 5.2% in stroke rate over the first 500 m of a 1000 m effort. The study crucially highlights the potential for

PAP gain in middle distance speed-power events. Acknowledging the highly-specialised biomechanics of ice hockey movements and lack of likely correlation with off-ice squat-based loading patterns, Matthews et al. (2010), alternatively, used a 10-second heavy resisted on-ice sprint as preload to ice sprint performance in national league players. Time over 25 m improved 2.6% following the resisted effort. Hancock (2004), similarly, used a resistive pulley-loading system as a PAP strategy in sprint swimming. Here, swimmers conducted 4 maximal 10 m efforts tethered to the power rack system with individualised load, rested 6 minutes and then performed a 100 m freestyle sprint. Overall time and 50 m split times improved equally for both male and female athletes following the CC protocol. While few existing studies have taken this approach, mimicking the performance outcome in loaded conditions appears to be a highly advantageous strategy warranting closer inspection.

2.5.3 Summary of Characteristics

While results of acute PAP studies appear equivocal, commonalities exist in the impact of protocol variables and participant characteristics. Design of a successful PAP strategy appears to be dependent on intricately balancing a number of inter-related variables: where trials show no response, mitigating factors associated with the balance of variables are frequently evident (Batista, et al., 2011; Hanson, et al., 2007; P. Jones & Lees, 2003; Witmer, et al., 2012).

2.5.3.1 Protocol Factors

Studies consistently report that a high load is required to influence net potentiation (Matthews, et al., 2009; McBride, et al., 2005; Rahimi, 2007; Smilios, et al., 2005). However, the intensity required is equally dependent on the volume of CC applied (Gullich & Schmidtbleicher, 1996). This suggests that PAP is related to CC workload rather than absolute intensity *per se*. In fact, Lowery et al. (2012)

compared three trial conditions of low- , moderate- , and high- intensity CC controlling for total work by maintaining volume-load, and found that both moderate- and high- intensity protocols produced a similar potentiation of performance. Distinction with the high-intensity trial was only observed in the longer window of effect observed in this condition. Potentiation of acute performance has been observed at short (Baker, 2003), medium (Chiu, et al., 2003) and long (Saez Saez de Villarreal, et al., 2007) time intervals post-CC. With reference to the PAP decay characteristics established through TP and RP, these outcomes may be indicative of the predominance of different potentiation and fatigue mechanisms being influenced by the intensity-volume combination. The inter-relation of intensity-volume-recovery time presents as one of the critical factors delineating trial response.

Multiple set protocols appear to be more consistent than those applying a single set (Gourgoulis, et al., 2003; Kilduff, et al., 2008; Radcliffe & Radcliffe, 1996; West, et al., 2012). Where the CC set is repeated, the rest period between sets has additional impact, highlighting the importance of protocol density on the fatigue-potentiation relation (Rixon, et al., 2007; Tsolakis, et al., 2011). Results of the Boullosa et al. (2012) study, comparing a standard set and cluster-spaced set, equally suggest that density of *repetitions* within a set influences the post-CC recovery time. A protocol utilising appropriate recovery between repeated high-intensity CC, possibly allows adequate stimulus to be achieved without inducing over-riding fatigue. The recurrent success of 10x1 or 5x1 protocols at 90% 1RM load support this recommendation (Chatzopoulos, et al., 2007; Gilbert & Lees, 2005; J. C. Smith, et al., 2001).

The intensity-volume-density-recovery interaction is further mediated by the mode and muscle groups of contraction. Potentiation of subsequent performance has been observed following dynamic-heavy resistance (Nibali, et al., 2011), dynamic-power (Radcliffe & Radcliffe, 1996) and isometric (Rixon, et al., 2007) CC modes. There is little to suggest that one may have advantage over the other, though the optimal CC variable combination appears to be unique to each mode and some disparity exists in the response characteristics observed. Tillin and Cooke (2009) have related this to the intrinsic nature of the fatigue and potentiation each mode of contraction evokes. Comparing PAP in upper and lower limb movement patterns, additionally, suggests that the protocol variables need to be moderated by the size and functional properties of the muscle concerned (Farup & Sorensen, 2010; Gilbert & Lees, 2005). It would seem that higher contraction velocities and smaller muscle size demand a concomitant reduction in the degree of stimulus to ensure a prevailing performance gain (Baker, 2003; Clevidence, 2008).

2.5.3.2 Participant Factors

Training status is consistently observed to delineate results, with those of higher training status showing greater propensity for performance improvement post-CC (Berning, et al., 2010; Chiu, et al., 2003; Rixon, et al., 2007). Movement execution is already highly coordinated and level of recruitment already maximised in high-level athletes and, as such, these participants would be more able to capitalise on the increased functional capacity PAP affords (D. J. Smith, 2003). Association of skill level to training status further suggests that the small degree of improvement afforded by PAP would be clouded by the inherent performance variability of *unskilled* participants (Langdown et al., 2012; Sakurai & Ohtsuki, 2000). In addition, a higher training status implies a greater fatigue resistance. However, studies testing participants of lower training status have still shown positive response, and the CC protocol and recovery time allowed post-CC may simply need to be participant-appropriate (Chiu, et al., 2003). Confirming characteristics determined by TP, Chui et al. (2004) and Terzis et al. (2009) both established a correlation between PAP response and expression of myosin heavy chain (MHC) type II isoforms - those of higher type II content demonstrating greater response. Accordingly, magnitude of PAP appears to be higher in sprint trained athletes (Bomfim Lima, et al., 2011). However, endurance athletes, characterised by a more prevalent expression of type I MHC isoforms, have still shown some degree of effect (Boullosa, et al., 2011; Hamada, Sale, & Macdougall, 2000). Comparing the 2 types of athlete, Paasuke et al. (2007) suggest that an increased fatigue resistance in endurance-trained athletes would allow PAP response to more readily prevail. While the magnitude of response may be lower, the study observes a potentiated performance improvement that is sustained over a longer time frame in endurance athletes.

Studies that median-split trial groups based on measures of strength found increased results in stronger participants (Gourgoulis, et al., 2003). Others observed a positive correlation between strength and the magnitude of response (Bellar, et al., 2012; Kilduff, et al., 2008; Ruben, et al., 2010) and a negative correlation with recovery time required to observe positive effect (Jo, et al., 2010). Studies in female participants show equivalent outcomes to that of males (DeRenne, 2010), but, where sex comparison is made within a trial, results are divided – studies equally report no difference (McCann & Flanagan, 2010) or else a greater response in males (Radcliffe & Radcliffe, 1996; Rixon, et al., 2007; Terzis, et al., 2009). Those studies reporting distinction may simply have acknowledged strength-mediated difference rather than sex *per se*.

A large number of studies agree that overall response is highly individualised (Comyns, et al., 2006; Crewther, et al., 2011; McCann & Flanagan, 2010; Nibali, et al., 2011; Till & Cooke, 2009; Turki, et al., 2011). This has been most commonly infered from the distinct recovery times needed to observe an increased, as opposed to decreased or unchanged, performance measure (Bevan et al., 2009; Chaouachi, et al., 2011; Jo, et al., 2010). The expression of potentiation and fatigue in succeeding performance is, evidently, dictated by the CC variables, but mediated by the characteristics of the participant themselves. The outcome response is then characterised by a unique time window shaped by both. This conclusion alone highlights the inherent difficulty in establishing significant group effects in PAP studies.

2.5.3.3 Performance Outcomes

Studies observing PAP in ballistic action of the lower and upper limb (Baker, 2003; Boullosa, et al., 2012), repetitive or cyclical explosive action (Okuno, et al., 2013; Thatcher, et al., 2012), concentric or stretch-shortening influenced exercise modes (Fletcher, 2012) and speed-power performance of varying durations (Feros, et al., 2012; Matthews, et al., 2004), suggest CC protocols can influence performance gain in many performance modes so long as conditions for observing PAP are optimised and biomechanical specificity is achieved.

Closer inspection suggests that the CC protocol might have distinct effects on discrete phases of performance, consequent to the kinematic and kinetic profile therein (Yetter & Moir, 2008). In studies where the key performance measure, such as distance or time, is unchanged, an improved biomechanical profile has often been observed in the post-CC test (Esformes, et al., 2011; Kilduff, et al., 2011). Further, Chiu and Salem (2012) have shown variance in the PAP response at each joint contributing to the performance movement. It is possible, then, that movement strategy and/or performance conditions could subsequently be altered to take advantage of functional improvements afforded by PAP. While results of the Comyns et al. (2010) study suggest that a learning effect may exist, contrasting opinions are upheld on the degree to which PAP response can be trained (Sale, 2002; G. G. Sleivert et al., 1999). Few longitudinal studies exist and more research is required to substantiate this proposition.

In conclusion, evidence suggests that prior exercise influences both fatigue and potentiation of subsequent performance. While the effects co-exist, execution of a maximal or near-maximal CC prior to acute exercise performance may affect a net performance gain through increased excitation of the neuromuscular pathways and improvements in electro-mechanical efficiency. Mechanisms of potentiation appear to exist along the chain of command with increased central processing, highest order MU recruitment and sensitivity of the cross-bridge mechanism, together with architectural improvements in force transmission, reduction in EMD and a more beneficial metabolic environment, offering the possibility of increased force production or rate of force development. Studies of PAP in ballistic exercise present a number of factors that must be reconciled for prevailing conditions of potentiation to be achieved. The complex interaction of type-intensity-volume-density of CC protocol creates a distinct time window of effect that is further mediated by the individual’s training and fibre-type characteristics. Influence of PAP across discrete phases of the goal movement further reflects a biomechanical specificity of response congruent to performance across the force-velocity relationship. The performance coach or sports scientist must, therefore, understand and consolidate these observations in order to create a successful outcome.

CHAPTER 3 - METHODOLOGY

3.1 EXPERIMENTAL APPROACH TO THE PROBLEM

The study tested the acute potentiating effects of a high-inertia ergometer warm-up intervention on subsequent sprint cycling performance. Employing a randomized, counterbalanced, cross-over design with repeated measures, three conditions were tested on three separate days: a standardised warm-up followed by either a dynamic (DYN) or isometric (ISO) potentiation protocol and a control condition (CON) where subjects actively rested for the total equivalent time following the same standardised warm-up. Performance was assessed in a short (~6 seconds) maximal acceleration from standing start to maximum velocity on an inertial-load ergometer, immediately following the standardised warm-up (Pre) and at 4 (Post4), 8 (Post8) and 16 (Post16) minutes after the potentiation strategy. The study design, therefore, provided comparison of different modes of CC on performance across the force-velocity relation, while allowing assessment of the time window of any observed effect.

3.2 PARTICIPANTS

Six highly-trained sprint cyclists (4 male, 2 female, Table 3.1) were recruited for the trials. The athletes were either national development squad riders or riders who had trained and competed at national and international level alongside the current national high performance squad. Trials were conducted towards the end of the competitive season a few weeks after the national track cycling championships. The athletes were in near peak performance condition, with no musculoskeletal injuries. In addition to their performance status, participants were selected for the study based on having a minimum of two years strength training background and training exclusively for sprint events.

All participants had the risks and benefits of the investigation explained to them (Appendix 1), completed a pre-exercise health questionnaire (Appendix 2) and provided written informed consent (Appendix 3) prior to commencing the trials. Ethical approval was provided by the Massey University Ethical Committee (Appendix 4).

Table 3.1 Summary of Participant Characteristics.

Variables	Mean ± SD
Age (years)	19.2 ± 3.2
Height (cm)	175.2 ± 7.0
Body mass (Kg)	75.5 ± 9.8
Sprint cycling (years)	4.0 ± 1.5
Strength training (years)	3.5 ± 1.2
Peak Isometric Pedal Torque (Nm)*	255.85±37.75

*** average of peak left and right leg torque produced in isometric potentiation protocol**

3.3 PROTOCOL

Trials were conducted in the Sport Science Laboratory of Massey University's Albany Campus over a 4-week period, with test days separated by at least one full week (Figure 3.1). Environmental conditions in the laboratory for all trials represented current daily room temperature, humidity and air pressure on each occasion and was recorded as 21.87 ± 0.40°C, 45 ± 5%, and 1008 ± 10 mmHg respectively (DSE deluxe weather station, DSE Ltd, New Zealand). A tendency has been reported for improved power performance in tests conducted later in a day and so testing on each day was conducted in a single afternoon session with athletes timetabled for arrival in sequential order (Chtourou & Souissi, 2012). Scheduling of arrival times maintained testing for each athlete within an hour of the same start time each day in order to control for circadian rhythm. A single familiarisation session, following the same protocol, was conducted 4-weeks prior to testing. While it would have been preferable for this session to have been closer to the test days, the athletes' competitive schedule meant this was not possible.

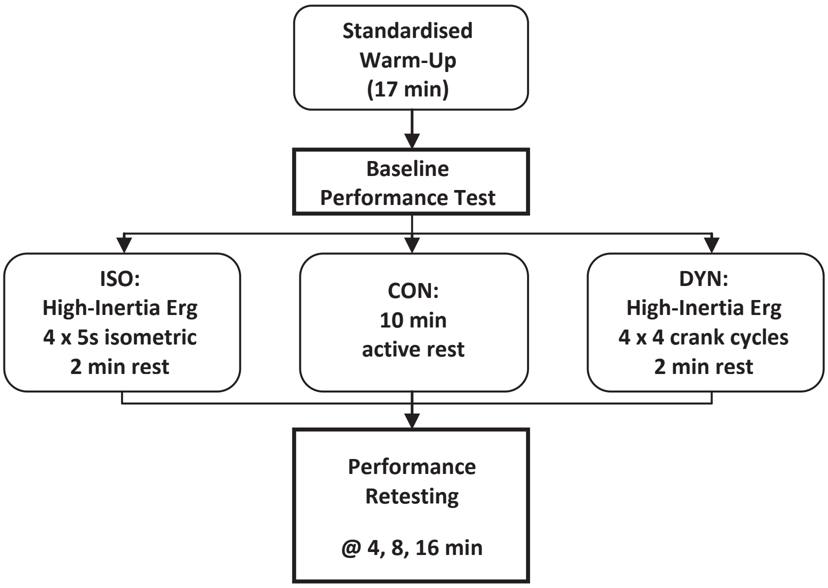


Figure 3.1 Summary of the Experimental Method.

Participants were instructed to arrive at the laboratory having refrained from eating within the 2-hour period prior to testing and having maintained a normal diet without supplementation or caffeine intake for the previous 24 hours. Participants further recorded all fluid in-take during this period to ensure euhydration status before starting the trial. Fluid in-take during the trial was restricted to water. This was permitted *ad libitum*.

On each test day the athletes arrived at the laboratory at their designated time and remained seated for at least 20 minutes to ensure they were in a rested state prior to recording baseline measures of heart rate (Short-range telemetry: Polar S610i, Polar Electro, Finland) and blood lactate (BD-microtainer contact-activated lancet, Lactate Pro LT-1710 hand-held analyser, Arkray, Kyoto, Japan). Athletes provided bike set-up information determined by their own track bike and both the test (inertial-load) and potentiation (high-inertia) ergometers were adjusted to match the required seat height and handlebar height. The test ergometer was, additionally, adjusted to optimise seat and handlebar fore-aft position for each athlete. Each athlete provided their own clipless racing pedals which were transferred to the relevant ergometer prior to each component of the trial.

Having recorded baseline measures and adjusted the bike set-up, participants completed a 17-minute standardised warm-up on the test ergometer. The content of the warm-up was based on the experimental protocol of Tomaras and MacIntosh (2011) which reportedly produced higher peak power output and greater work done in subsequent sprint performance, when compared to a traditional sprint cycling warm-up. Where the original protocol had utilised a fixed gearing of 46:16, the current warm-up was conducted on the test ergometer which restricted gearing to 62:13. As observed in Table 3.2 the two key components of the protocol are a progressive build up in intensity as determined by relative heart rate and an acceleration of speed before completing a 6-second maximal sprint. Despite the difference in gearing, the current trial followed the exact execution of the protocol with step-wise incremental heart rate achieved by combination of increasing speed and application of the ergometer's friction-brake.

Table 3.2 Standardised Warm-Up Protocol.

Time (min:s)	Classification	Instruction
0:00– 5:00	General warm-up	60% HRmax
5:00–10:00		65% HRmax
10:00–15:00		70% HRmax
15:00–15:30	Acceleration	Progressive to 35 km/h
15:30–15:36	Sprint	6-s maximal
15:36–17:00		Recovery Cycle lightly, as if preparing to stop on track

On completion of the warm-up, athletes remained seated and stationary whilst the ergometer was prepared for the first test effort. The test ergometer was custom-built to modified design specifications based on the inertial-load ergometer used by Martin et al. (1997); where Martin and co's ergometer utilised an intermediate drive system, the current design utilised a single-geared system with increased gear ratio (62:13) and flywheel weight (32kg) to create the required inertia. The inertial-load ergometer allows determination of a complete power profile in a single effort with resistance provided solely by the moment of inertia of the flywheel. Test conditions for the current study involved the athlete conducting a seated acceleration with maximal effort from a standing start, aiming to achieve highest velocity in as short a time as possible. Lasting ~6 seconds, the effort, therefore, provided performance data across the functional range of the force-velocity curve, from which the power-velocity relationship, temporal profiles and total work done, could be derived. During the test efforts pedal torque was obtained using SRM cranks (Schoberer Rad Messtechnik, Jülich, Germany) with strain-gauges at the hub, calibrated at the beginning of each test day as per manufacturer's instructions. Sensors on the crank and flywheel provided information on the pedal and flywheel angular velocities. SRM data was captured at 256 Hz and downloaded to personal computer for analysis.

Pre-intervention sprint tests were conducted within 2 minutes of finishing the warm-up. In preparation for the test, athletes were asked to position their pedals with the right foot leading and pedal at 60° past top dead centre (TDC). Measures of heart rate and blood lactate were then taken and when the athlete was ready, the data-logger was started and they were given a count-down "3-2-1-GO!". The athlete then accelerated all-out for ~6 seconds, remaining seated in the saddle throughout the effort. When acceleration had deemed to plateau, they received the command "done", the data-logger was stopped and the athlete decelerated back to standstill. Strong verbal encouragement was given throughout the test.

Following 4-minutes active rest, participants executed one of three interventions: a dynamic (DYN) potentiation protocol, an isometric (ISO) potentiation protocol or a control trial (CON) consisting of active recovery for the total equivalent time. The potentiation protocols were conducted on a custom-built high-inertia ergometer designed to provide maximal loading over the first 4-5 cranks of acceleration (Section 3.4). On completion of the appropriate intervention, participants rested actively for a further 4 minutes before repeating the test effort on the inertial-load ergometer. Repeat testing was additionally conducted at 8 and 16 minutes post-potentiation with participants instructed to maintain active rest conditions between tests. Each repeat effort was conducted under the same conditions as the baseline test and to maintain accuracy in the timing of repeat trials, athletes were asked to be ready to go on the test ergometer 2 minutes ahead of each test point. Active rest was specifically monitored during the recovery periods in order to maintain core temperature of the athletes: activities consisted of walking around the laboratory and intermittent unloaded cycling on a stationary ergometer (Monarch Ergomedic 874E, Netherlands). At the conclusion of the trial, the athlete completed a 15-minute cool down of their own choice on the same ergometer.

3.4 POTENTIATION PROTOCOL AND ERGOMETER

The potentiation ergometer was designed to provide a means of reproducing the kinematic profile of sprint cycling in a high-load CC protocol (Figure 3.2). The structure of the frame was built to replicate a sprint bike set-up with low-set dip bars and seat in a forward position approximating a bicycle seat tube angle of 75°, as commonly used by sprinters. Stabilisation of the ergometer base was reinforced by a lateral cross-frame support. To satisfy the high load requirements of a potentiating stimulus, two design methodologies were used to increase the inertial load of the bike. A double-geared drive-train with intermediate drive wheel between the crank and flywheel was used to ‘over-gear’ the system: gearing of 58:28x48:16 provided an overall gear ratio of 6.21:1. The flywheel itself was specially cast and consisted of a 70 cm diameter wheel, weighing 40 kg, with most of the mass of the wheel towards the rim. Winged flanges were attached to each spoke of the wheel to provide additional rotational air resistance.

Figure 3.2 Custom-built Potentiation Ergometer.

The high-inertia of the bike, therefore, provided the base loading for all participants. Supplementary loading could then be added by a friction braking system consisting of a tensioned-arm that lowered a rubber roller onto the rim of the flywheel. The width of roller matched that of the rim, which, at 8cm additionally maximised the rolling resistance working against the wheel. The degree of braking applied provided a means of individualising the load experienced to match the relative strength of the participants. Although this was done in a non-quantifiable manner, it provided at least some compensation for individual strength characteristics: assessment of the participants' relative strength was made based on the maximal isometric torque produced on the ergometer during familiarisation trials. The design of the three loading components ensured that pedalling action would be smooth and that the overall 'feel' of pedalling would be maintained despite the high resistance experienced.

Protocol design involved two distinct CC strategies. In DYN, participants conducted 4 sets of 4 complete pedal revolutions (4 half revolutions per leg) at maximal effort with 2 minutes rest between sets. In executing the CC, athletes were instructed to have the intention to achieve maximum acceleration despite the loading restriction. In ISO, the flywheel was prevented from turning by placing a metal bar through the spokes. Participants then conducted 4 sets of 5-second maximal contractions of each leg with 2 minutes rest between sets. Since muscle recruitment changes through the crank cycle, the pedal position for each repetition of MVC was moved in order to complete one MVC at each of four different pedal positions through the primary power generating phase of the crank. Contractions were, therefore, conducted at 60°, 90°, 120°, 150° past TDC. Choice of MVC duration was made based on assessment of the most consistent strategies of existing studies. The 4 repetitions of DYN presented approximately the same total time under tension per leg in the dynamic condition.

Potentiation efforts were conducted under sprint start conditions. A countdown was given from 10 to 1, with the athlete rising out the saddle on “3” , shifting their position back over their saddle and on “GO!” thrusting the hips forward to accelerate the bike. Under isometric conditions the athletes were instructed to have the same intention to accelerate the bike. Crank torque during the potentiating stimulus was recorded throughout each execution of the protocols using AXIS cranks (AXIS Cranks Pty Ltd., Queensland, Australia) recording at 100 Hz.

3.5 DATA ANALYSIS

Through the course of the sprint, instantaneous torque was recorded directly and instantaneous power calculated as instantaneous torque x cadence. The completion of 20 half crank cycles (10 half cycles by each leg) was established as a point of reference for comparative analysis. Analysis of instantaneous data was conducted as per the original inertial-load test methodology described by

Martin et al. (1997). For each half crank cycle instantaneous peak torque (T_i) and power (P_i), representing the highest values of torque and power during contractions of each leg and values of torque and power averaged over a full revolution alternating right to left and left to right legs (T_{rev} , P_{rev}), were derived from the raw data. Since the initial pedal stroke started part way through the first half crank cycle, data pertaining to $T_{rev}1$ and $P_{rev}1$ was incomplete and hence these points were omitted. The crank angle where peak torque was produced (PTA) was then, additionally, determined for each half crank cycle. The highest values of the instantaneous and averaged measures were established as T_{i_max}, T_{rev_max}, P_{i_max} and P_{rev_max} ; the half crank cycle where peak power values were produced recorded as HCC P_{i_max} and HCC P_{rev_max}. The instantaneous data was then used to derive the torque- and power- cadence relationships for both peak and averaged values using linear and quadratic regressions, respectively. The quadratic regression applied a 2nd order polynomial constrained to pass through the origin.

Intercepts of the torque-cadence linear relationship, representing maximal instantaneous and average torque, T_{i0} and T_{rev0}, and cadence, f_{i0} and f_{rev0} , were then obtained by extrapolation. Apex of the instantaneous and average power-cadence quadratic relationships, P_{qi_max} and P_{qrev_max} , and corresponding cadence value, representing optimal cadence, f_{qi_opt} and f_{qrev_opt}, were calculated as the vertex of the quadratic equation. Data points from each half crank cycle and those derived from the regression equations, were compared across the 3 trial conditions at each of the 4 testing points. A summary of instantaneous measures is presented in Table 3.3.

Table 3.3 Summary of Instantaneous Measures Analysed.

MEASURE	DESCRIPTION
T_i 1-20	Peak torque of half crank cycles 1-20
T_{rev} 2-20	Torque per revolution alternating right/left half crank cycles 2-20
T_{i_max}	Maximum value of T_i produced
T_{rev_max}	Maximum value of T_{rev} produced
PTA 1-20	Crank angle where T_i was produced (half crank cycles 1-20)
T_{i0}	Extrapolated torque intercept value of linear T_i - cadence relationship
f_{i0}	Extrapolated cadence intercept value of linear T_i - cadence relationship
T_{rev0}	Extrapolated torque intercept value of linear T_{rev} - cadence relationship
f_{rev0}	Extrapolated cadence intercept value of linear T_{rev} - cadence relationship
P_i 1-20	Peak power of half crank cycles 1-20
P_{rev} 2-20	Power per revolution alternating right/left half crank cycles 2-20
P_{i_max}	Maximum value of P_i produced
P_{rev_max}	Maximum value of P_{rev} produced
HCC P_{i_max}	Half crank cycle where P_{i_max} was produced
HCC P_{rev_max}	Half crank cycle where P_{i_max} was produced
P_{qi_max}	Apex of quadratic P_i - cadence relationship
P_{qrev_max}	Apex of quadratic P_{rev} - cadence relationship
f_{qi_opt}	Optimal cadence derived from quadratic P_i - cadence relationship
f_{qrev_opt}	Optimal cadence derived from quadratic P_{rev} - cadence relationship

To assess the effects of the potentiation protocols on distinct phases of the sprint, performance was then divided into the segments presented in Table 3.4. Markers creating start and end points for the segment data were established by calculating the equivalent metres of development for one crank cycle and multiplying by the number of crank cycles representing the beginning and duration of the segment. Data was then analysed over an equivalent distance of the sprint.

A number of performance variables were derived from the raw data and compared within each segment or as an overall outcome, as indicated in Table 3.5. Average values represented the measure averaged across the cranks cycles with the segment. Peak overall values were the highest value achieved across the whole effort. Time to peak value was the time from start of the sprint to the highest value. Final value was the value at the end of the sprint. Rate of power development was calculated as power at the end of the segment minus power at the start of the segment divided by time taken for the segment. Work done was calculated as the area under the power-time curve. Change in peak torque angle (PTA) was derived from the absolute angles at which peak instantaneous torque was produced for each half crank cycle: this angle is seen to move to progressively later in the crank cycle with increasing cadence. Change in PTA is then calculated as the angle for the final half crank cycle minus that of the first half crank cycle within the segment.

Table 3.4 Sprint Segments of Analysis.

SEGMENT	DESCRIPTION
S1	Half crank cycles 1-2
S2	Half crank cycles 3-4
S3	Half crank cycles 5-10
S4	Half rank cycles 11-20
S1-4	Half crank cycles 1-20

Table 3.5 Summary of Segment and Overall Measures Analysed.

VARIABLE	SEGMENT MEASURES	OVERALL MEASURES
POWER	average, rate of power development	peak, time to peak
TORQUE	average, change in peak torque angle	peak, time to peak
CADENCE	average	final
VELOCITY	average	final
WORK DONE	total	
PERFORMANCE TIME	total	

3.6 STATISTICAL ANALYSIS

Results are reported as mean ± standard deviation. Linear and quadratic regression models of the torque-cadence and power-cadence relationships, respectively, were fitted using the least squares method. Comparison of baseline measures of heart rate and blood lactate was made using a one-way ANOVA. A repeated measures ANOVA was used to compare the 3 trial x 4 time conditions for heart rate, blood lactate, segment and overall measures, intercept and vertex values derived from the linear and quadratic regression lines of instantaneous data. Statistical analysis using ANOVA's was carried out using Statistical Package for the Social Sciences software version 20.0.0 (SPSS Inc, Chicago, Ill, USA). Where statistical significance was found *post hoc* analysis was carried out using Holms-Bonferroni adjusted paired t-tests. The null hypothesis was rejected at an alpha level of $p < 0.05$. This analysis was included to illustrate that the method of null hypothesis significance testing may not necessarily be appropriate for this type of experiment (Chaouachi, et al., 2011).

Within-subjects contrasts were conducted between Pre and each of Post4, Post8 and Post16 values of all dependent variables including instantaneous torque and power data points from each half crank cycle. The magnitude of pre-to-post changes was assessed using effect size (ES) and percentage of change. The between-subject standard deviation for the measures was used to convert the log-transformed changes in performance into standardized (Cohen's d) changes in the mean. To make magnitude-based inferences about true (population) values of the effect of the intervention on performance, the uncertainty in the effect was expressed as 90% confidence limits and as likelihoods that the true value of the effect represents substantial beneficial or harmful change (Hopkins, et al., 2009). If chance of benefit and harm were both >5%, the true effect was assessed as unclear, otherwise, quantitative chances of benefit or harm were assessed qualitatively as follows: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possible; 75-95%, likely; 95-99, very likely; >99%, almost certainly. The smallest standardized change considered to be worthwhile was calculated from 0.2 of the standard deviation of the data. The threshold of a clinical meaningful effect was set at 75% (Liow & Hopkins, 2003). Descriptive statistics, Cohen's d, confidence limits and magnitude-based inferences were calculated using a custom-written Excel spreadsheet (Hopkins, 2005).

CHAPTER 4 – RESULTS

4.1 OVERVIEW OF SPRINT AND CONDITIONING PERFORMANCES

Mean duration of the sprint was 13.72 ± 1.29 complete crank cycles, representing an equivalent distance of 135.92 ± 12.74 m. Mean time to complete the full duration was 6.22 ± 0.86 s, while mean time to complete 10 complete crank cycles was 5.09 ± 0.31 s. A summary of the torque produced during the conditioning protocols is provided in Table 4.1.

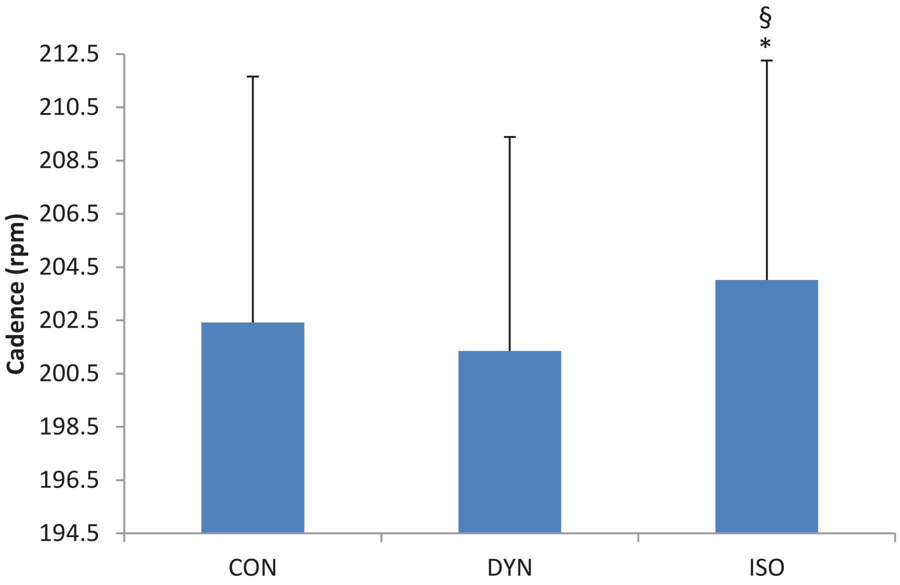
Table 4.1 Torque Production During Conditioning Protocols.

CC	Peak torque per crank cycle (mean of 4 repetitions): mean ± sd, Nm							
Protocol	1 Right	1 Left	2 Right	2 Left	3 Right	3 Left	4 Right	4 Left
DYN	245.3±36.7	249.6±38.8	232.1±31.8	224.6±24.3	218.7±25.6	204.9±19.4	195.9±34.2	191.5±12.3

	Mean 5-second isometric torque (at each of 4 crank angles): mean ± sd, Nm							
	1 Right	1 Left	2 Right	2 Left	3 Right	3 Left	4 Right	4 Left
ISO	238.5±37.5	238.3±35.5	254.6±38.0	257.1±37.5	229.8±49.3	221.6±44.3	191.1±47.4	176.0±49.7

4.2 SEGMENT AND OVERALL PERFORMANCE MEASURES

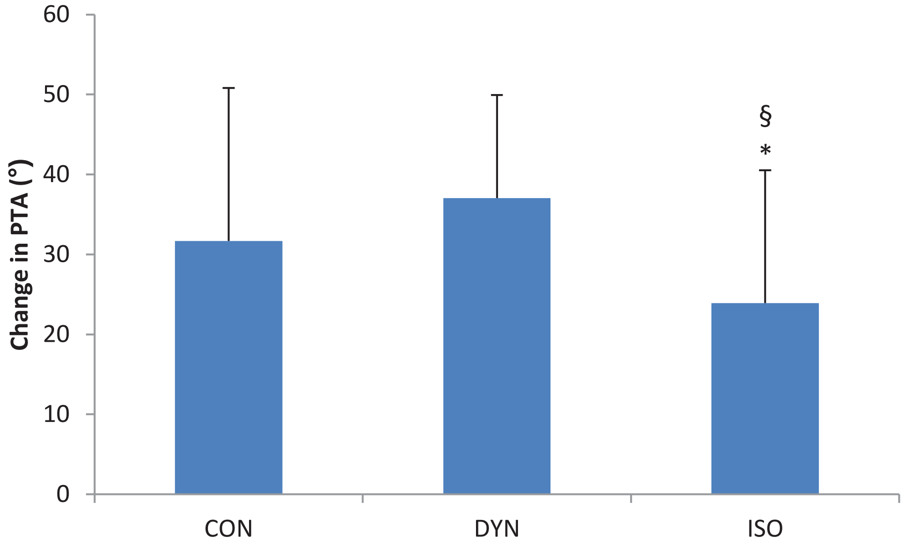
In analysing results using repeated measures ANOVA, three measures showed a significant main effect for trial: final cadence (p=0.009), change in PTA S4 (p=0.008) and change in PTA S1-4 (p=0.031). Post hoc testing revealed that final cadence was significantly higher in ISO as compared to CON (ISO: 204.02 ± 8.24 rpm, CON: 202.4 ± 9.23 rpm, p=0.026) and DYN (DYN: 201.35 ± 8.03 rpm, p=0.001) (Figure 4.1). No significant difference was observed between CON and DYN (p=0.158).



** significantly different to CON (p=0.026); § significantly different to DYN (p=0.001)*

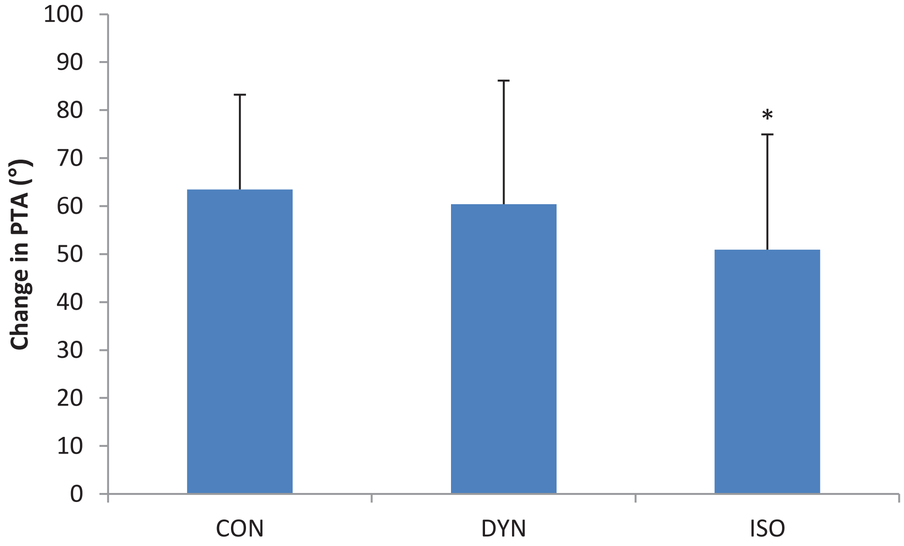
Figure 4.1 Trial Conditions of Final Cadence.

Pairwise comparisons of trial conditions in Change in PTA S4, representing the change in PTA across half crank cycles 11-20, showed a significant reduction in ISO versus CON (ISO: 23.90 ± 16.61°, CON: 31.68 ± 19.12°, p=0.044) and in ISO versus DYN (DYN: 37.04 ± 12.88°, p=0.000) (Figure 4.2). There was no significant difference between DYN and CON (p=0.092). Change in PTA S1-4, representing the change in PTA across the full 20 half crank cycles, similarly showed ISO to be significantly lower than CON (ISO: 50.94 ± 24.03°, CON: 63.50 ± 19.71°, p=0.012) (Figure 4.3). DYN was not significantly different from CON (p=0.085) or ISO (p=0.419).



** significantly different to CON (p=0.044); § significantly different to DYN (p=0.000)*

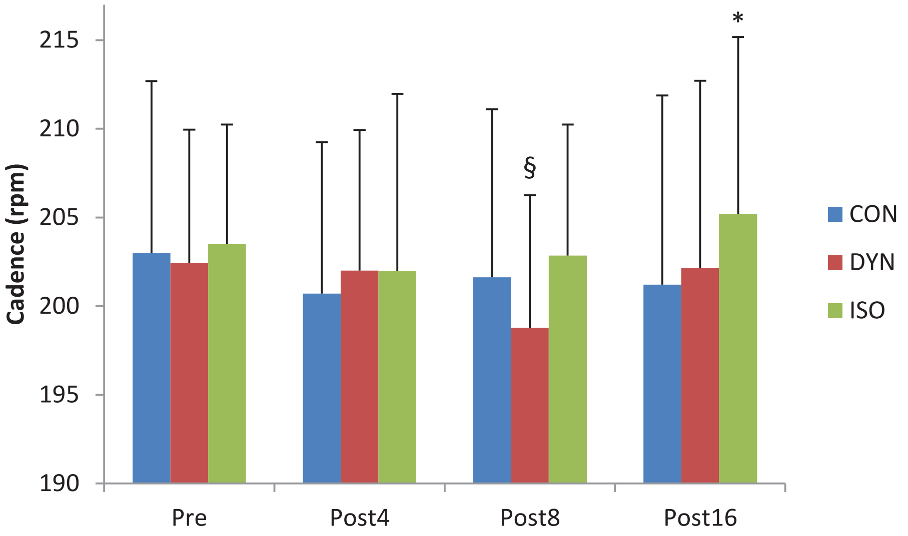
Figure 4.2 Trial Conditions for Change in PTA Over S4 (half crank cycles 11-20).



** significantly different to CON (p=0.012)*

Figure 4.3 Trial Conditions for Change in PTA Over S1-4 (half crank cycles 1-20).

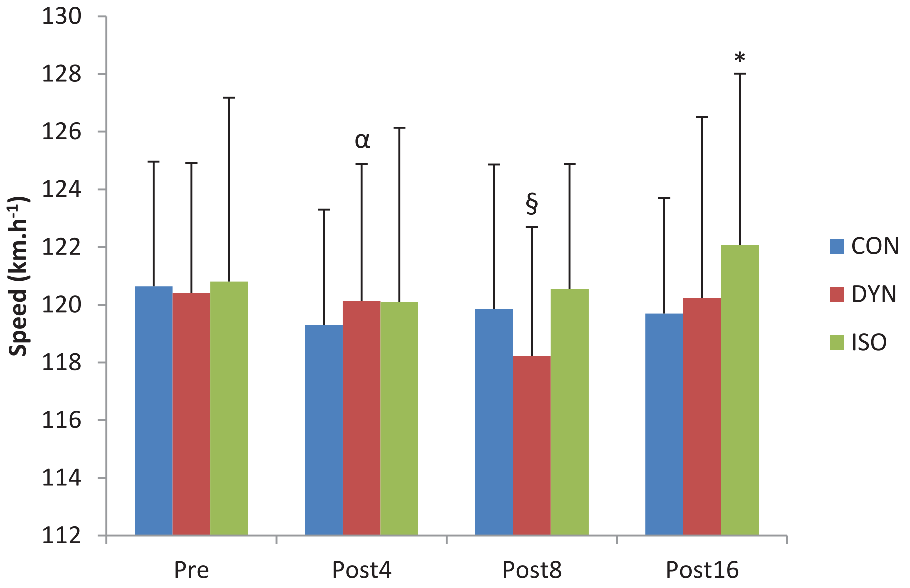
Final cadence also observed a significant interaction of trial x time (p=0.031), subsequent post hoc testing demonstrating a significantly higher final cadence in ISO Post16 as compared to CON Post16 (ISO Post16: 205.20 ± 9.97 rpm, CON Post16: 201.21 ± 9.66 rpm, p=0.014), and a significantly lower final cadence in DYN Post8 as compared to ISO at the same time point (DYN Post8: 198.785 ± 7.48 rpm, ISO Post8: 202.84 ± 7.39 rpm, p=0.011) (Figure 4.4).



** significantly different to CON Post16 (p=0.014); § significantly different to ISO Post8 (p=0.011)*

Figure 4.4 Trial x Time Conditions for Final Cadence.

While analysis of final velocity would have been expected to yield results equivalent to those of final cadence, some discrepancies presented. Final velocity demonstrated a trend for significant interaction of trial x time (p=0.054), post hoc analysis revealing ISO Post16 to be significantly higher than CON Post16 (ISO Post16: 122.07 ± 5.94 km.h^{-1}, CON Post16: 119.70 ± 6.34 km.h^{-1}, p=0.015), and DYN Post8 significantly lower than ISO Post8 (DYN Post8: 118.22 ± 4.48 km.h^{-1}, ISO Post8: 120.53 ± 4.34 km.h^{-1}, p=0.014) (Figure 4.5). However, here DYN Post4 was additionally significant to CON Post4 (DYN Post4: 120.13 ± 4.74 km.h^{-1}, CON Post4: 119.30 ± 4.94 km.h^{-1}, p=0.049).



** significantly different to CON Post16 (p=0.015); § significantly different to ISO Post8 (p=0.014)*
α significantly different to CON Post4 (p=0.049)

Figure 4.5 Trial x Time Conditions for Final Velocity.

A large number of measures demonstrated a significant main effect for time. These measures depicted a gradual decline in performance across each sprint of the trial reflective of the repeated measures design. Since the design itself accommodates for such outcomes, this data is omitted from the analysis. A summary of these results is provided in Appendix 5 (Tables A5.1 to A5.3).

Repeating analysis using within-subjects contrasts, meaningful improvement was observed in a number of overall measures (Table 4.2), in measures across the full sprint segment S1-4 (Table 4.3), and discrete segments S1 and S4 (Tables 4.4 and 4.5). Notably, no meaningful outcomes were observed in S2 or S3.

Overall measures showed both equivalence and disparity from those established in ANOVA (Table 4.2). Results of ISO Post 16 showed meaningful improvements in final cadence (91% likely) and final velocity (75% likely), while the dynamic trial showed similar outcomes at the same time point (final cadence – 89% likely; final velocity – 75% likely). DYN Post4 was, similarly, consistent in observing meaningful improvement in both final cadence and final velocity (99% very likely, 90% likely, respectively). However, DYN Post4, additionally, affected a greater than 75% likelihood of exceeding smallest worthwhile change (SWC) in peak torque (94% likely), time to peak torque (91% likely) and time to peak power (88% likely). No meaningful change was observed in peak power in any trial or time condition.

Table 4.2 Meaningful Changes in Overall Measures.

		Post-CC measure (* units)		**Change in Measure from Pre-CC value (%)**		**Cohen's d**	**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Final Cadence	DYN Post4	202.01 ±7.92	200.71 ±8.53	-0.22±1.21	-2.64±1.59	0.53	0.53	0.33	99	very likely
	DYN Post16	202.16 ±9.55	201.21 ±9.66	-0.20±1.71	-2.44±2.51	0.48	0.06	0.92	89	likely
	ISO Post16	205.20±9.97	201.21±9.66	-0.47±2.40	-2.44±2.51	0.46	0.13	0.80	91	likely
Final Velocity	DYN Post4	120.13±4.74	119.30±4.94	-0.24±1.19	-1.81±1.47	0.39	0.14	0.63	90	likely
	DYN Post16	120.23±6.27	119.70±6.34	-0.21±1.68	-1.52±2.45	0.32	-0.01	0.66	75	likely
	ISO Post16	122.07±5.94	119.70±6.34	1.06±3.98	-1.52±2.45	0.53	-0.35	1.41	76	likely
Peak Torque	DYN Post4	220.67±26.33	206.00±26.52	6.24±5.95	-0.23±4.37	0.65	0.16	1.14	94	likely
Time to Peak Torque	DYN Post4	0.38±0.19	0.50±0.11	-21.73±35.10	18.31±34.72	-1.01	-2.08	0.05	91	likely
Time to Peak Power	DYN Post4	2.41±0.40	2.58±0.37	-11.15±7.01	-4.10±5.69	-0.45	-0.83	-0.08	88	likely

** cadence - rpm; velocity – ms^{-1}; torque – Nm; time to peak – s*

Considering performance across the full 20 half crank cycles, the most substantial changes in S1-4 were observed in the DYN Post4 trial (Table 4.3). DYN Post4 showed a substantial reduction in performance time, reflecting a faster time to complete the fixed duration (81% likely). This was affected by an improvement in average velocity which showed a 97% likelihood of exceeding SWC. The DYN Post4 trial showed additional improvements in average power (86% likely), while improvements in average torque and work done in this trial were possibly meaningful (70% and 71% respectively). Supporting results of ANOVA analysis, change in peak torque angle showed a meaningful decrease in the ISO Post16 condition (76% likely), and a possible decrease at ISO Post8 (73%).

Table 4.3 Meaningful Changes in S1-4 Measures.

Measure	Trial/Time	Post-CC measure (* units)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Average Power	DYN Post4	1050.67± 175.18	1005.00±173.52	1.59±1.91	-3.28±2.80	0.27	0.13	0.42	86	likely
Average Torque	DYN Post4	82.46±8.99	80.18±8.66	0.76±2.15	-2.14±2.39	0.27	-0.02	0.56	70	possibly
Average Velocity	DYN Post4	72.05±4.50	70.73±4.73	1.43±1.14	-0.92±0.81	0.36	0.23	0.49	97	very likely
Change in PTA	ISO Post8	47.88±24.77	65.65±21.93	24.77±48.7	6.08 ± 17.97	0.15	-0.89	1.20	73	possibly
	ISO Post16	47.91±24.74	67.62±21.61	23.08±31.86	9.97 ±16.30	0.11	-0.82	1.03	76	likely
Performance Time	DYN Post4	5.02±0.31	5.12±0.35	-0.80±1.63	1.01±0.84	-0.30	-0.52	-0.08	81	likely
Work Done	DYN Post4	5190.50±484.74	5069.17±520.19	0.24±2.06	-2.82±2.67	0.27	0.00	0.54	71	possibly

** power - watts; torque - Nm ; velocity – ms^{-1}; PTA - ° ; performance time – s; work done – joules*

Examining the first two half crank cycles, meaningful changes in S1 measures are presented in Table 4.4. Outcomes in DYN Post4 were predominant. In this trial condition a substantial improvement in average velocity (85% likely) was concomitant to a meaningful reduction in performance time (92% likely) over this phase of the sprint. The same trial observed a meaningful increase in average torque (90% likely), which, alongside a possible meaningful increase in average cadence (71%), supported a substantial increase in average power (87% likely). A meaningful increase (87% likely) in RPD was also observed in this trial condition. While a possible meaningful increase in average cadence was additionally affected by DYN Post16 (73%), the 75% threshold of meaningful inference was not exceeded in any other measure or trial condition.

Table 4.4 Meaningful Changes in S1 Measures.

		Post-CC measure (* units)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Average Cadence	DYN Post4	44.33±3.01	43.33±3.83	1.22±6.12	-2.05±2.48	0.42	-0.32	1.17	71	possibly
	DYN Post16	44.33±2.34	43.50±3.21	1.30±4.96	-1.56±2.70	0.37	-0.15	0.89	73	possibly
Average Power	DYN Post4	736.00±131.53	696.33±145.41	4.04±6.52	-2.98±3.39	0.35	0.12	0.58	87	likely
Average Torque	DYN Post4	167.41±19.87	160.11±22.16	5.12±6.20	-2.79±1.56	0.38	0.14	0.62	90	likely
Average Velocity	DYN Post4	26.01±1.64	25.14±2.14	2.05±3.15	-1.40±2.20	0.47	-0.03	0.96	85	likely
Performance Time	DYN Post4	1.23±0.08	1.29±0.10	-3.91±3.74	1.21±3.13	-0.86	-1.67	-0.04	92	likely
RPD	DYN Post4	861.24±203.77	803.10±209.41	5.40±6.00	-3.14±5.57	0.34	0.12	0.55	87	likely

** cadence - rpm; power - watts; torque - Nm; velocity – ms^{-1}; performance time – s; RPD – watts.s^{-1}*

In the final phase of the sprint, S4 (Table 4.5), meaningful changes were most prevalent in ISO Post16. In this trial condition meaningful increase in average torque (81% likely), alongside a possible increase in average cadence (72%), affected a concomitant increase in average power that was in excess of the 75% likelihood of exceeding SWC (76% likely). Change in peak torque angle was substantially reduced in ISO Post16 (75% likely) reflecting a smaller drift in the crank angle where peak torque is developed over half crank cycles 11 to 20. Possible meaningful reductions in this measure were also present at the ISO Post4 (74%) and Post8 (71%) time points. Outcomes with respect to this measure therefore reflect those established in ANOVA analysis. ISO Post16 also observed a meaningful improvement in work done (81% likely); increase in work done was similarly meaningful in the dynamic trial at this time point (DYN Post16: 75% likely), and possibly meaningful at the Post4 time point (DYN Post4: 74% possible). The DYN Post16 trial additionally demonstrated a possible increase in average torque (71%) during this, final, phase of the sprint.

The trial interventions had no meaningful effect on S2, representing half crank cycles 3 and 4, or S3, representing half crank cycles 5 to 10 of the sprint.

Table 4.5 Meaningful Changes in S4 Measures.

Measure	Trial/Time	Post-CC measure (* units)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Average Cadence	ISO Post16	174.50±11.47	172.50±9.85	0.57±1.58	-1.05±1.09	0.25	0.08	0.42	72	possibly
Average Power	ISO Post16	1022.71±145.39	977.33±136.54	-0.83±3.30	-6.01±6.98	0.32	-0.01	0.66	76	likely
Average Torque	DYN Post16	55.59±4.48	53.76±4.68	-1.40±4.29	-4.97±6.05	0.36	-0.20	0.93	71	possibly
	ISO Post16	55.23±4.24	53.76±4.68	-0.88±3.92	-4.97±6.05	0.39	-0.01	0.78	81	likely
Change in PTA	ISO Post4	20.46±11.97	33.44±18.82	-58.90±97.22	27.59±148.85	-0.83	-2.72	1.06	74	possibly
	ISO Post8	23.19±17.73	28.98±22.98	-117.64±255.5	-7.90±28.71	-1.05	-3.57	1.47	71	possibly
	ISO Post16	26.80±15.90	33.61±20.08	-18.92±37.06	16.33±27.53	-0.34	-0.84	0.16	75	likely
Work Done	DYN Post4	1778.17±131.35	1737.67±119.77	-0.27±4.67	-3.74±4.24	0.33	-0.12	0.78	74	possibly
	DYN Post16	1774.17±140.98	1721.50±149.78	-0.53±3.84	-4.78±6.33	0.40	-0.02	0.82	86	likely
	ISO Post16	1771.62±141.20	1721.50±149.78	-0.39±3.78	-4.78±6.33	0.42	-0.03	0.86	81	likely

** cadence – rpm; power - watts; torque - Nm; PTA - ° ; work done - joules*

4.3 INSTANTANEOUS MEASURES

Examining the instantaneous data across the sprint, Figure 4.6 shows an instantaneous torque-cadence plot of the first 20 half crank cycles of one sprint of a representative participant. Plots of T_i and T_{rev} for each half crank cycle and the subsequent linear regression lines are shown in Figure 4.7. Linear extrapolation yielded the intersects of x- and y- axis at f_{i0}, f_{rev0} and T_{i0}, T_{rev0} as indicated.

Figure 4.8 shows the instantaneous power-cadence plot of the first 20 half crank cycles of the same sprint. Plots of P_i and P_{rev} for each half crank cycle and the subsequent quadratic regression lines are shown in Figure 4.9. P_{qi_max} and P_{qrev_max} indicate the apex of the curves, with f_{qi_opt} and f_{qrev_opt} derived as the vertex of the relevant equations as shown.

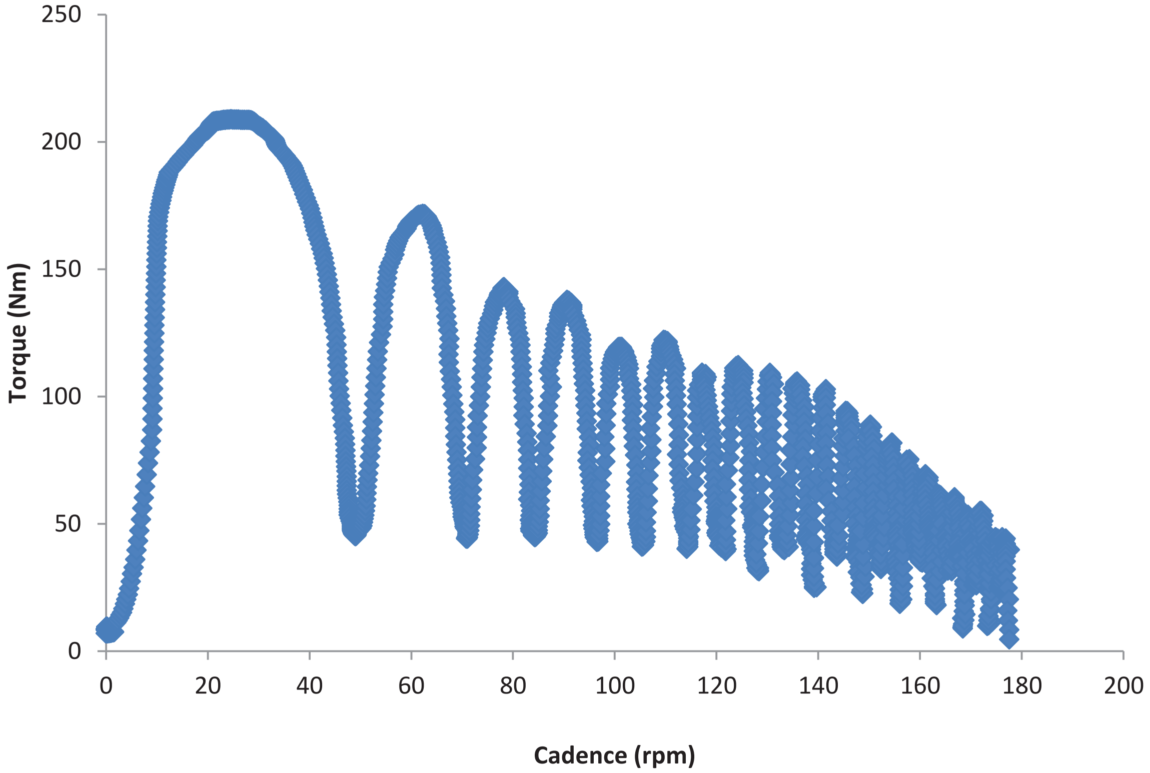
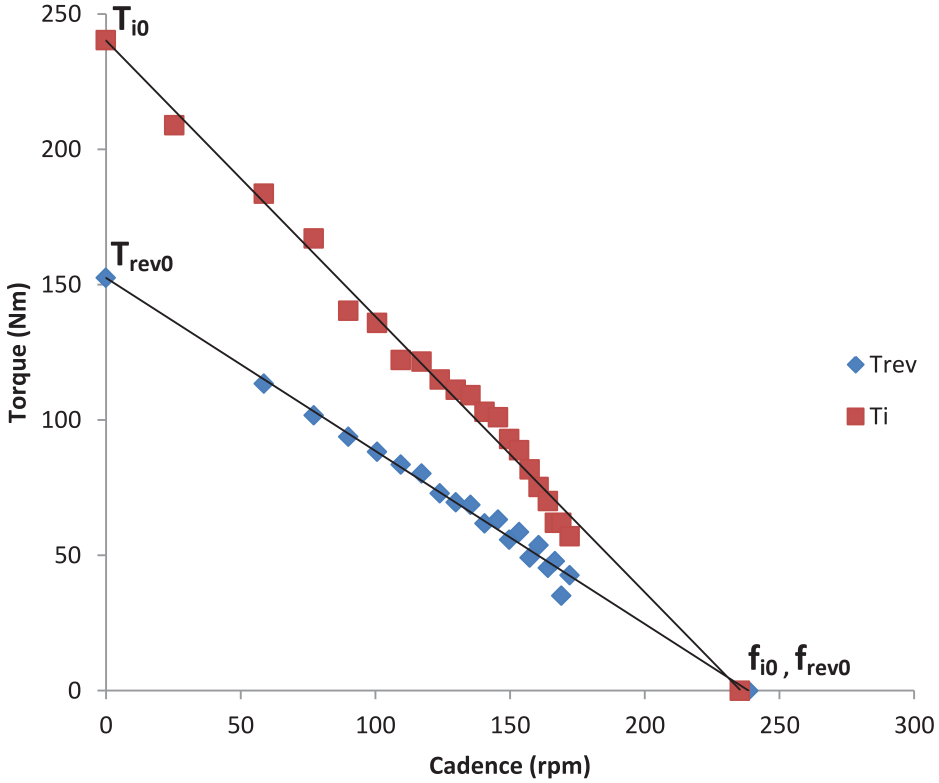


Figure 4.6 Instantaneous Torque-Cadence Plot for a Representative Participant.



Linear regression yielded the following equations:
T_i=-1.0187 cadence + 240.13, R^2=0.9902; T_{rev}=-0.6392 cadence + 152.47, R^2=0.9913

Figure 4.7 T_i and T_{rev} Versus Cadence for the Instantaneous Data Presented in Figure 4.6.

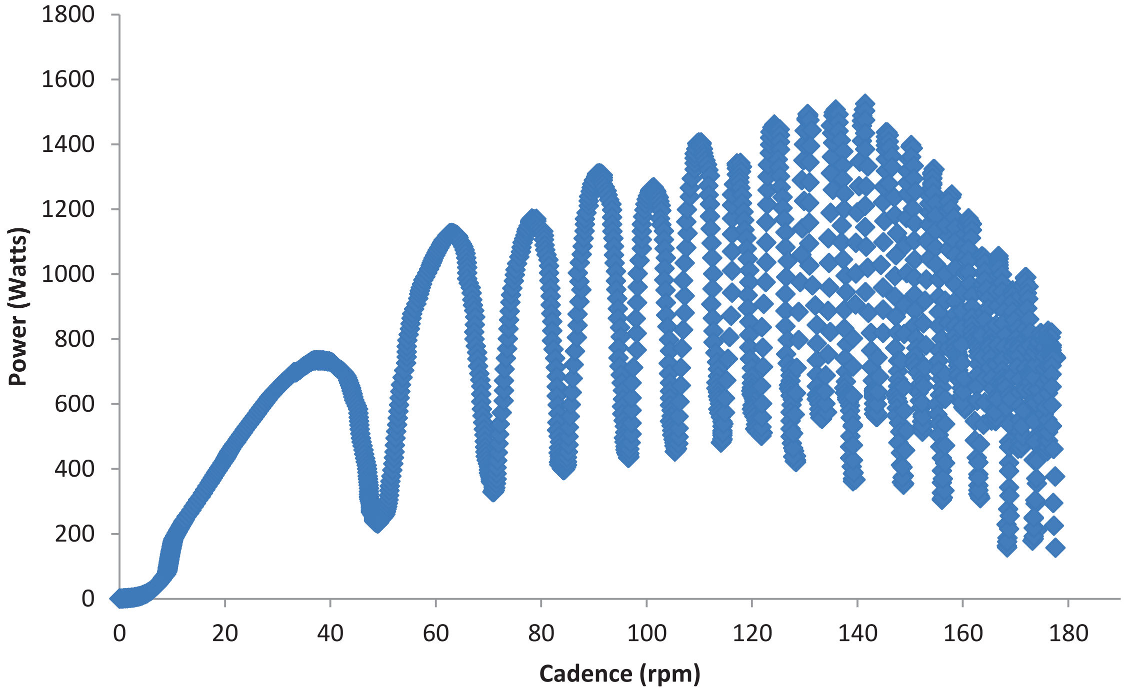
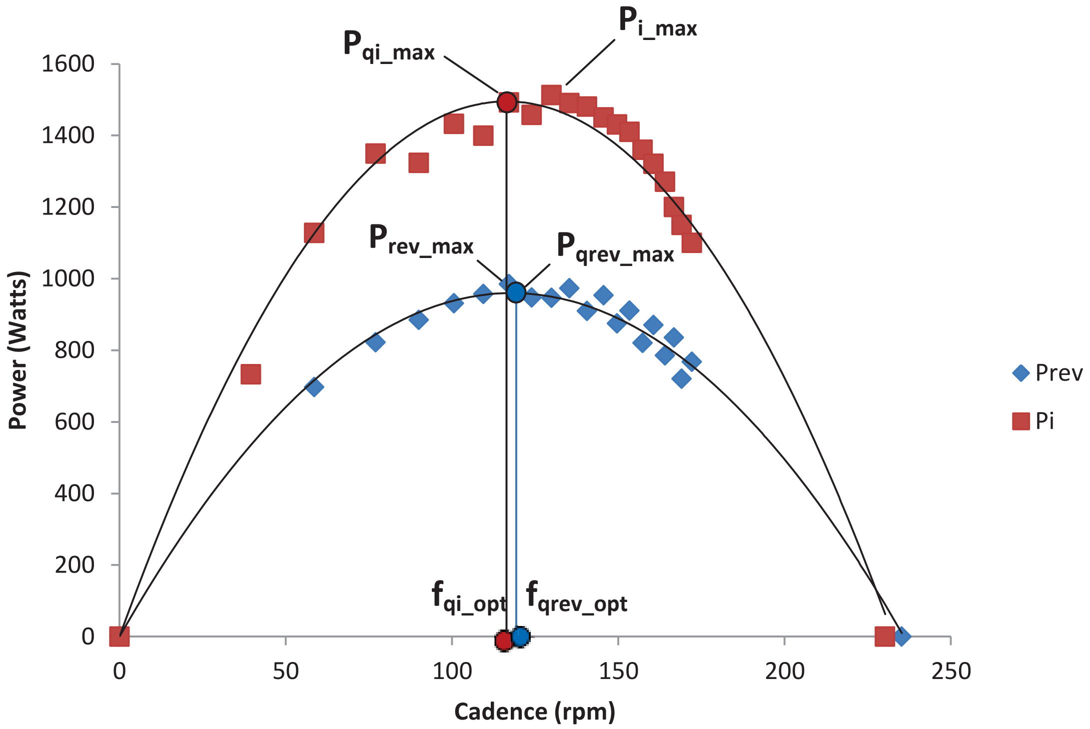


Figure 4.8 Instantaneous Power-Cadence Plot for the Representative Sprint Shown in Figure 4.6.



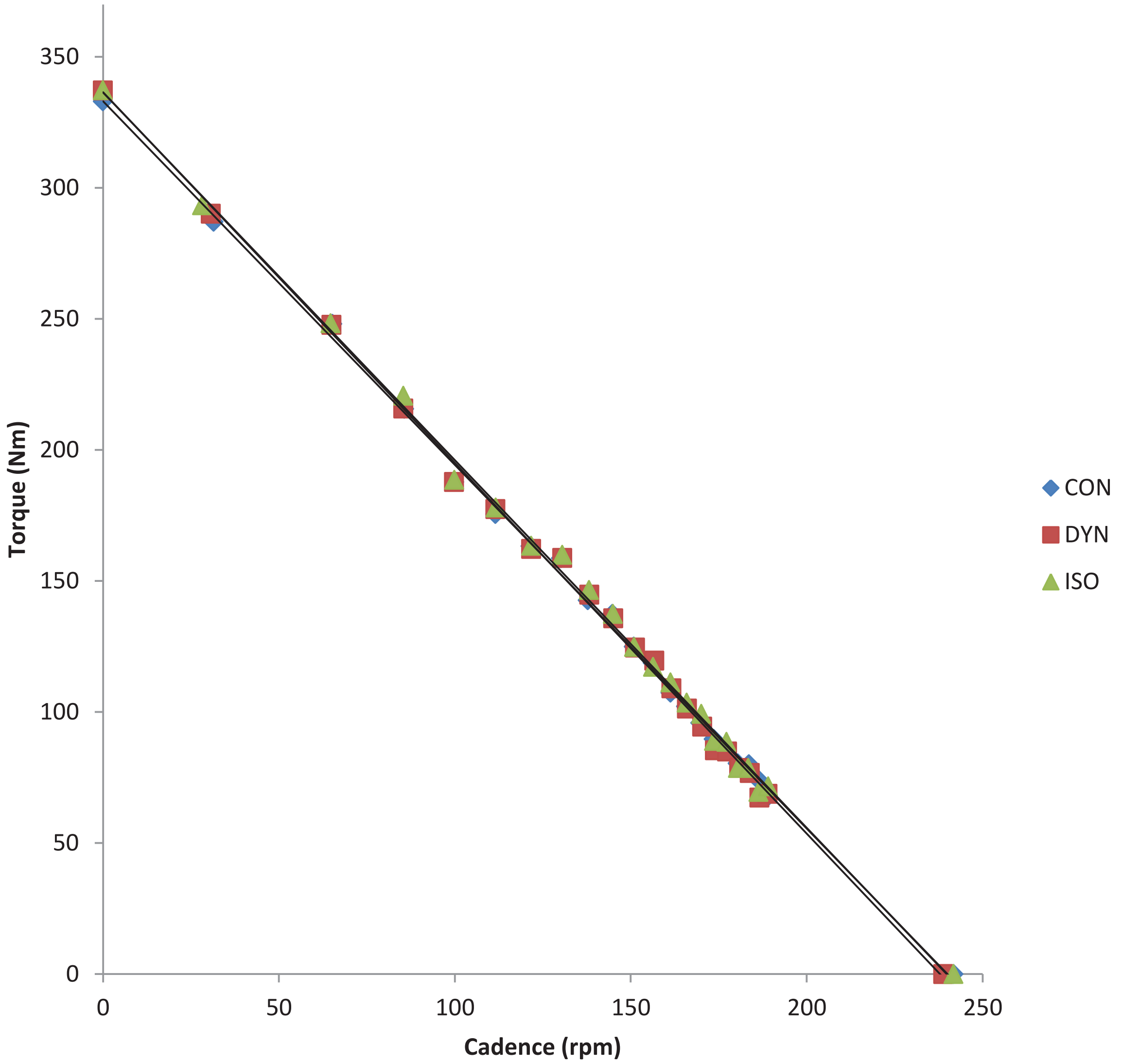
Quadratic regression yielded the following equations:
P_i=-0.1104(cadence)^2 + 25.701 cadence, R^2=0.9842; P_{rev}=-0.069(cadence)^2 + 25.701 cadence, R^2=0.9895

Figure 4.9 P_i and P_{rev} Versus Cadence for the Instantaneous Data Presented in Figure 4.8.

Repeated measures ANOVA was used to examine intercept and vertex values derived from the linear and quadratic regression lines of instantaneous data. No significant main effect for trial or interaction of trial x time was observed in any measure. A significant main effect for time was observed in both apex and peak values of each instantaneous power measure. These measures showed a gradual decline in performance across each sprint of the trial reflecting the repeated measures design. Since the design itself accommodates for such outcomes, this data is omitted from the analysis. A summary of these results is provided in Appendix 5 (Table A5.4).

Analysis of intercept and vertex measures was repeated using within-subjects contrasts; examination of torque and power measures for each half crank cycle (T_i 1-20, T_{rev} 2-20, P_i 1-20, P_{rev} 2-20) was, additionally, included in this analysis. Plots of T_i and T_{rev} versus cadence, and P_i and P_{rev} versus cadence for each trial at Pre, Post4, Post8 and Post16 time points are shown in Figures 4.10 to 4.25, respectively, with error bars omitted for clarity. Meaningful inferences were derived from changes between Pre- and Post- CC trials, hence, plots at isolated time points simply provide visual reference of where deviation from CON has occurred. Interpretation should be made in conjunction with the table of meaningful changes which are included in Appendix 5 for reference (Tables A5.5 to A5.16).

Pre-CC plot of T_i versus cadence is shown in figure 4.10 and demonstrates equivalence in individual data points and linear regression lines.

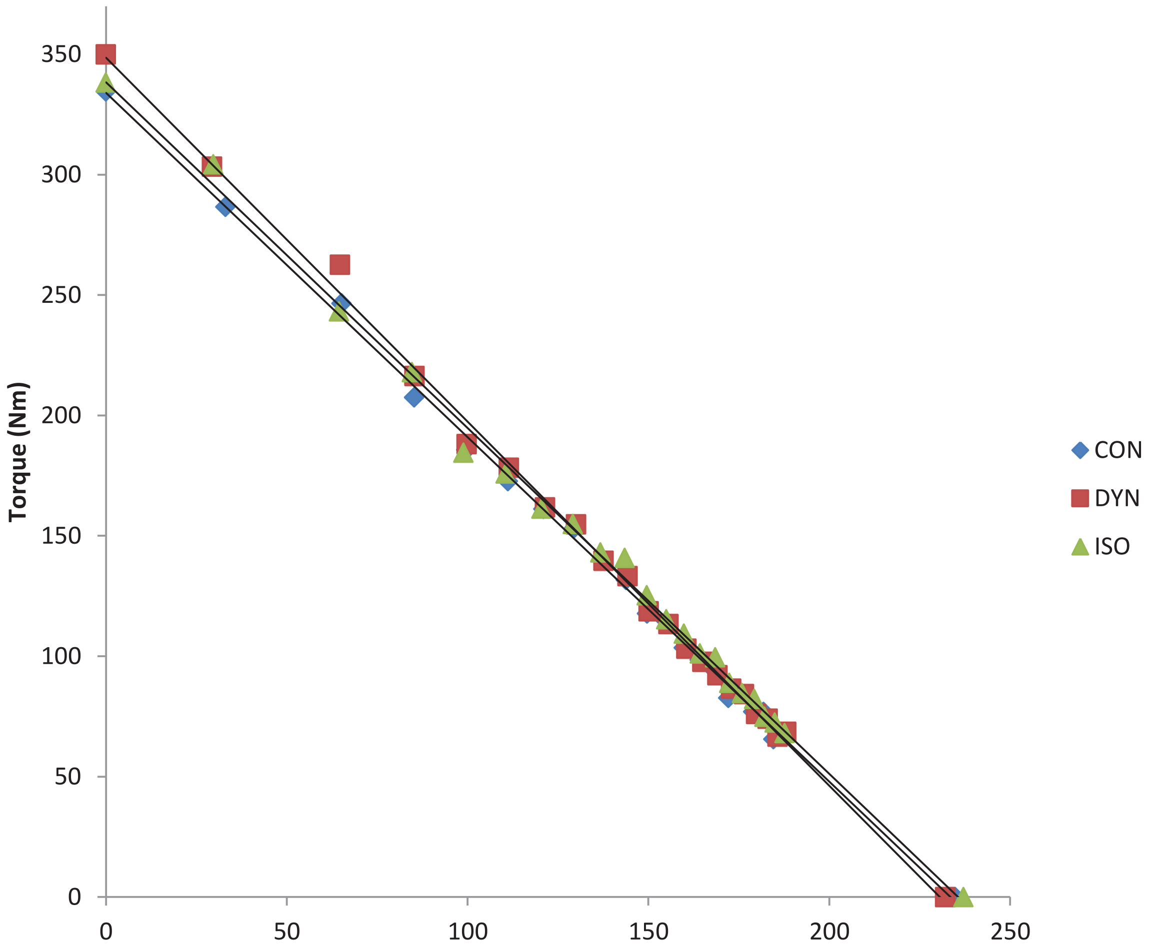


Linear regression yielded the following equations: CON: T_i=-1.3875 cadence + 333.07, R^2=0.9984; DYN: T_i=-1.4142 cadence + 336.4, R^2=0.9981; ISO: T_i=-1.4024 cadence + 336.31, R^2=0.998

Figure 4.10 T_i Versus Cadence for Pre-CC Trials.

Intermediate data points depict the peak torque of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. Pre intervention trials show concurrence at each point and minimal disparity in regression lines.

Figure 4.11 depicts the linear regression lines for each trial at the Post4 point. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.5). In DYN Post4 a steeper gradient of the regression line is indicative of meaningful increases in T_i present in each of the first 3 crank cycles in DYN Post4. This affected a meaningful increase in T_{i_max} , achieved at the first half crank cycle (91% likely) (Table 4.6). The regression line of ISO Post4, instead, presents a shallower gradient, illicited by meaningful torque increases at the mid and end points of the sprint with crank cycles here demonstrating changes greater than 75% likelihood of exceeding SWC. Neither T_{i0} nor f_{i0} were substantially increased in either DYN or ISO.



Linear regression yielded the following equations: CON: T_i=-1.43 cadence + 333.94, R^2=0.9984; DYN: T_i=-1.5116 cadence + 348.5, R^2=0.9977; ISO: T_i=-1.4359 cadence + 338.31, R^2=0.9973

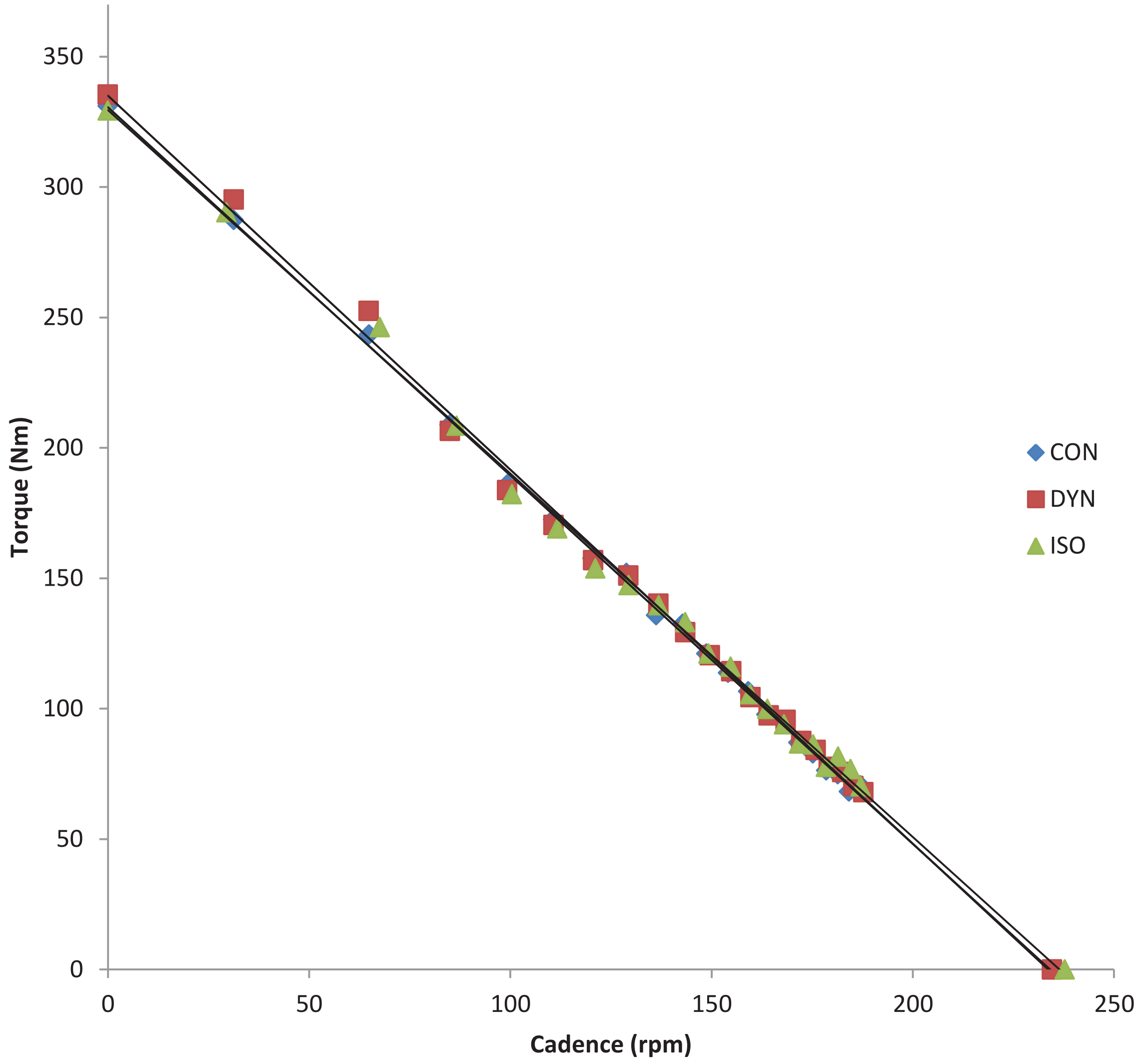
Figure 4.11 T_i Versus Cadence for Post4 Trials.

Intermediate data points depict the peak torque of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. The regression line of DYN trial has a steeper gradient than that of CON, reflecting increased torque in the high-torque region of the relation. ISO presents a shallower gradient in the regression line as a result of an increase in torque towards the high-cadence region of the relation.

Table 4.6 Meaningful Changes in T_i and f_i for Post4 Trials.

		Post-CC measure (Nm)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Ti_max	DYN Post4	303.29±32.82	286.66±46.28	7.58±2.22	1.69±4.75	0.46	0.13	0.79	91	likely

Linear regression lines for trials at the Post8 point are shown in Figure 4.12. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.6). Here, less divergence is evident and meaningful increase was only observed in odd half crank cycles towards the end of the sprint in each of DYN and ISO. Values of T_{i_max}, T_{i0} and f_{i0} showed no meaningful change in either trial condition.

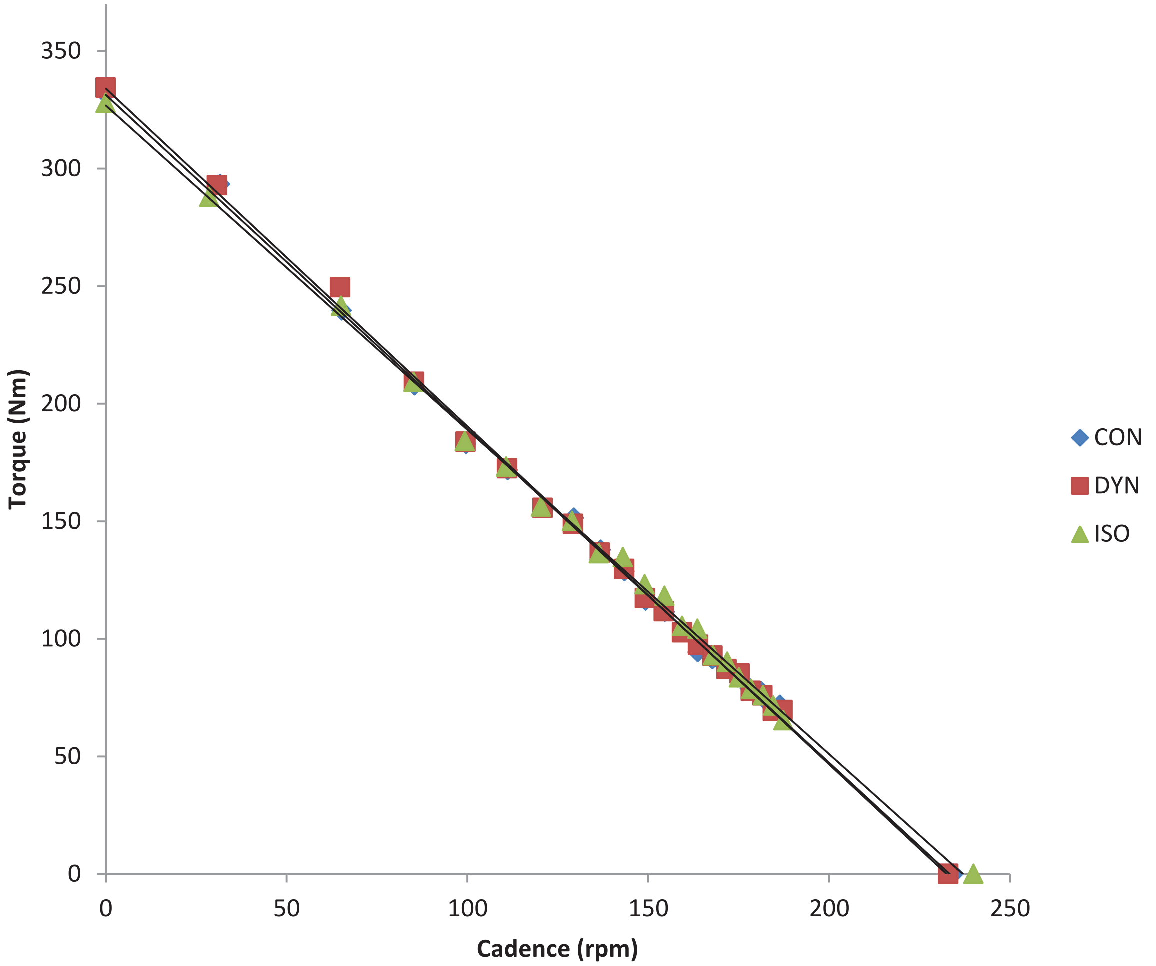


Linear regression yielded the following equations: CON: T_i=-1.4117 cadence + 330.52, R^2=0.999; DYN: T_i=-1.4338 cadence + 334.95, R^2=0.9973; ISO: T_i=-1.3933 cadence + 329.43, R^2=0.9972

Figure 4.12 T_i Versus Cadence for Post8 Trials.

Intermediate data points depict the peak torque of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. The regression lines of DYN and ISO show little divergence from CON, with only odd data points distinct from the control condition.

Figure 4.13 depicts outcomes at the Post16 time point. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.7). An extended zero-torque intersect and shallower gradient of the regression line is observed in ISO, characterising the predominance of the ISO trial at this time point. Observations are supported by meaningful torque increase in half cranks cycles somewhat consistently from the mid-point through to the latter part of the sprint, and meaningful increase in peak unloaded cadence, f_{i0} , (79% likely, Table 4.7); while T_{i_max} and T_{i0} were not substantially changed. Changes in DYN are less evident, with meaningful increases in T_i only present in half crank cycles toward the very end of the sprint. Here T_{i_max}, T_{i0} and f_{i0} showed no meaningful change.



Linear regression yielded the following equations: CON: T_i=-1.413 cadence + 331.3, R^2=0.9983; DYN: T_i=-1.437 cadence + 334.08, R^2=0.9983; ISO: T_i=-1.3645 cadence + 326.85, R^2=0.9985

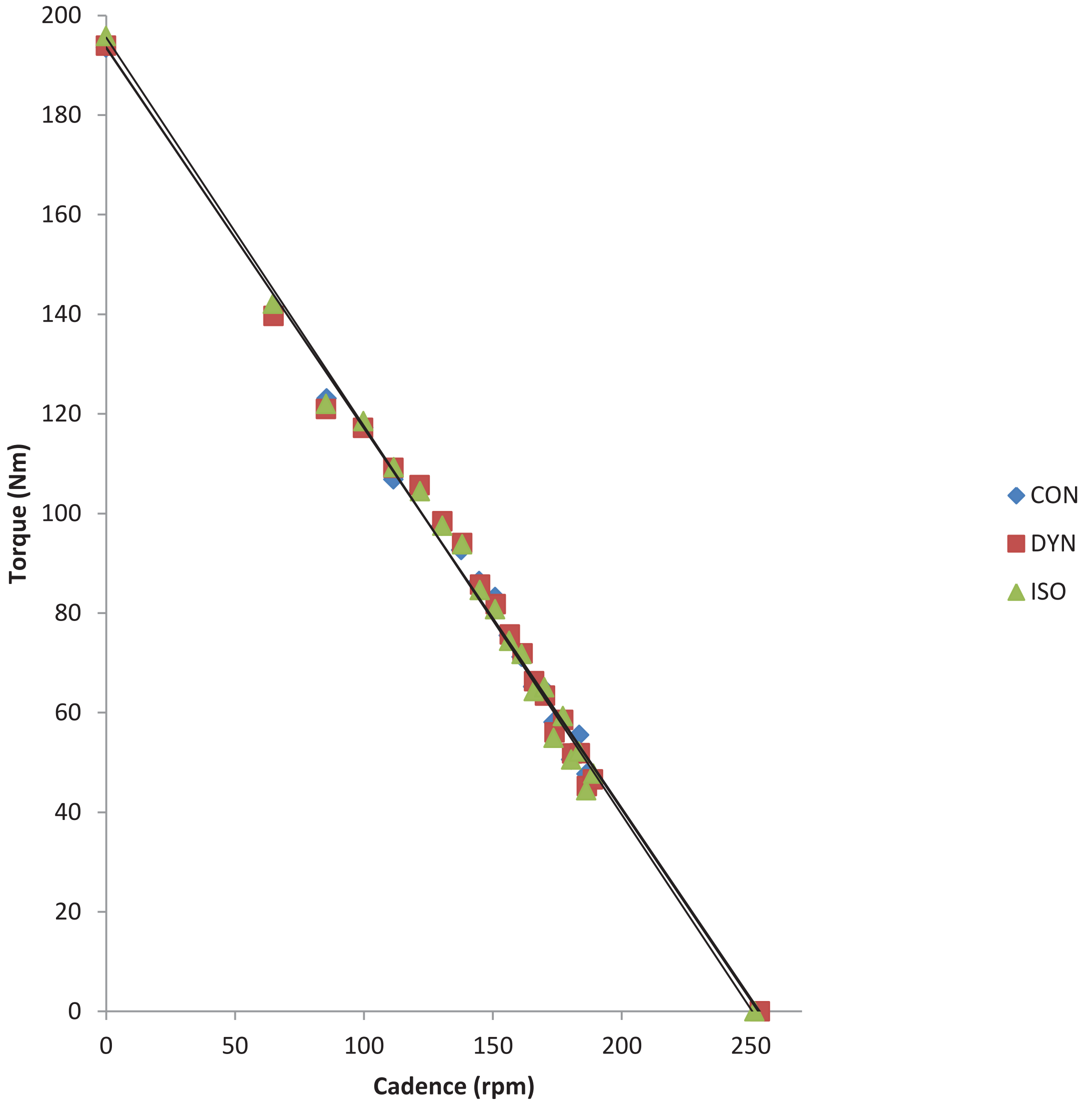
Figure 4.13 T_i Versus Cadence for Post16 Trials.

Intermediate data points depict the peak torque of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. In ISO, increases in torque in the high-cadence region, alongside an increase in cadence at zero-torque intersect, affect a shallower gradient of linear regression line as compared to CON. Less divergence is evident in DYN with increase in torque restricted to a few data points at the high-cadence region of the curve.

Table 4.7 Meaningful Changes in T_i and f_i for Post16 Trials.

Measure	Trial/Time	Post-CC measure (rpm)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
fi0	ISO Post16	239.54±10.41	234.46±9.07	-0.92±3.32	-3.07±1.91	0.50	-0.21	1.20	79	likely

Pre-CC plot of T_{rev} versus cadence is shown in figure 4.14 and demonstrates equivalence in individual data points and linear regression lines.



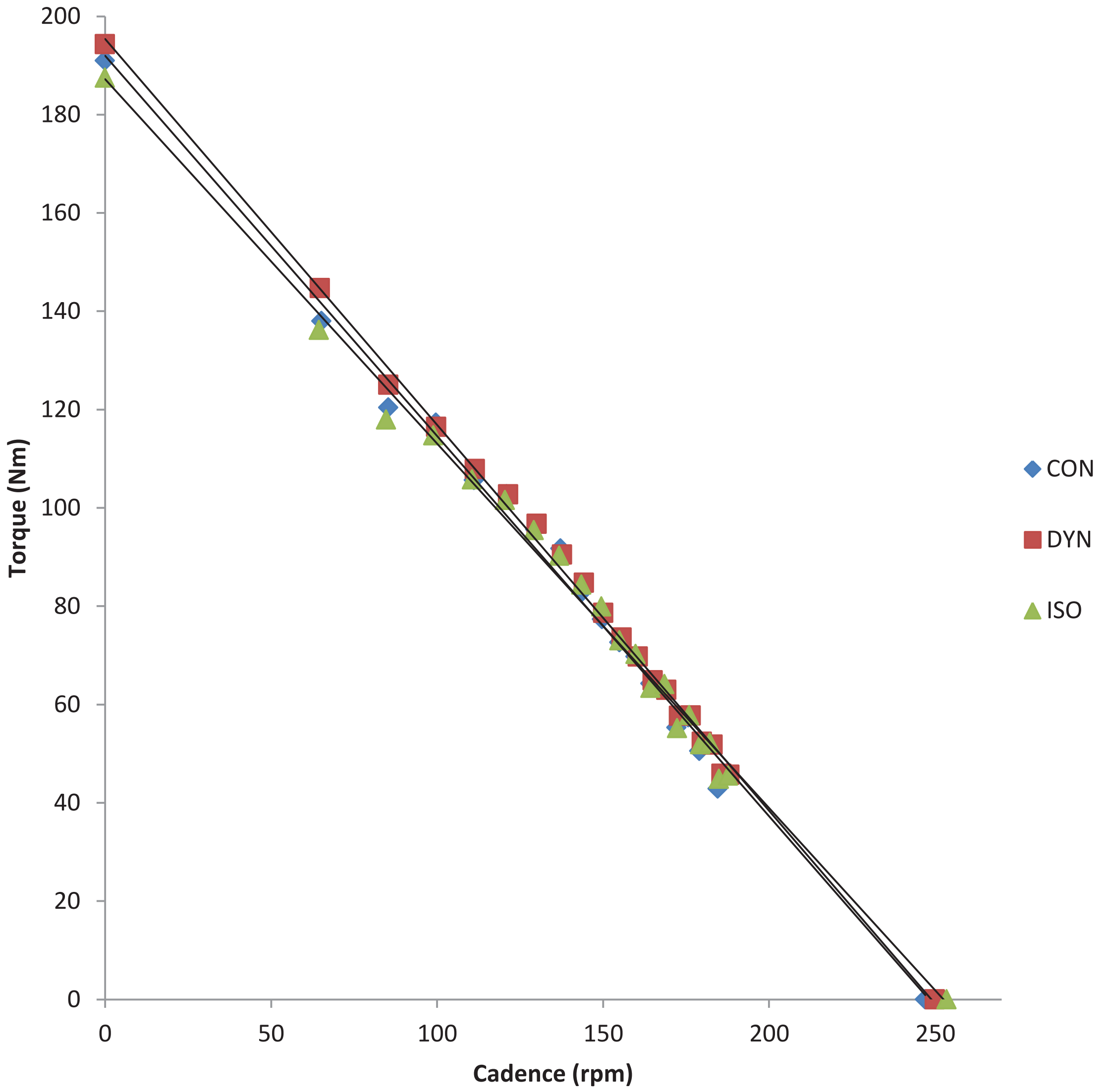
Linear regression yielded the following equations: CON: T_{rev}=-0.763 cadence + 193.45, R^2=0.9946; DYN: T_{rev}=-0.7654 cadence + 193.65, R^2=0.9921; ISO: T_{rev}=-0.78 cadence + 195.56, R^2=0.9932

Figure 4.14 T_{rev} Versus Cadence for Pre-CC Trials.

Intermediate data points depict the average torque per revolution of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. Pre intervention trials show concurrence at each point and minimal disparity in regression lines.

Plots of T_{rev} versus cadence at the Post4 point are presented in Figure 4.15. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.8). Results of T_{rev} are similar to those of T_i with divergence in DYN most apparent at the high-torque extremity of the torque-cadence relationship in DYN. The DYN trial elicited meaningful increases in torque over the first 2 half crank cycles, with T_{rev_max} therefore meaningfully higher than control (96% very likely, Table 4.8). Further increases in torque were observed towards the end of the sprint in this trial with a small number of half crank cycles showing torque increases representing greater than 75% likelihood of exceeding SWC. ISO, instead, presents a shallower gradient in the regression line, affected by positive changes in half crank cycles at the mid- and end- points of the sprint. While T_{rev_max} was unaffected by ISO, this trial condition affected a *detrimental* change in maximal isometric torque production, expounded by T_{rev0} observing a 98% (very likely) meaningful *reduction* in torque (Table 4.8). No meaningful change in f_{rev0} was observed in either trial.

Figure 4.16 shows outcomes at the Post8 time point. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.9). Little divergence is evident in regression lines. DYN and ISO elicited similar changes, with odd half crank cycles at the mid- and end- points of the sprint observing improvement with greater than 75% likelihood of exceeding SWC. Neither trial affected meaningful change in T_{rev_max} , T_{rev0} or f_{rev0}.



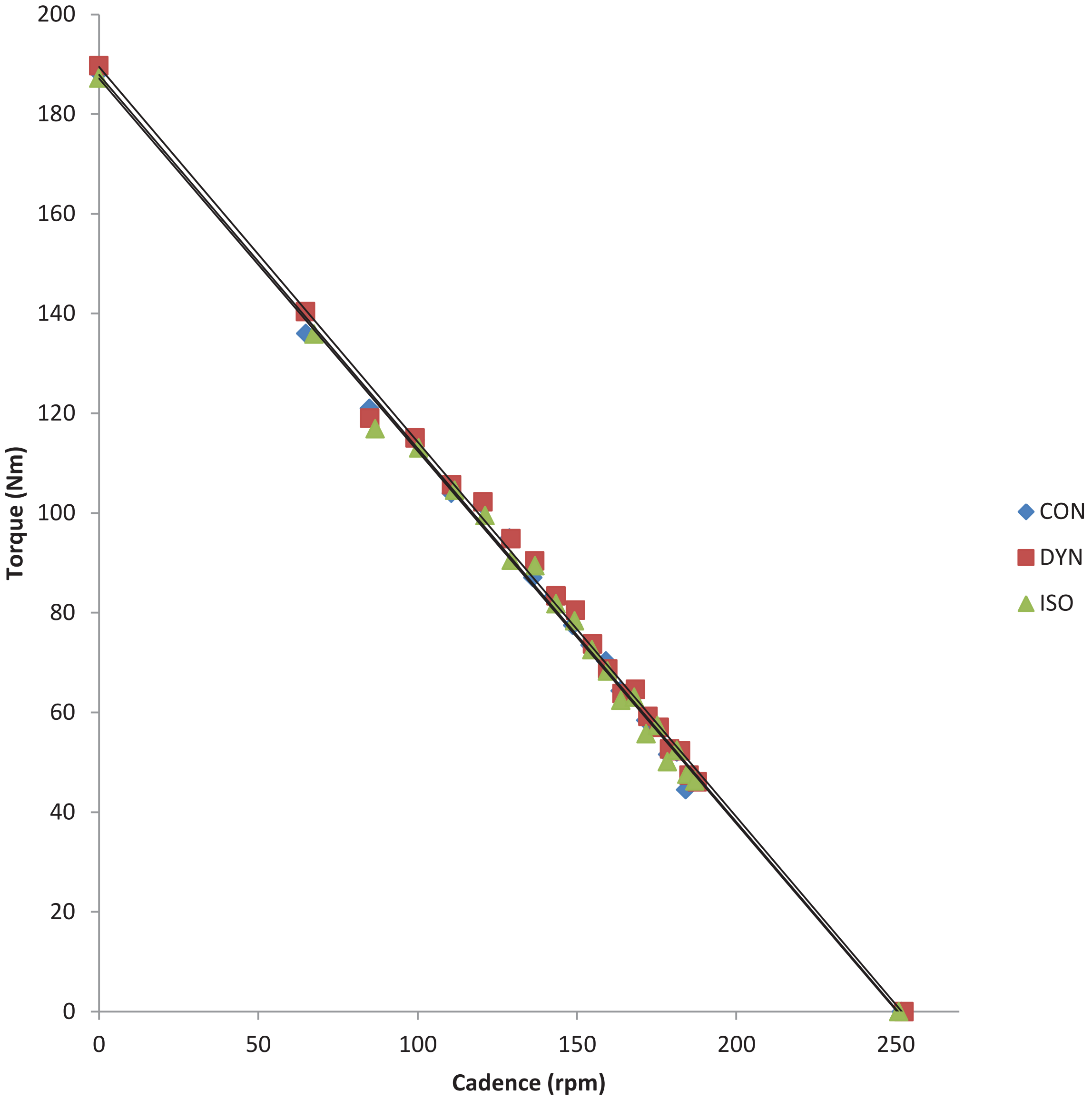
Linear regression yielded the following equations: CON: T_{rev}=-0.7717 cadence + 191.98, R^2=0.994; DYN: T_{rev}=-0.785 cadence + 195.41, R^2=0.9977; ISO: T_{rev}=-0.7387 cadence + 187.22, R^2=0.9937

Figure 4.15 T_{rev} Versus Cadence for Post4 Trials.

Intermediate data points depict the average torque per revolution of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. The regression line of DYN trial has a steeper gradient than that of CON, reflecting the substantial increase in torque in the high-torque region of the relation. ISO presents a shallower gradient in the regression line as a result of an increase in torque towards the high-cadence region and decrease in torque at the high-torque region of the relation.

Table 4.8 Meaningful Changes in T_{rev} and f_{rev} for Post4 Trials.

		Post-CC measure (Nm)		**Change in Measure from Pre-CC value (%)**		**Cohen's d**	**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Trev0 (lower)	ISO Post4	187.50±30.28	192.97±29.90	-4.51 ± 2.17	-0.60 ± 4.75	-0.26	-0.43	-0.10	98	very likely
Trev_max	DYN Post4	144.71±18.47	138.02±17.70	3.55±2.81	-2.28±5.24	0.45	0.23	0.68	96	very likely

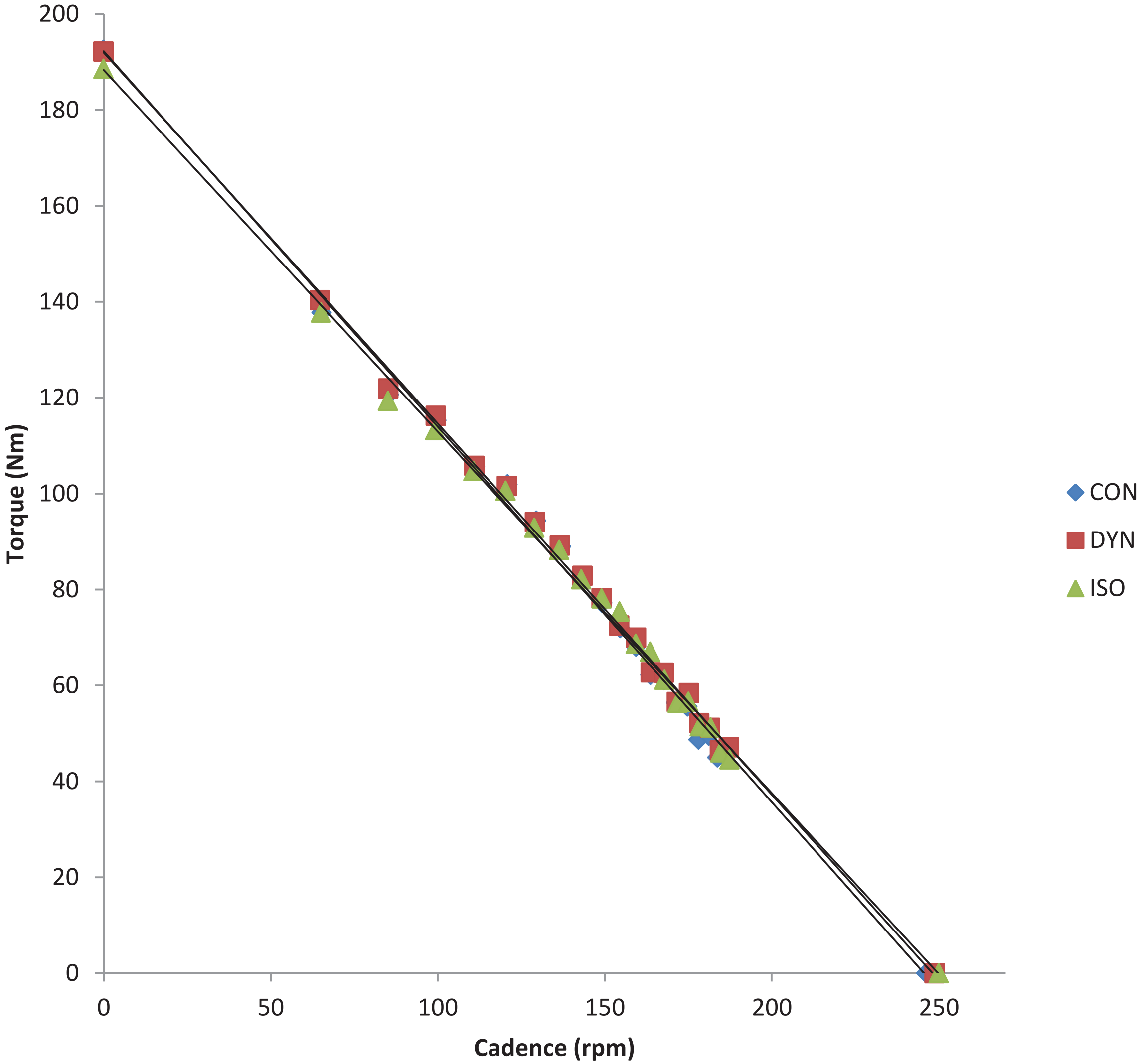


Linear regression yielded the following equations: CON: T_{rev}=-0.7489 cadence + 187.86, R^2=0.9966; DYN: T_{rev}=-0.7518 cadence + 189.44, R^2=0.9962; ISO: T_{rev}=-0.747 cadence + 187.12, R^2=0.9963

Figure 4.16 T_{rev} Versus Cadence for Post8 Trials.

Intermediate data points depict the average torque per revolution of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. The regression lines of DYN and ISO show little divergence from CON, with only odd data points distinct from the control condition.

Comparison of T_{rev} in trials at the Post16 time point is shown in Figure 4.17. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.10). When compared to the CON trial, ISO observes similar distinctions to those observed in T_i , with a lower gradient and higher cadence intersect in the regression line. The trial affected meaningful increases in torque of half crank cycles from mid-way to the end of the sprint, while, as in analysis of T_i , affecting a substantial increase in f_{rev0} with 79% likelihood of exceeding SWC (Table 4.9). DYN presents less divergence, affording increases across a few half crank cycles toward the end of the sprint only. No meaningful change was observed in T_{rev_max} , T_{rev0} or f_{rev0} in this condition.



Linear regression yielded the following equations: CON: T_{rev}=-0.7806 cadence + 192.28, R^2=0.9962; DYN: T_{rev}=-0.7736 cadence + 191.99, R^2=0.9976; ISO: T_{rev}=-0.7533 cadence + 188.36, R^2=0.9969

Figure 4.17 T_{rev} Versus Cadence for Post16 Trials.

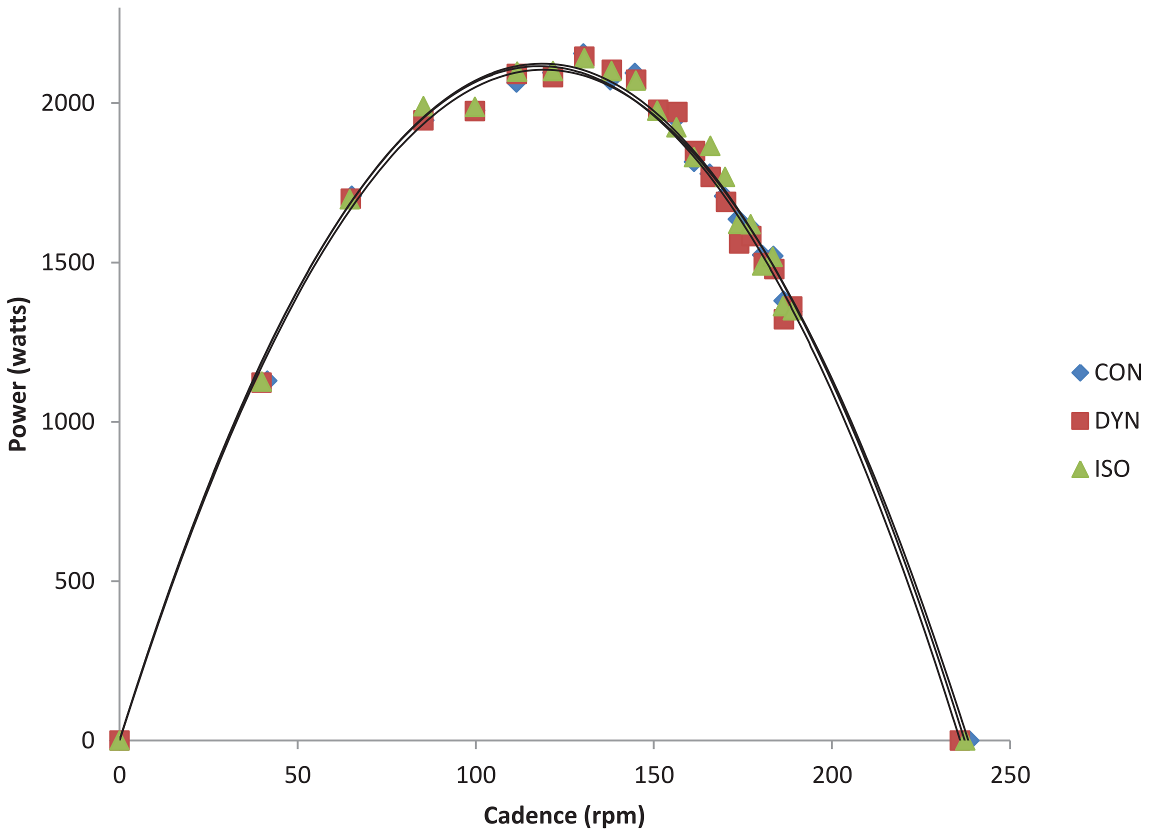
Intermediate data points depict the average torque per revolution of each half crank cycle across the sprint. Axis intersect points are derived from linear extrapolation. In ISO, increases in torque from the mid- to end- point of the relation, alongside an increase in cadence at zero-torque intersect, affect a shallower gradient of linear regression line as compared to CON. Less divergence is evident in DYN with increase in torque restricted to a few data points at the high-cadence region of the curve.

Table 4.9 Meaningful Changes in T_{rev} and f_{rev} for Post16 Trials.

Measure	Trial/Time	Post-CC measure (rpm)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
frev0	ISO Post16	250.05±8.54	246.32±10.16	-0.6±2.46	-2.93±3.34	0.57	-0.32	1.45	79	likely

Quadratic regression lines for P_i and P_{rev} versus cadence in each trial are presented in Figures 4.18 to 4.25 with comparison made at each time point pre- and post- CC.

As observed in Figure 4.18, pre-CC outcomes for P_i show little disparity between trial conditions.



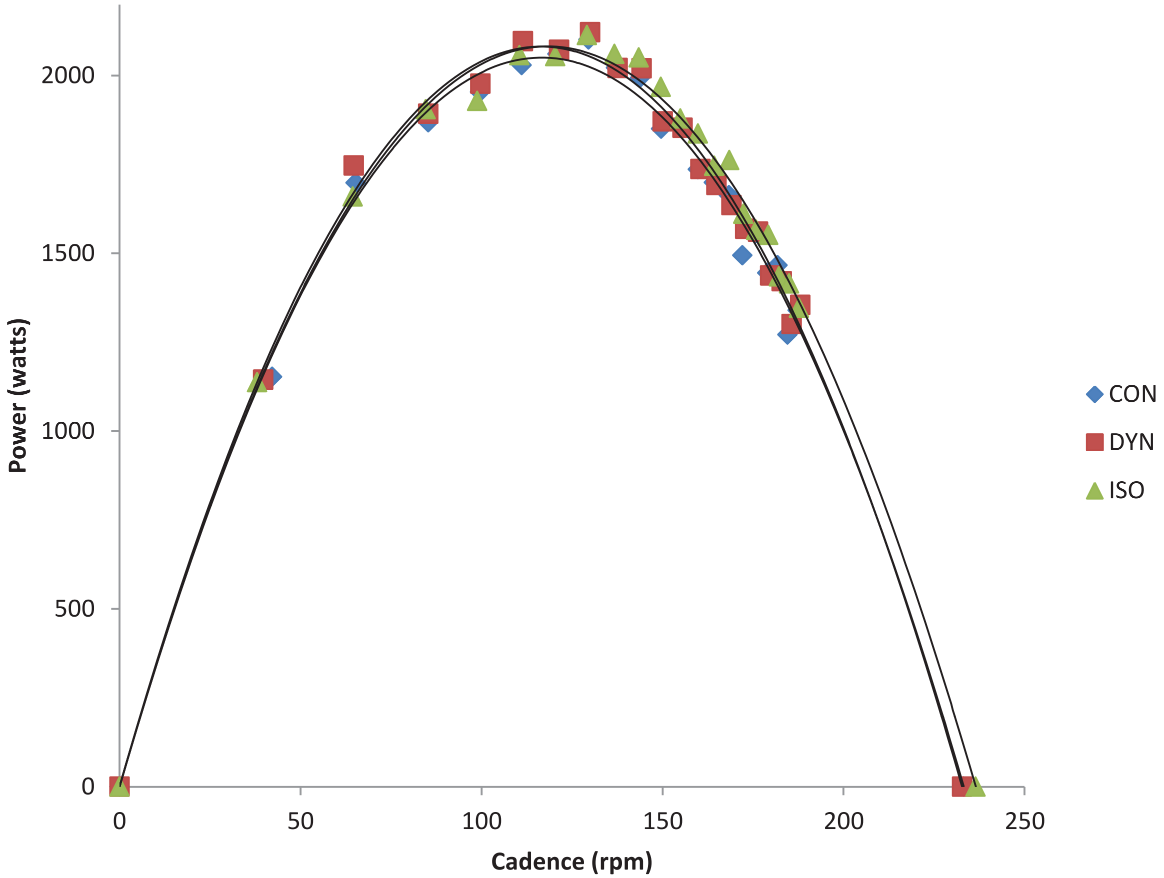
Quadratic regression yielded the following equations: CON: P_i=-0.1483(cadence)^2 + 35.336 cadence, R^2=0.9949; DYN: P_i=-0.152(cadence)^2 + 35.864 cadence, R^2=0.9937; ISO: P_i=-0.1509(cadence)^2 + 35.805, R^2=0.9948

Figure 4.18 P_i Versus Cadence for Pre-CC Trials.

Intermediate data points depict the peak power of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. Pre intervention trials show concurrence at each point and minimal disparity in regression lines.

Figure 4.19 compares the trials at Post4 time point. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.11). DYN appears to have affected an upwards shift in the regression line. However, neither P_{qi_max} nor P_{i_max} showed meaningful change and outcomes have predominantly been elicited by increase in P_i of half crank cycles during the start and end stages of the sprint. A meaningful decrease (90% likely) in HCC P_{i_max} , the half crank cycle where peak power was produced, further depicts an earlier development of peak power in this trial (Table 4.10), though no meaningful change was observed in f_{qi_opt} . ISO appears to have affected an upward-right shift in the regression line. This is substantiated by meaningful increase in P_i of a number of half crank cycles from midway through to the end of the sprint, and meaningful increase in f_{qi_opt} (75%, likely, Table 4.10). No meaningful change in either P_{qi_max} or P_{i_max} was observed in this trial condition.

Figure 4.20, depicts P_i versus cadence of trials at Post8. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.12). Comparison with CON suggests that ISO and to a lesser extent DYN produced a right (but not upward) shift in the relationship. Table 4.11 confirms meaningful increases in f_{qi_opt} following both interventions (ISO: 75% likely; DYN: 93% likely), while meaningful increases in P_i were restricted to the latter half crank cycles of the sprint in each case. Neither protocol produced a meaningful change in P_{qi_max} or P_{i_max}.



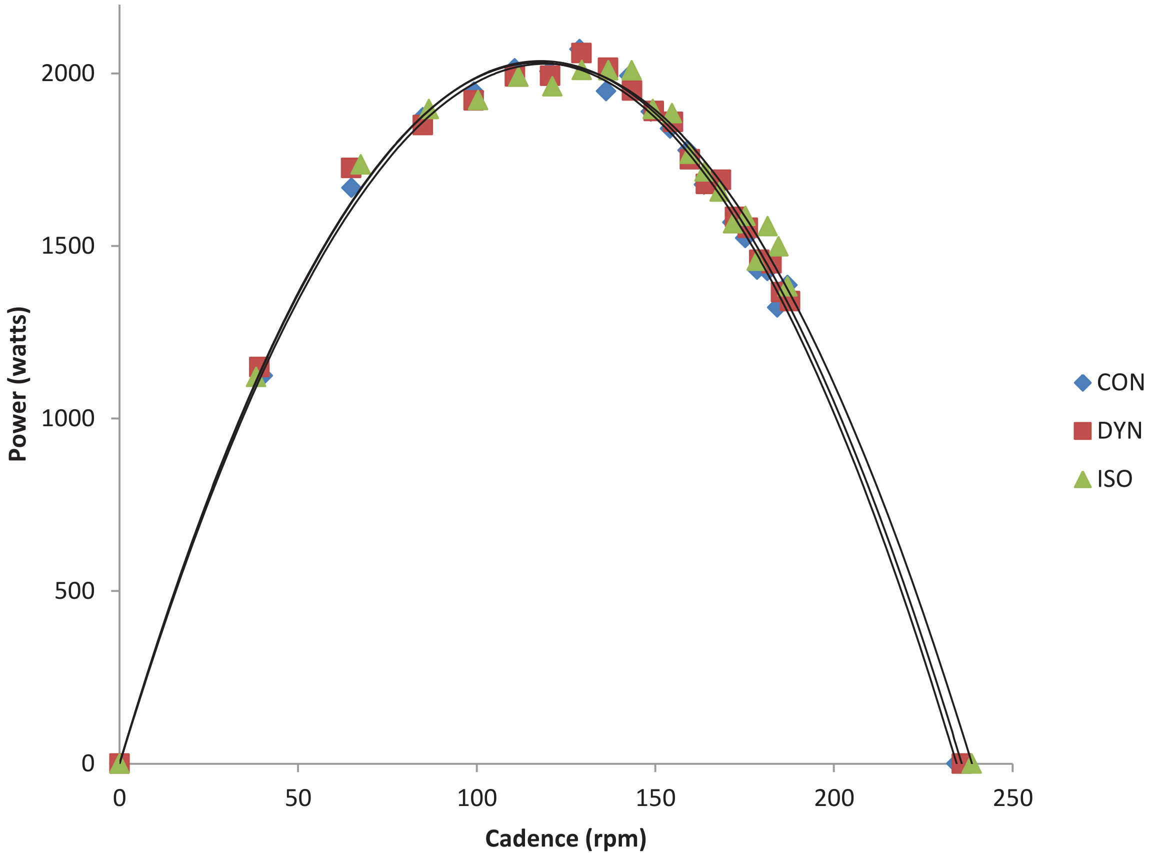
Quadratic regression yielded the following equations: CON: P_i=-0.1508(cadence)^2 + 35.172 cadence, R^2=0.9933; DYN: P_i=-0.1537(cadence)^2 + 35.775 cadence, R^2=0.9952; ISO: P_i=-0.1489(cadence)^2 + 35.217, R^2=0.9962

Figure 4.19 P_i Versus Cadence for Post4 Trials.

Intermediate data points depict the peak power of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. DYN observes an increase in peak power of points on the ascending and descending regions of the relation, alongside an earlier occurrence of peak. ISO affects an up-right shift of the relation through increases in power in the mid-high region of the relation and a shift upward in optimal cadence.

Table 4.10 Meaningful Changes in P_i and f_{qi} for Post4 Trials.

		Post-CC measure (*rpm and § number)		**Change in Measure from Pre-CC value (%)**			**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Cohen's d**	**lower**	**upper**	**%**	**Qualitative Inference**
fqi_opt*	ISO Post4	119.10±5.27	117.25±3.91	-0.65±2.96	-2.43±1.50	0.51	-0.33	1.34	75	Likely
HCC Pi_max §	DYN Post4	5.83±1.72	7.83±2.14	-26.02±29.10	6.46±21.00	-1.05	-2.26	0.17	90	Likely



Quadratic regression yielded the following equations: CON: P_i=-0.148(cadence)^2 + 34.68 cadence, R^2=0.9963; DYN: P_i=-0.1465(cadence)^2 + 34.541 cadence, R^2=0.9958; ISO: P_i=-0.1425(cadence)^2 + 34.001, R^2=0.9926

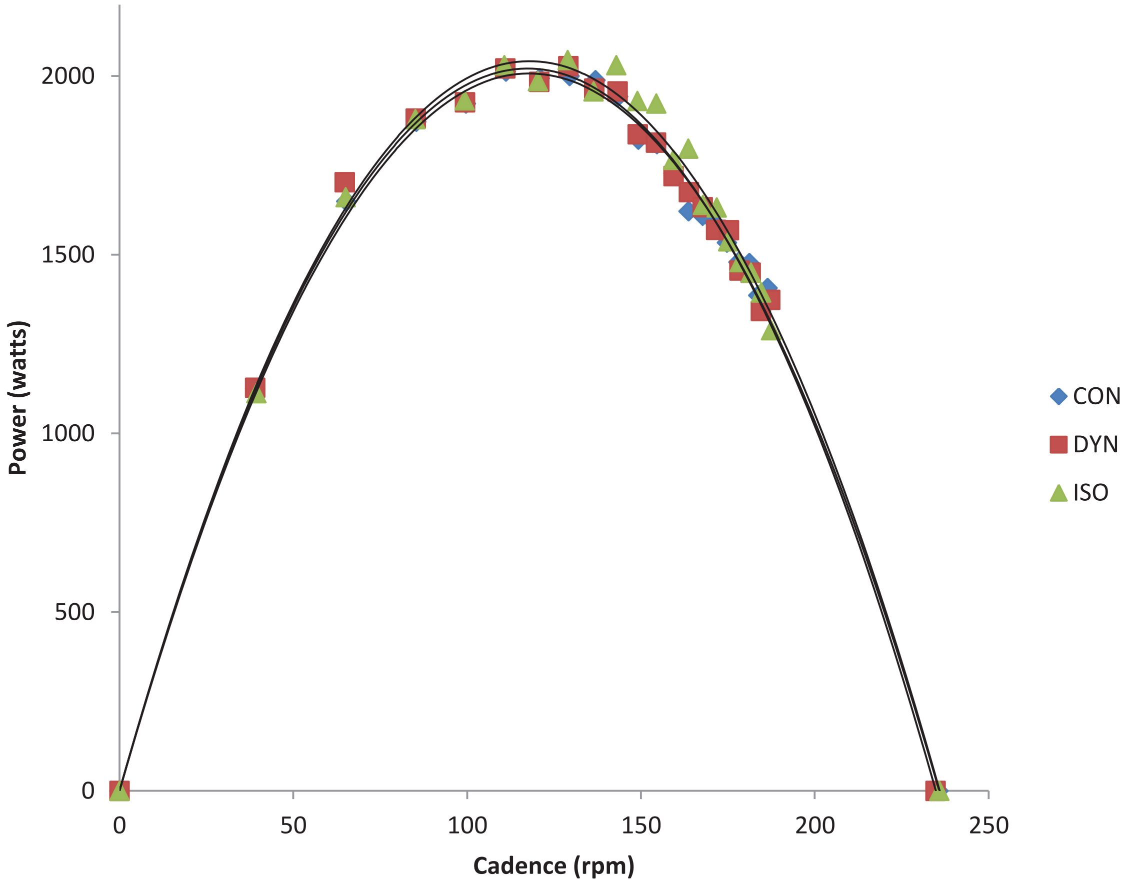
Figure 4.20 P_i Versus Cadence for Post8 Trials.

Intermediate data points depict the peak power of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. DYN and ISO both observe a small rightward shift in the relation with increases in power in the high-cadence region of the relation, alongside an upward shift in optimal cadence.

Table 4.11 Meaningful Changes in P_i and f_{qi} for Post8 Trials.

		Post-CC measure (rpm)		**Change in Measure from Pre-CC value (%)**			**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Cohen's d**	**lower**	**upper**	**%**	**Qualitative Inference**
fqi_opt	DYN Post8	118.83±3.67	117.99±3.02	0.07±2.04	-1.78±1.40	0.49	0.15	0.83	93	likely
	ISO Post8	119.63±4.83	117.99±3.02	-0.19±3.98	-1.78±1.40	0.45	-0.46	1.36	75	likely

Figure 4.21 depicts P_i versus cadence at Post16. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.13). In contrast to results of Post4 and Post8, regression lines at Post16 suggest an upward (but not right) shift in ISO. Meaningful increases were elicited in half crank cycles near the apex of the curve in ISO, while no meaningful change was present in f_{qi_opt} . DYN observes less divergence, affecting only a single meaningful increase in P_i at the outset of the sprint and single possible increases in a half crank cycle at the end of the sprint. Here again, no meaningful change was present in either P_{qi_max} or P_{i_max}.

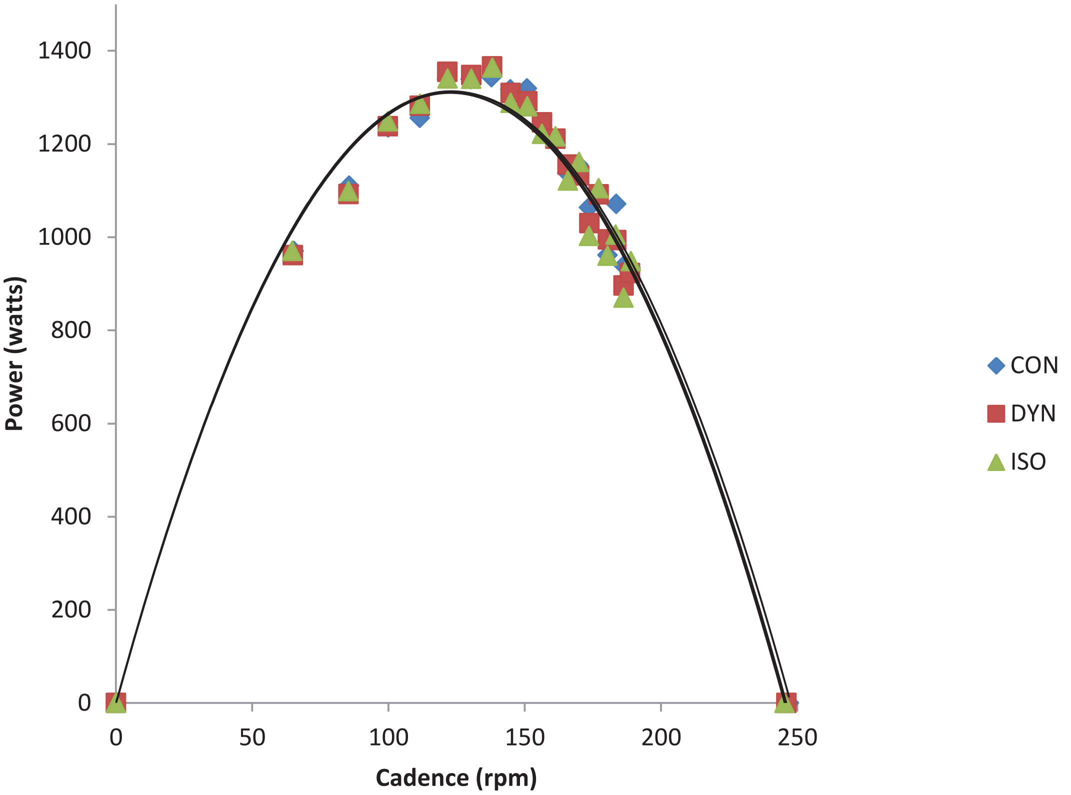


Quadratic regression yielded the following equations: CON: P_i=-0.1444(cadence)^2 + 34.052 cadence, R^2=0.996; DYN: P_i=-0.1466(cadence)^2 + 34.425 cadence, R^2=0.996; ISO: P_i=-0.1467(cadence)^2 + 34.425, R^2=0.9953

Figure 4.21 P_i Versus Cadence for Post16 Trials.

Intermediate data points depict the peak power of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. ISO observes an upwards shift through increases in power through the apex of the relation. Improvements in DYN are restricted to single data points on the ascending and descending limbs of the relation.

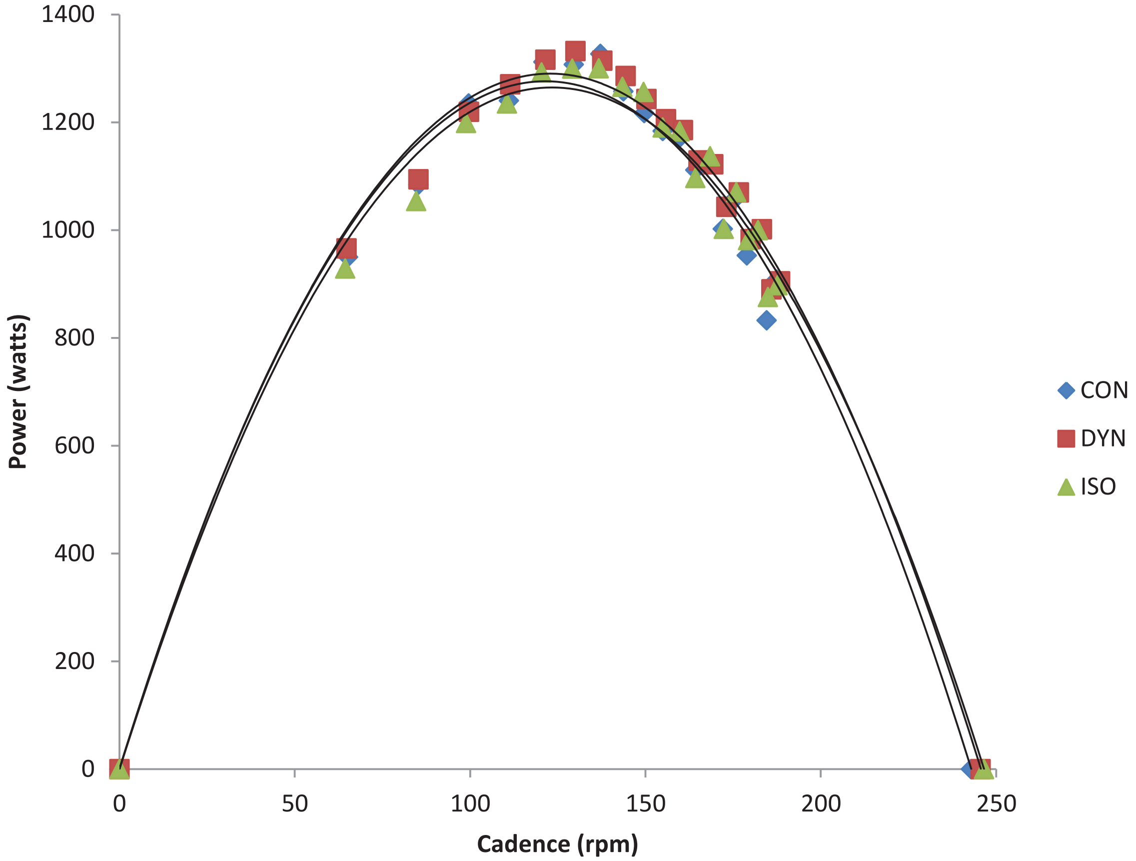
Examining P_{rev}, Pre-CC trials show little difference between the trial conditions (Figure 4.22).



Quadratic regression yielded the following equations: CON: P_{rev}=-0.0856(cadence)^2 + 21.19 cadence, R^2=0.9868; DYN: P_{rev}=-0.0868(cadence)^2 + 21.35 cadence, R^2=0.9863; ISO: P_{rev}=-0.087(cadence)^2 + 21.349, R^2=0.9863

Figure 4.22 P_{rev} Versus Cadence for Pre-CC Trials.
Intermediate data points depict the average power per revolution of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. Pre intervention trials show concurrence at each point and minimal disparity in regression lines.

Figure 4.23 presents P_{rev} versus cadence at the Post4 time point. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.14). Comparison of outcomes reveals similarities to that of P_i at the same time point. DYN affected change in P_{rev}, through the ascending, apex and descending regions of the relation. This is supported by meaningful increase in P_i in half crank cycles at the start, mid and end points of the sprint. Further correspondence to results of P_i is observed, with the half crank cycle where peak power was produced showed a meaningful reduction following DYN (85% likely, Table 4.12); DYN, therefore, benefiting an earlier development of peak power. ISO appears to have elicited an up-right shift of the regression line with meaningful increase in optimal cadence, f_{qrev_opt} (84% likely, Table 4.12), and P_{rev} of a number of half crank cycles from midway through to the end of the sprint. No meaningful change of f_{qrev_opt} was observed in DYN and neither intervention elicited meaningful change in P_{qrev_max} or P_{rev_max}.



Quadratic regression yielded the following equations: CON: P_{rev}=-0.0865(cadence)^2 + 21.013 cadence, R^2=0.9862; DYN: P_{rev}=-0.0855(cadence)^2 + 21.008 cadence, R^2=0.9921; ISO: P_{rev}=-0.0832(cadence)^2 + 20.513, R^2=0.987

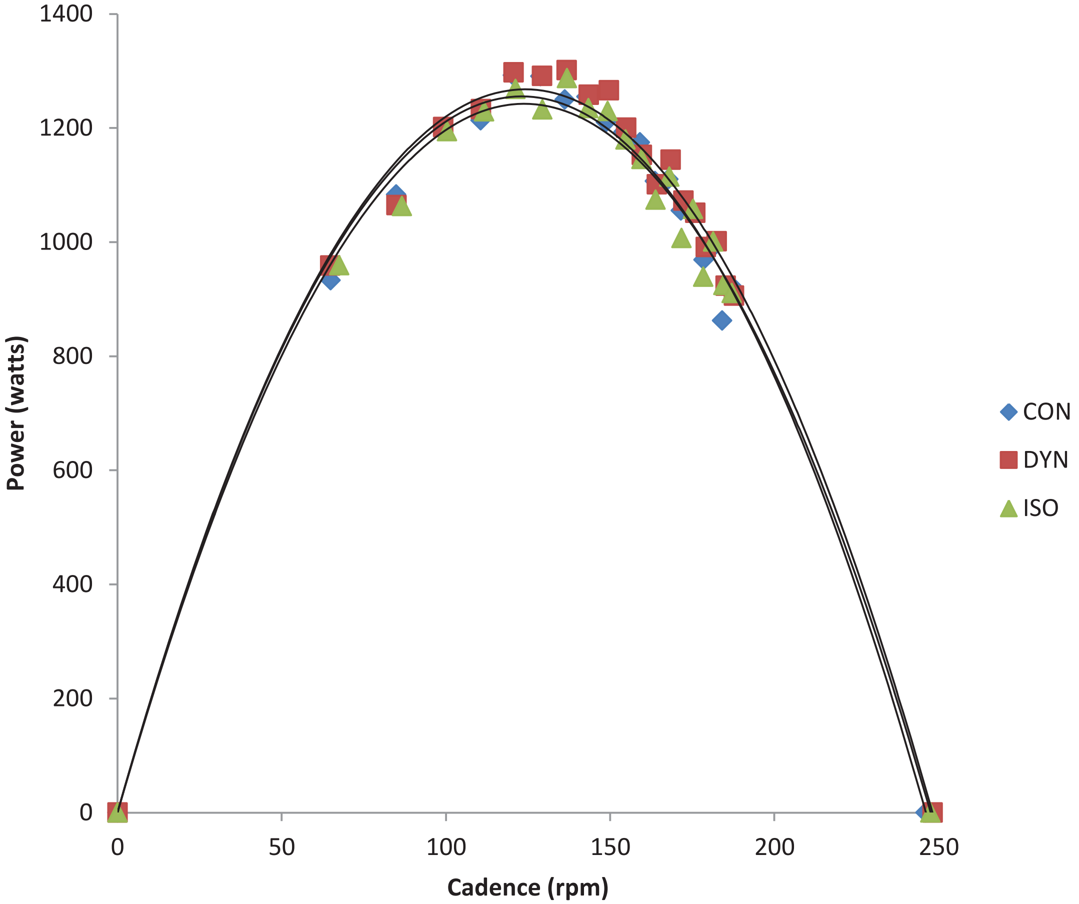
Figure 4.23 P_{rev} Versus Cadence for Post4 Trials.

Intermediate data points depict the average power per revolution of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. DYN observes an increase in peak power of points on the ascending, apex and descending regions of the relation, alongside an earlier occurrence of peak. ISO affects an up-right shift of the relation through increases in power in the mid-high region of the relation and a shift upward in optimal cadence.

Table 4.12 Meaningful Changes in P_{rev} and f_{qrev} for Post4 Trials.

Measure	Trial/Time	Post-CC measure (*rpm and § number)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
fqrev_opt*	ISO Post4	123.84±5.36	122.07±3.84	0.56±2.40	-1.92±2.38	0.54	-0.10	1.19	84	Likely
HCC Prev_max §	DYN Post4	5.83±0.98	6.67±1.03	-13.99±11.49	1.42±18.72	-0.59	-1.26	0.08	85	Likely

With reference to Figure 2.24, plots of trial outcomes at the Post8 point show little divergence. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.15). Here, trials affected relatively few meaningful changes in P_{rev} , with DYN and ISO each affecting meaningful increases in only a few half crank cycles at the mid and end of the sprint. No meaningful outcomes were observed in P_{rev_max}, P_{qrev_max}, f_{qrev_opt} or HCC P_{rev_max}.

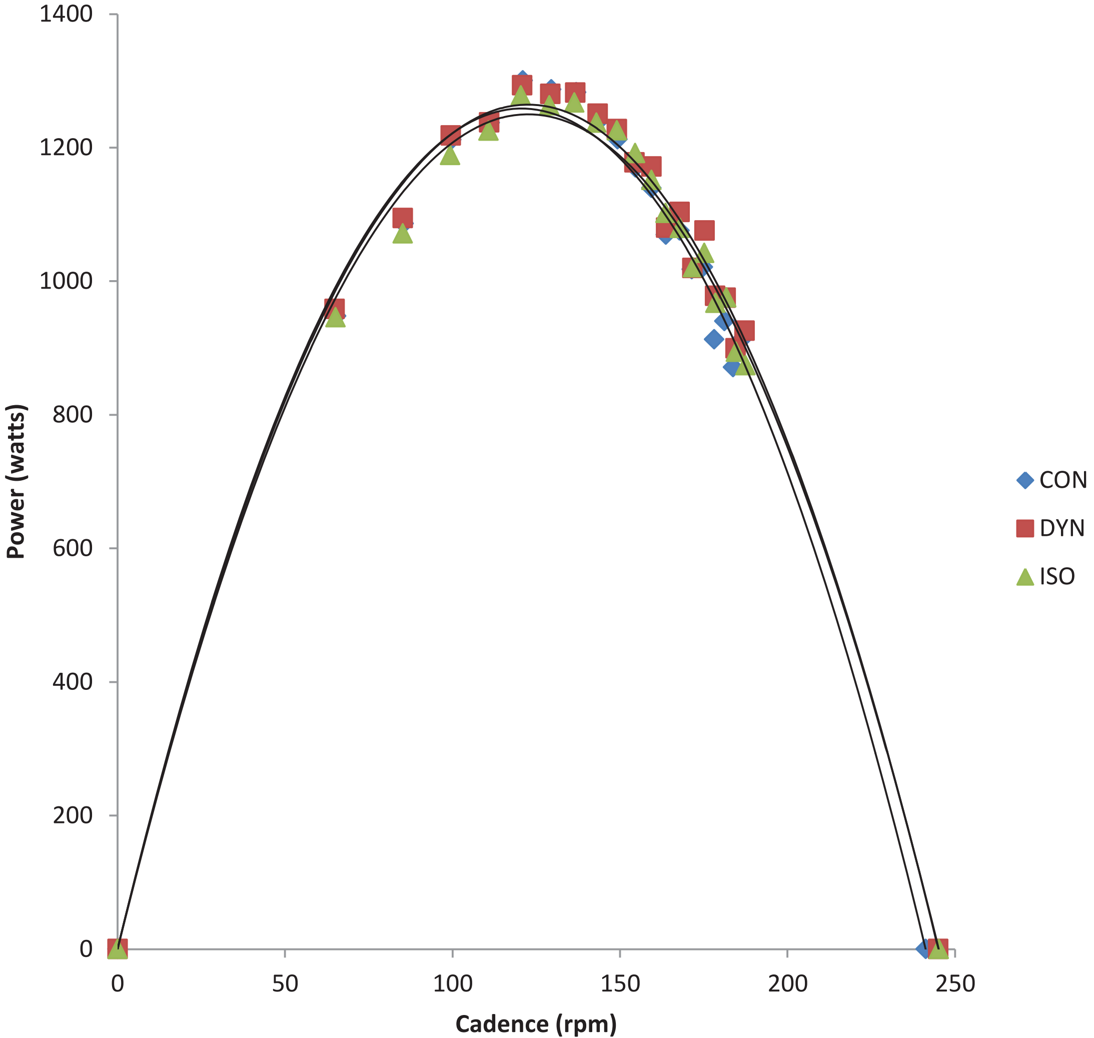


Quadratic regression yielded the following equations: CON: P_{rev}=-0.0829(cadence)^2 + 20.405 cadence, R^2=0.9923; DYN: P_{rev}=-0.0824(cadence)^2 + 20.438 cadence, R^2=0.9924; ISO: P_{rev}=-0.0811(cadence)^2 + 20.076, R^2=0.991

Figure 4.24 P_{rev} Versus Cadence for Post8 Trials.

Intermediate data points depict the average power per revolution of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. DYN and ISO both observe little divergence from CON, with only a small up-right shift of each regression line through increases in power of odd data points of the mid/high-cadence region of the relation.

Figure 4.25 shows P_{rev} versus cadence in trials at Post16. Data relating to meaningful outcomes of individual data points is presented in Appendix 5 (Table A5.16). Quadratic regression line of the ISO appears to be shifted right as compared to that of CON, with this trial condition evoking a meaningful increase in optimal cadence, (82% likely, Table 4.13) and in P_{rev} of a number of half crank cycles from mid-way to end of the sprint. DYN affects a less pronounced shift, with meaningful increase in optimal cadence, f_{rev_opt} , (83% likely, Table 4.13) and in P_{rev} of half crank cycles at the very end of the sprint and. No meaningful changes were observed in P_{qrev_max}, P_{rev_max} and HCC P_{rev_max} in either condition.



Quadratic regression yielded the following equations: CON: P_{rev}=-0.0865(cadence)^2 + 20.866 cadence, R^2=0.9918; DYN: P_{rev}=-0.0842(cadence)^2 + 20.639 cadence, R^2=0.9939; ISO: P_{rev}=-0.0832(cadence)^2 + 20.394, R^2=0.9945

Figure 4.25 P_{rev} Versus Cadence for Post16 Trials.

Intermediate data points depict the average power per revolution of each half crank cycle across the sprint. Vertex is derived from quadratic regression applying a 2nd order polynomial constrained to pass through the origin. ISO observes a right shift through increases in power from the mid to high-cadence regions of the relation and shift to higher optimal cadence. The regression line in DYN is shifted right through higher optimal cadence and improvements in power in the high-cadence region of the relation.

Table 4.13 Meaningful Changes in P_{rev} *and* f_{qrev} *for Post16 Trials.*

		Post-CC measure (rpm)		Change in Measure from Pre-CC value (%)			90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Cohen's d**	**lower**	**upper**	**%**	**Qualitative Inference**
fqrev_opt	DYN Post16	123.24±3.60	121.32±5.38	-0.24±2.36	-2.58±3.99	0.49	-0.10	1.07	83	likely
	ISO Post16	123.43±4.50	121.32±5.38	0.25±2.74	-2.58±3.99	0.62	-0.23	1.47	82	likely

4.4 METABOLIC MEASURES

One-way ANOVA showed no significant difference in baseline measures of heart rate (p=0.671). Analysing Pre- and Post-CC data using repeated measures ANOVA revealed no significant main effect for trial (p=0.863) or interaction of trial x time (p=0.126). A significant main effect for time across trials (p=0.000) reflected the repeated measures nature of the design. Since this outcome is accommodated by the design, results here are summarised in Appendix 5 (Table A5.17).

One-way ANOVA showed no significant difference in baseline measures of blood lactate (p=0.252). Repeated measures ANOVA analysis of Pre- and Post-CC measures revealed a trend for significant main effect of time (p=0.056) again reflecting the repeated measures design. Since this outcome is accommodated by the design, results here are, again, summarised in Appendix 5 (Table A5.17).

Repeat analysis of metabolic measures using within-subjects contrasts presented some distinct outcomes from those of ANOVA analysis. While the trend for decline in heart rate from Pre- to Post-CC trials was similarly evident, meaningful differences between control and specific trial conditions were apparent (Table 4.14). Change in heart rate from Pre to Post8 surpassed the 75% likelihood of exceeding the SWC in both DYN and ISO (DYN: 78% likely, ISO: 97% very likely), with heart rate remaining higher at Post8 following both CC interventions. Changes at Post4 were, similarly, very likely (97%) meaningful in ISO; heart rate again higher prior to this trial. While the DYN Post4 trial did not exceed the 75% likelihood, a 70% possible inference suggests the change in heart rate, reflecting a higher heart rate than CON at the Post4 time point, may still be meaningful. Meaningful differences between DYN and ISO also existed with heart rate at ISO Post4 substantially higher than that of DYN at the same time point (83% likely) (Table 4.15).

No meaningful differences were observed in blood lactate between control and either DYN or ISO at any time point. However, as with heart rate outcomes, blood lactate was meaningfully higher at the post4 time point in ISO as compared to DYN (79% likely) (Table 4.15).

Table 4.14 Meaningful Changes Pre- to Post- CC in Metabolic Measures.

		Post-CC measure (* units)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
HR	DYN Post4	114.50±17.14	110.33±13.53	-15.78±11.16	-21.61±11.03	0.57	-0.77	1.92	70	possibly
	DYN Post8	115.50±17.72	110.50±11.79	-14.97±11.69	-21.28±8.00	0.62	-0.37	1.62	78	likely
	ISO Post4	118.00±10.06	110.33±13.53	-9.78±5.50	-21.61±11.03	1.21	0.39	2.03	97	very likely
	ISO Post8	115.83±13.91	110.50±11.79	-11.92±7.15	-21.28±8.00	0.96	0.30	1.61	97	very likely

**HR = heart rate, bpm ; BLa = blood lactate, mmol.L^{-1}*

Table 4.15 Meaningful Changes DYN to ISO in Metabolic Measures.

		Post-CC measure (* units)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**ISO Mean ± SD**	**CON Mean ± SD**	**ISO Mean ± SD**	**DYN Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
HR	DYN-ISO Post4	118.00±10.06	114.50±17.14	-9.78±5.50	-15.78±11.16	0.73	-0.30	1.75	83	likely
BLa	DYN-ISO Post4	4.82±2.29	3.95±2.08	-28.43±45.51	-46.09±43.12	0.55	-0.25	1.35	79	likely

**HR = heart rate, bpm ; BLa = blood lactate, mmol.L^{-1}*

4.5 SUMMARY OF TRIAL OUTCOMES

A complete listing of significant (ANOVA) and meaningful (Within-subjects contrasts) outcomes for each trial condition is provided in Appendix 6. Instantaneous variables are aligned to segment/overall variables where there is relevant association, thereby providing an overview of results for each trial-time combination.

CHAPTER 5 – DISCUSSION

The primary objective of this study was to examine the effects of an appropriately designed acute post-activation potentiation protocol (PAP) on subsequent sprint cycling performance. The main finding was that conducting 4 x 4 crank cycles of a dynamic, high-inertia ergometer conditioning stimulus at a 4-minute time interval ahead of sprint performance, successfully evoked improvement in overall performance time. A reduction in time to complete the first two crank cycles was central to this outcome. In support, biomechanical improvements affected by the PAP protocol were predominantly on the ascending limb of the power-cadence relation. In contrast, the isometric protocol of 4 x 5-second maximal voluntary contractions (MVC), was most successful when conducted 16-minutes prior - here augmenting performance through the final segment of the sprint. While no reduction in performance time was observed in this condition, meaningful changes in biomechanical parameters, therefore, supported enhancement of the *descending* limb of the power-cadence relationship. Results suggest that, by adhering to protocol guidelines advocated by existing research, consistent performance improvements can be realised. The biomechanical assessment afforded by crank technology further suggests there may be distinct PAP characteristics evoked by different CC modes.

Key features of the study design presented ideal conditions for prevailing PAP: the biomechanical specificity of the CC movement pattern, application of a multiple set, low density CC protocol and highly-trained sprint status of participants (McGregor, 2011; Xenofondos, et al., 2010). Evidentially, application of an appropriate protocol design can ensure a potentiated performance gain in concentric-only, cyclical-action, explosive activity - refuting claims that only single-action activities (French et al., 2003) or movements with an eccentric component (Cabrera, et al., 2009) would show discriminatory effect. The inimitable feature of this research is the ergometer used as the PAP stimulus. Since PAP augments function at sites throughout the chain of command, from pre-motor and motor command to the collagenous structures delivering force to the skeleton (Etnyre & Kinugasa, 2002) (Docherty, et al., 2004) (Grange et al., 1993) (Comyns, et al., 2007; Mahlfeld, et al., 2004), mimicking the outcome movement pattern in a loaded manner maximises the potential for excitation of the primary movement pathways. Studies of Feros et al. (2012), Hancock (2004) and Matthews et al. (2010), each affecting functional gain using a resisted performance pattern as CC, support this contention. The same feature notably distinguishes Lawrence et al.'s (2010) examination of sprint cycling. The current study extends the success of the Lawrence research team by constructing a more robust and sprint-specific ergometer, which accommodates the superior strength and power capacity of elite athletes, while providing closer accuracy to the movement kinematics of sprinting.

With workload implicated in achieving minimum stimulus thresholds, previous studies have attempted to reconcile the need for a CC of an appropriate volume and intensity with its concurrent impact on fatigue: increasing volume affects LFF (Skurvydas & Zachovajevas, 1998) and a lengthening of the decay time of fatigue (Miyamoto, et al., 2012), where increasing intensity, instead, affects HFF (Chiu, et al., 2004). The success of the current study may, therefore, be attributable to the multiple set protocol in satisfying threshold conditions through the cumulative effects of repeat stimulation. Brief bursts of maximal work would have ensured excitation, while the two-minute rest between sets would have been sufficient for residual NM fatigue to subside and energy-providing phosphagens to be restored. The success of the protocol confirms the assertions of Boullosa et al. (2012) and Gullich and Schmidbleicher (1996) that total time under tension (TUT), rather than contraction time *per se,* is central to success.

Though studies consistently report response to PAP is highly individualised (Chaouachi, et al., 2011; McCann & Flanagan, 2010; Nibali, et al., 2011), in the current study a large number of significant

(ANOVA) or meaningful (magnitude-based inference) group effects were recorded. In addition to the impact of CC activity and protocol, the highly-trained sprint status of the participants has, apparently, presented sufficient conditions of homogeneity to observe a consistent response. These athletes would be characterised by a predominance of fast-twitch fibres, high degree of strength training experience, fatigue resistance, greater relative strength, ability to more readily and fully recruit highest order MU and ability to maintain consistency of performance – mitigating factors in the ability to elicit and observe an over-riding potentiation (Clevidence, 2008). In such a case, a more uniform potentiation response is, perhaps, unsurprising.

However, skilled performance further requires a high degree of coordination and psychomotor ability. In such a case, simply being elite is not tantamount to being an expert in executing the performance measure. Unsuccessful studies that have tested, for example, fencers performing CMJ (Tsolakis, et al., 2011), rugby players sprinting (Comyns, et al., 2010) or performing cycle sprints (Parry, et al., 2008), and soccer players jumping or sprinting (Till & Cooke, 2009), may not be examining athletes capable of consistently reproducing maximal performance in these movements. Indeed, where McFarlane et al. (1993) determined that skilled technique is a limiting factor in speed development, Comyns et al. (2010) observed a distinct *lack* of technique proficiency in their field sports participants as compared to trained sprinters. The authors concluded that such deficiencies may have prevented PAP manifesting in faster sprint times. Mechanisms of potentiation may be more beneficial and, as a result, more readily observed, in athletes who have already maximised their performance potential in the test measure. In support, Bomfim Lima et al. (2011), testing elite sprinters, saw consistent improvement in sprint performance; Bellar et al. (Bellar, et al., 2012) observed increased heel-turn throw performance in track and field throwers; Hancock (2004) improved swim sprint in highly trained swimmers; Feros et al. (2012) equally found improvement in 1000 m rowing testing elite level rowers. Though Batista et al. (2011) were unsuccessful in their examination of elite track and field jumpers performing CMJ, the fixed recovery time of 4 minutes and poor movement specificity of leg press as the CC may have confounded results. Finally, Hilfiker et al. (2007) further acknowledged that the full training status of the athletes will be additionally determined by the training phase in which the trials are conducted. Few studies have reported this information. However, the success of the current study may well be further attributed to the trials being conducted at the end of the competitive season where the athletes were in near peak form. In agreement with Clevidence (2008), the benefit afforded by small changes in performance execution may be more readily observed in athletes who have already maximised their functional potential.

PAP research outcomes may not only be a function of how able the athlete is to capitalise on its effects, but additionally how sensitive the study design is to detecting change. In the current study, crank technology provided the opportunity to examine a large number of biomechanical and performance measures. Each measure was assessed over discrete segments of the sprint, further allowing determination of the specific sprint phase (and hence biomechanical conditions) where PAP had altered performance. Positive group effects were observed in every trial condition. However, disparity existed in the particular measures and segments affected in each case.

The magnitude and consistency of measures and segments showing improvement was substantially different across trials, indicative of CC mode-recovery time combinations that were apparently more or less successful in benefiting performance. The greatest consistency in performance improvements were observed in three trials: DYN Post4, where increases in maximal torque and a number of measures in the first segment of the sprint were concomitant to a meaningful decrease of both segment 1 time and overall performance time; ISO Post16 which affected meaningful increases in peak unloaded cadence, optimal cadence and a number of measures in the final segment of the sprint, though failed to achieve any improvement in performance time; DYN Post16 which affected minor improvements at the start of the sprint and improvements in a few measures in the final segment, but again was unable to affect an overall reduction in performance time. In such cases, where performance changes in DYN Post4 were predominantly on the ascending limb of the power-cadence relationships, those of ISO Post16 were largely on the descending limb, where DYN Post16 revealed elements of each, albeit to a lesser degree.

The DYN Post4 trial was the only condition where improvements in biomechanical measures were concomitant to a meaningful change in the overall time to complete the sprint. This CC mode-recovery time combination was, therefore, the most successful in evoking performance improvement. A reduction in time to complete segment 1, associated with an increase in average velocity through this phase, was central to this outcome. Where time to complete segment 1 increased by ~1.21% with respect to baseline in the control trial at this time point, DYN Post4 observed a ~3.91% decrease, representing a very high, 92%, likelihood of exceeding the smallest worthwhile change (SWC). Notably this trial was the only one demonstrating improvement in torque over the first stage of the sprint - both segment and instantaneous measures confirming increase over the first two half cranks cycles, where maximum torque was produced. Maximum torque improved by over 6% in response to the dynamic intervention, representing a substantial PAP response. During the first segment, improvements in average cadence additionally contributed to an increase in segment average power. Change from baseline values reflected ~7% improvement when compared to the concomitant decline in control condition.

In the final segment of this sprint, inconsistent improvements in torque and power saw only three half crank cycles show meaningful improvement. Consequently, changes in average torque and power across this segment did not reach statistical threshold, though were sufficient to affect an increase in work done across the segment. Across the complete sprint, meaningful changes through segments 1 and 4 affected an increase in total work done and an overall improvement in average torque, power and velocity. A small but meaningful increase in final velocity was observed: change from baseline in this measure representing a ~1.57% improvement from control conditions. Notably, improvements in final velocity showed concurrence in the statistical relevance implicated by ANOVA and magnitude-based inference analysis. Such equivalence of outcomes inferred by the two statistical techniques was uncommon - ANOVA analysis upheld the null hypothesis in comparisons of a number of dependent measures, where magnitude-based inferences revealed apparently meaningful changes. Current results therefore support the assessment of Chaouachi, et al. (2011) that null hypothesis significance testing may not necessarily be appropriate for this type of experiment.

In contrast to DYN Post4, ISO Post16 affected no changes in the first half of the sprint. Where DYN Post4 produced changes in maximal torque and average cadence through segment 1, ISO Post16 conversely improved torque and cadence only in the *final* phase of the sprint. DYN Post4 affected only minor changes in instantaneous torque and power through segment 4, where ISO Post16 produced improvements in the torque of nearly all pedal strokes from mid-way to the end of the sprint. These results affected an improvement in average torque of the final segment, such that, in conjunction with improvement in average cadence, an improvement in average power was observed through this phase. Change from baseline average power here represented over 5% improvement when compared to that of the control trial. However, despite associated improvements in work done, changes in performance time over this segment failed to reach statistical threshold. The lack of meaningful change in average velocity may be implicated in this outcome: where correlation of this parameter to average cadence should be exact, small deviations in this relationship were observed, suggestive of mechanical inefficiencies in the ergometer drive mechanism. This conclusion is further supported by discrepancies present in ANOVA analysis of final cadence and final velocity, which failed to mirror outcomes in the DYN Post4 trial. Outcomes in this trial condition demonstrate the need for sensitivity in analysis of PAP, since interpretation of time as the sole dependent measure would have led to an unfavourable conclusion despite the intervention having meaningfully enhanced performance.

Changes in DYN Post16 were less substantial. An increased average cadence across segment 1 was not accompanied by any improvement in torque, though power over a single half crank cycle was improved during this phase. Again, the lack of relationship to average velocity is noted, with no meaningful change observed in this parameter during this segment. Improvements in instantaneous torque through each of half crank cycles 14 to 19 affected an increase in average torque, and consequently, work done across segment 4. While the magnitude of torque improvements supported an increase in instantaneous power of a number of half crank cycles, no meaningful change was observed in segment average power; a lack of concomitant change in average cadence may be implicated in this outcome. Performance time was similarly unaffected in this trial condition. The effect of the dynamic CC protocol at a later time window appears to depict both disparate and similar effects to those at the 4-minutes, suggestive of changes in the PAP-fatigue relationship by this time point.

Assessing potentiation of a vertical jump, Chaouachi et al. (2011) observed that biomechanical variables associated with the jump expressed their potentiated maxima at distinct recovery times post-CC. The authors conclude that unique time-window characteristics may be indicative of the predominant PAP mechanism affecting performance in each case. Baudry and Duchateau (2004) similarly concluded that different times were required to observe peak performance after each of isometric, dynamic or electrically-evoked stimulus. Considering DYN Post4 and ISO Post16, the distinct outcomes and opposing timeframes in these trials may, therefore, suggest the prevalence of different PAP mechanisms evoked by each stimulus protocol. Houston et al. (1985) demonstrated a return to baseline in MRLC phosphorylation by 10-minutes post CC, suggesting that any performance improvement thereafter *must* be by an alternative mechanism. The time course of this, peripheral, mechanism of potentiation has frequently been identified as following an exponential decay from almost immediate maximum (Baudry & Duchateau, 2004; Bulow, et al., 1993; Gossen & Sale, 2000; Hamada, Sale, MacDougall, et al., 2000; Vandervoort, et al., 1983). In contrast, central mechanisms are seen to evoke an initial post-activation depression (PAD) before subsequent PAP prevails (Gullich & Schmidtbleicher, 1996). Though a 4-minute recovery time has been observed as adequate time for PAD to disperse following single-joint isometric CC (Trimble & Harp, 1998), results of prior studies using compound muscle actions corroborate that dynamic CC's are largely successful in this time frame where isometric contractions are not. Comyns et al. (2007), Deneke et al. (2010), Lawrence et al. (2010), Matthews et al. (2004), Mitchell and Sale (2011), Rahimi (2007) and Yetter and Moir (2008), each using dynamic exercises as CC, successfully demonstrated post CC improvements using 4-minute recovery times. While this time frame is lower than the 7-10 minute recommendations of the Wilson et al. (2013) PAP meta-analysis, the authors equally acknowledged that outcomes were mediated by training status; the report concurs that 3-7 minutes is, in fact, optimal for highly trained participants. This conclusion is verified succinctly by Chiu et al. (2003) who observed performance improvements at 5 minutes post-CC in trained athletes, where an 18.5-minute recovery was required in recreational participants.

Relatively few studies have examined a compound isometric action. Of these, most all have been unsuccessful testing performance within a 12-minute timeframe post-CC (Batista, et al., 2011; El Hage, et al., 2011; Tsolakis, et al., 2011; Turki, et al., 2011). Exceptionally, Feros et al. (2012) observed benefit at an earlier time frame, rowing performance improving 4-minutes after an isometric rowing-pull CC protocol. However, this study may be distinguished in the use of a combined sub-maximal and maximal contractions and in assessing a power-endurance performance activity; performance conditions were, therefore, substantially different from sprint or explosive efforts. Equally Gullich and Schmidtbleicher (1996), testing jump performance following an isometric leg press, found improvements as early as 3 minutes. In this case, the protocol offered long recovery times between repeat CC (on average 5 minutes), while the CC exercise itself is unique in having been conducted unilaterally, thereby imposing somewhat different conditions for stabilising musculature as compared to static bilateral exercises. Further, the authors critically note that a repeat trial under the same conditions failed to produce benefit in this time frame when conducted following a high intensity training day. This observation is unique in PAP research to-date and emphasizes that PAP outcomes must inherently be considered in union with fatigue.

To this author’s knowledge only three studies have been published directly comparing isometric and dynamic effort. The study of El Hage et al. (2011) compared a single set of 3R 85%1RM dynamic or 5-second MVC isometric half squats but failed to provide insight - no significant differences were observed in either condition. The low protocol volume in the dynamic condition and short recovery times (0, 2 and 4 minutes post CC) may well be contributing factors. Comparing 3 sets of 3-second isometric squats with a single set of 3R 90%1RM dynamic squats, Rixon et al. (2007) concluded that the isometric trial produced higher jump height and peak jump power. However, the poorly matched workloads present un-equivalent conditions for comparison and, although comparing a slightly higher intensity in the dynamic protocol, El Hage et al. have already shown that a single 3R squat is unlikely to be successful. In the only other trial comparing contraction types, Esformes et al. (2011) contrasted a single 7-second MVC with single 3RM set in bench press ahead of bench-press throw performance. The authors determined that the isometric effort produced greater improvements in peak power at a single recovery time of 12 minutes post-CC. Though substantial differences in upper body exercises have previously been established, results of the current study suggest that comparison at an earlier recovery time may well have allowed the dynamic protocol to prevail.

In addition to the distinct recovery timeframes, observation of the torque-cadence and power-cadence relationships further lend weight to the potentially different PAP mechanisms evoked by each CC stimulus. The relationships produced were equivalent to those observed by Dorel et al. (2005) and Martin et al. (1997). Martin et al.'s intercept values at zero cadence (T_{i0} = 320 ± 12 Nm, T_{rev0} = 203 ± 9 Nm), and zero torque (f_{i0} = 234 ± 6 rpm, f_{rev0} = 237 ± 5 rpm), were comparable to findings of the current study; intercept values of Dorel et al. (T_{rev0}=235.7 ± 19.1 Nm, f_{rev0}= 260.0 ± 8.6 rpm) were somewhat higher, in-keeping with the world-class status of the cyclists involved. The DYN Post4 and ISO Post16 trials were unique in being the only conditions where the extremities of the torque-cadence relationships were affected, again showing characteristic separation. While f_{i0} and f_{rev0} showed meaningful increases following the isometric protocol, the dynamic trial observed increase in maximal *dynamic* torque, but failed to improve the extrapolated values of peak isometric torque, T_{i0} or T_{rev0} ; these variables were, therefore, unaffected by any trial condition. Early studies of twitch potentiation observed a ceiling to improvements in muscle force production (Vandenboom, et al., 1993). However, in concentric contraction conditions, force production continued to be improved to all but the highest frequencies of contraction (Abbate, et al., 2000). The distinction in response between T_{i0}/T_{rev0} and T_{i_max}/T_{rev_max} may be indicative of this ceiling – potentiated maximum pedal torque reflecting an increased muscle force production in concentric contraction conditions, where saturated levels of Ca^{2+} would limit the influence of the MRLC phosphorylation PAP mechanism on peak isometric force.

The characteristic improvements in early torque production of this dynamic CC trial, alongside the relatively short recovery time, may, therefore, be indicative of a peripherally-mediated increase in force production. However, improvements in time to peak torque, time to peak power and average cadence were also evident. With no meaningful change in peak power, an increased rate of power development (RPD) through segment 1 must be associated with a faster time to peak: a conclusion supported by instantaneous peak power being produced during an earlier half crank cycle in this condition. These performance improvements imply that an increase in rate of force development (RFD) was additionally present during this phase of the DYN Post4 sprint. Increased sensitivity of C^{2+} binding sites affects an increased rate of attachment of actin-myosin cross-bridges and greater rate of transition from weak- to strong- binding, resulting in a greater number of force generating cross-bridges during contraction (Rassier & Macintosh, 2000). In such a case, increased MRLC phosphorylation would support both stronger and *faster* binding of cross-bridges, appropriately accounting for results in this phase.

Through the enhancement of initial torque and cadence, the DYN Post4 trial predominantly affected change on the ascending limb of the power-cadence relationship; changes on the descending limb, associated with improvements in torque only, had limited impact on performance. Conversely, changes in ISO Post16 were solely through improvements on the descending limb. However, the characteristics of the changes were somewhat different to those of the same region in DYN Post4, additionally improving cadence over this region of the curve. While enhancement of maximal force and early power production was, therefore, prevalent in DYN, ISO principally enhanced performance at higher leg speeds and, hence, muscle contraction velocities. Increase in the zero torque intercept value of the torque-cadence relationship would additionally imply that the principle potentiation mechanism in this trial had a positive impact on peak unloaded shortening velocity of the contributing muscles. Sasaki and Ishii (2010) have shown that, in voluntary contractions, peak unloaded shortening velocity is affected by the recruitment pattern of MU; hence, an increased recruitment of fast twitch MU may be inferred in the ISO Post16 condition.

In the final phase of the sprint, ISO Post16 also supported a reduction in the change in PTA, suggesting an increased rate of force development and, thus, ability to produce torque earlier in the crank cycle. While muscle contraction velocity is related to pedal speed (mathematically the combination of crank length x crank angular velocity), the time available for excitation-contraction-relaxation is governed by pedal *rate*, i.e. cadence (Tomas et al., 2010). Accordingly, studies of cycling biomechanics have related the drift in PTA to the relatively greater impact of electromechanical delay (EMD) at higher cadences - a fixed EMD representing a greater time through the crank cycle at such pedal rates (Ettema, et al., 2009; Sarre & Lepers, 2007). Contraction times of 300 ms times have been reported as being required to produce maximal force in knee extensors and, during fast limb movements, the reduced time for contraction would result in the inability to achieve peak torques (Aagaard, et al., 2000). At 120 rpm time available for contraction through the first half of the crank cycle would be 250 ms, which may already be challenging the athletes' ability to develop peak power through the first half (power phase) of the crank cycle. With average cadence in segment 3 of the sprint already above 130 rpm, a reduction in EMD would certainly benefit force production during the 4th and final segment. A potentiated increase in RFD would also support the ability to reach a higher level of muscle force during the early phase of contraction. Mechanisms of PAP may, therefore, benefit the production of higher torques at high cadences, but also the maintenance of peak torque production in optimal crank sectors despite increased pedal rate. Though improvements in peak torque were equally observed through segment 4 following the dynamic CC, magnitude-based inferences demonstrated that changes in PTA were consistent across all time points following the ISO intervention, where they remained unaffected by DYN. In fact, outcomes for this measure were supported by significant main effect in ANOVA analysis; ISO demonstrated a significantly lower change in PTA as compared with control during S4 and across the full sprint, S1-4. In the final phase of the sprint, a higher peak torque may be indicative of either increased muscle force or increased

RFD. However *earlier* peak torque must certainly be the latter. This, again, supports the proposition that different mechanisms of PAP were predominant in each trial condition.

Improvements in force production have been demonstrated through central and peripheral mechanisms of PAP, evidenced by reflex potentiation (RP) (Gullich & Schmidtbleicher, 1996) and twitch potentiation (TP) (Baudry & Duchateau, 2007a) respectively. Equally, improvements in RFD may be affected by a number of means. Trimble and Harp (1998) have suggested that reflex potentiation may induce a greater neural drive that may improve both magnitude and rate of force production. Likening the execution of CC to therapeutic techniques of proprioceptive neuromuscular facilitation (PNF), the authors suggest that RP will facilitate central nervous system pathways and improve the athlete's ability to activate and coordinate muscle contraction. Several authors have suggested that increasing pedal stroke variability with cadence is associated with loss of coordinated function at high limb speeds (Bini & Diefenthaeler, 2009; Ettema, et al., 2009; Li, 2004), while further studies have correlated training improvements at high pedalling rates to increased neuromuscular coordination, as observed through the timing of EMG burst onset and offset of the primary contributing muscle groups (Neptune et al., 1997; Raasch et al., 1997). Neptune and Kautz (2001) examined activation and deactivation dynamics and determined that pedalling rates affected neural control strategies. The authors postulate that this may well represent the governing muscle property that limits performance. In response to an isometric CC, Etnyre and Kinugasa (Etnyre & Kinugasa, 2002) showed that increased neural excitability improved reaction time, processing time and muscle contraction time: indeed studies of psychomotor improvements in response to CC have shown improvements in both premotor and motor response that could suggest improvements in the processing and formulation of control strategies, as well as reduction in EMD (Etnyre & Kelley, 1989; Shea, et al., 1991). Improvements in peak torque of consistent half crank cycles in the latter half of the ISO Post16 sprint, concomitant with a reduction in the drift of PTA, therefore, suggests that, not only is torque developed faster following the isometric CC, but that coordinated function has improved. In such a case, improvements on the descending limb of the power-cadence relationship may well have derived from an increased neural excitability.

However, improvements in EMD may equally be affected by structural or architectural changes in muscle. Mahlfield et al. (2004) observed a reduction in the angle of pennation of the vastus lateralis following an isometric MVC, while Comyns et al. (2007) and Moir et al. (2011) each demonstrated that increased leg stiffness affected by PAP protocols was related to the intensity of the CC stimulus. This may suggest an increased propensity for effect following a maximal isometric contraction. These intrinsic changes in the contractile apparatus would each support a reduction in EMD through improved transmission of force to the bone. Indeed Watsford et al. (2010) demonstrated that increased MA stiffness in sprint cyclists contributes to both an increase rate of torque development and lower peak torque angle, while Ditroilo et al. (2011), comparing athletes of higher and lower MA stiffness in a 6-second cycle sprint, concluded that increased stiffness would assist in sustaining performance as fatigue developed through the course of the sprint. In such cases, structural and/or architectural improvements afforded by execution of a prior maximal contraction could certainly account for improvements in the second half of the sprint.

The ISO Post16 protocol additionally elicited an increase in optimal cadence, the cadence at which peak power was produced. A potentiated increase in from 121.32 ± 5.38 rpm to 123.24 ± 3.60 rpm in ISO Post16 is in-keeping with results of Martin et al. (1997), who observed an equivalent value of 122 ± 2 rpm. Of relevance to the current analysis, world-class sprinters in the study of Dorel et al. (2005), were observed to have a much higher optimal cadence of 129.8 ± 4.7 rpm. Since a given power output can be produced by multiple combinations of torque and cadence, the intrinsic muscle force-velocity relationship implies that each combination would affect differing degrees of muscle activation. With muscle contraction generated by both fast and slow twitch fibres, MacIntosh et al. (2000) concluded that, in sub-maximal conditions, optimal cadence represents the minimal activation required to generate a target power output. Utilising the Hill equation to generate power-cadence relationships, the authors demonstrated that the cadence at which peak power is produced at each level of activation shifts progressively higher with increases in peak force and velocity – analogous to increased recruitment of fast-twitch MU. In studies of maximal cycling, several authors agree that an increase in optimal cadence reflects increase in fast twitch MU recruitment (Hintzy et al., 1999) (Vandewalle et al., 1987), and Dorel et al. (2009) have intimated that a higher optimal cadence is, therefore, beneficial to performance – a result substantiated by comparison of current results to those of Dorel et al.'s earlier study. Further, in mechanistic analysis of PTP, Abbate et al. (2000), similarly observing the predominance of potentiation on the descending limb of the power-velocity relationship, related a concomitant shift to higher optimal cadence to a potentiated increase in rate of torque development. Since optimal cadence was unaffected by DYN Post4, distinction from ISO Post16 with respect to this measure may further support the proposition that different mechanisms of PAP were predominant in each of these trials.

However, increased recruitment of higher order MU through central mechanisms of PAP may equally predict improvements in maximal force production. If central mechanisms were predominant in the ISO Post16 trial, no such improvements in the high torque region of the torque-cadence relationship were observed. While this might preclude central improvements as being principal to ISO Post16 results, Nocella et al. (2011) determined that, in the early stages of fatigue, a decline in tetanic force may be accompanied by an increase in the rate of tetanic force development. Such a distinction predicts that an over-riding potentiation of RFD may, therefore, be observed, though improvements in peak force are not. Further, Wakeling et al. (2006) have shown that, in high cadence conditions, the prerequisite demand for high shortening velocities may supersede the hierarchical operation of the size principle, affecting an increased recruitment of fibres with a capacity for higher rates of shortening though demands on force production are low. Given the relatively greater magnitude of PAP at sub-maximal forces, it is reasonable that a potentiated increase in higher order MU recruitment would more substantially benefit performance during this, latter, phase of the sprint.

The inter-relationship of biomechanical changes and timeframes, therefore, suggests that improvements in the initial segment of DYN Post4 may be more predominantly peripheral, where those in the final segment ISO Post16 be more likely neural, psychomotor or architectural. In dispute of this premise, Tillin and Bishop (2009) proposed that mechanisms of PAP are more likely central in response to a dynamic CC and peripheral in response to isometric - additionally proposing that mechanisms of fatigue would demonstrate the reverse. With respect to PAP, two arguments are fundamental to their conclusions. In dynamic CC, the authors surmise that the eccentric component of the contractions would activate Ia neural fibres of muscle spindles, increasing the afferent volley at the spinal cord and affecting a reduction in transmitter failure from Ia fibres to α-motor units. The resulting increase in recruitment of higher order MU would, therefore, affect a potentiation of subsequent activity. With MU recruitment governed by the size-principle, isometric contractions would erstwhile directly affect an increased contribution of fast twitch fibres and, hence, indirectly, greater MRCL phosphorylation. The authors additionally speculate that the increased fibre recruitment might affect greater changes in intrinsic muscle properties. While the current findings appear at odds with this hypothesis, the assertion that improvements in force production is a corollary of increased contribution of the stretch reflex, is flawed in respect to concentric only CC. In fact, by admission, Tillin and Bishop have demonstrated that isometric contractions would be more likely to affect an increased contribution of higher order MU and, thus, centrally-mediated increase in force. Gullich and Schmidtbleicher (1996) concur with this assessment, determining that, since recruitment of all MU at maximal firing frequency is not possible in voluntary motor action, execution of a prior MVC over-comes an autonomously protected activation reserve, ultimately leading to an increased firing of highest order MU. The authors contend that, by the size principle, a maximal intensity contraction would be required to evoke this response. Tillin and Bishop equally stated that, while MU recruitment for isometric contractions would follow in hierarchical order, recruitment in dynamic contractions may be specifically related to joint angle and range of motion. In such a case, an isometric CC is again distinguished as more ostensibly eliciting central mechanisms of PAP.

However, increased recruitment of fast twitch muscle fibres is synonymous with increased activation of higher order MU (Kamen, 2004). While it is, therefore, unlikely that mechanisms evoked are exclusive, comparisons of CC stimulus in studies do suggest that different protocol conditions can affect different magnitudes of response. Preferential recruitment of fast twitch fibres, supporting the increased phosphorylation of MRLC, can be affected by high load or contraction velocity (Comyns, 2009). In comparing the effects of resistive loading in dynamic CC protocols, a number of studies have certainly cited increased effects at higher loads. In contrast, the recent meta-analysis of Wilson et al. (2013) suggests moderate loads of 60 to 84% 1RM are more successful. Equally, studies comparing high resistance and high power schemes have concluded that high power CC have greater success: further observing the lower relative loads required to induce PAP in this condition (Andrews, et al., 2011; Radcliffe & Radcliffe, 1996; Smilios, et al., 2005). While Behm and Sale (1993) have suggested that having the *intention* to lift high loads quickly will stimulate improvements in explosive force production, it may be that movement velocity moderates the loading required to elicit optimal PAP response. In the current PAP protocol, the high initial inertia of the potentiation erg creates the necessity for high muscular force at the outset, though force production requirements quickly decline as momentum increases, moving the contractile conditions towards the centre of the force-velocity relation and, hence, along the ascending limb of the power-velocity relationship. Expressing torque per pedal stroke in the dynamic CC protocol as a percentage of peak isometric torque produced during the isometric intervention, the relative load experienced by the athletes represented 97% MVC at the outset, declining to 74% MVC in the final pedal stroke. The success of the DYN Post4 condition may, therefore, be symptomatic of a CC that has presented a variable stimulus of load and movement velocity, shifting from high load to high power conditions within a single conditioning pattern – a unique benefit of the high-inertia ergometer.

Conversely, several authors have asserted that a high load would certainly be required to affect potentiation of the central nervous system (Gullich & Schmidtbleicher, 1996; Rahimi, 2007; Saez Saez de Villarreal, et al., 2007). However, few trials have attempted to verify its presence following an isometric contraction: none having done so using compound joint actions. In single joint isometric CC protocols, both magnitude of H-reflex response and aEMG have been used to confirm PAP (Tillin & Bishop, 2009). However, interpretation is hindered by the failure of the protocol to affect performance improvement in a number of cases (Cabrera, et al., 2009; Folland, et al., 2008; Gossen & Sale, 2000; M. Hodgson, 2005). In the case of Cabrera et al., Folland et al. and Gossen and Sale, these may well be explained by the short (1-5 min) recovery times allowed following the conditioning protocol, while Hodgson's results, directly contrasting those of Gullich and Schmidtbleicher (1996), may be attributable to methodological differences in H-reflex stimulation and in subject positioning during the execution of the test.

Gullich and Schmidtbleicher observed an increase in explosive plantar flexion force production concomitant to increased H-reflex response following an isometric CC, clearly demonstrating that isometric contractions can affect central mechanisms of PAP. While Iglesias-Soler et al. (2011) determined that a maximal (but not-sub maximal) isometric contraction could potentiate power in plantar flexion, a lack of H-reflex increase led the authors to conclude that PAP was not related to reflex excitability. A distinction in this trial was H-reflex testing being restricted to the soleus muscle. Gullich and Schmidtbleicher instead tested both gastrocnemius and soleus, finding the former, a predominantly fast twitch muscle group, to have a magnitude of response far in excess of that in the soleus, a predominantly slow twitch muscle group. Demonstrating performance improvement in bench press throw following an isometric contraction, Esformes et al. (2011) concluded that lack of a concomitant increase in aEMG meant that the CC had not affected neural activation. A single, 12-minute recovery time, confounds the ability to determine whether central mechanisms would have prevailed at an alternative point. Interestingly, Gullich and Schmidtbleicher only observed increased H-reflex from the 4th to 11th minute while potentiated explosive force prevailed from 4 until at least 13 minutes and as long as 20 minutes in some participants. While this accentuates the divergent PAP characteristics of distinct muscle groups, these results additionally infer the existence of a non-central PAP mechanism that is capable of augmenting performance over longer time-frames.

As contested by Tillin and Bishop (2009), the increased fibre recruitment following an isometric CC might alternatively have affected structural or architectural changes in muscle. None of the existing studies assessing leg stiffness concomitant to performance have done so post isometric CC (Gouvêa et al., 2013). However, in dynamic conditions both Comyns et al. (2007) and Moir et al. (2011) compared outcomes following a number of load conditions up to 93% 1RM and determined that increases in stiffness were related to the load and thus intensity of contractions provoked. This might signify that maximal isometric contractions would be the optimal stimuli. Studies have observed increased stiffness from as early as 2 minutes (Moir, et al., 2011) to as late as 12 minutes (Boullosa, et al., 2012) post-CC. However, in the latter case high-inter-individuality of results confounded consistent interpretation of outcomes. Chaouachi et al. (2011) have stated that stimulated changes in muscle stiffness may last as long as 90 minutes, though this is yet to be established within an acute PAP setting. The maximum timeframe of improvements in leg stiffness is, therefore, unconfirmed and no correlation has been attempted between load and the time window of effect. In the only study that has thus far assessed changes in pennation, repeat testing at 2 recovery time points following an isometric contraction observed that the beneficial decrease in pennation angle further reduced with time (Mahlfeld, et al., 2004). These studies provisionally suggest that changes in structural and/or architectural muscle properties might contribute to improved performance at later recovery times. The overlap of structural and neural improvement time-windows would then support the proposition of Comyns et al. (2007) that these changes reflect an integrated PAP mechanism - increased nervous system excitation allowing the athlete to modulate stiffness in response to functional demands.

If DYN Post4 results reflect predominantly peripheral improvements in force and rate of force production in the early part of the sprint and ISO Post16 predominantly neural, psychomotor or structural in the latter, the results of DYN Post16 may be indicative of components of each. Changes in cadence and an isolated measure of instantaneous power in the first segment, alongside a lack of improvement in maximal torque suggest that only improvements in RFD were present in early stages of the sprint. Increases in optimal cadence have previously been observed as indicating an improved RFD. Consequently, a consistent increase in this measure in both 16-minute trials suggests prevalence of improvements in RFD, rather than force production *per se*, at the longer timeframe of recovery following both CC-type. Changes in DYN Post16, as in ISO Post16, were more prevalent in segment 4. However, in contrast to the isometric intervention, improvements in torque production were not accompanied by improvements in cadence or change in peak torque angle in DYN Post16. Such characteristics infer differences must exist in the prevailing PAP mechanisms present in each case. While the decay of MRLC phosphorylation by 10-minutes infers that peripheral mechanisms would be unlikely to be present at a later timeframe, the higher optimal cadence of DYN Post16 indicates an increased recruitment of fast twitch MU may, instead, be present. The DYN Post16 condition, therefore, shows both similarities and disparities with DYN Post4 at the start of the sprint and ISO Post16 at the end, aptly demonstrating that multiple mechanisms of PAP may be evoked by CC protocols and that the characteristic response observed is a complex function of the contraction type and time window of recovery.

Without confirmation of the presence of PAP, this study is unable to assert with any degree of certainty the mechanisms involved. However, appreciation of the concomitant mechanisms of fatigue elicited may assist in the interpretation of the neurophysiological consequences of the CC protocol. Fatigue will equally display distinct characteristics affected by the nature of the protocol and the time window of observation (Clevidence, 2008; Rassier & Macintosh, 2000). Tillin and Bishop’s conclusions of preferential peripheral fatigue following dynamic CC and central fatigue following isometric CC were established on the basis of findings of Babault et al. (2006). The authors conducted a fatiguing protocol of repeated concentric and isometric contractions and observed that concentric contractions affected first peripheral (a decrease in force production capacity due to action potential failure, excitation-contraction coupling failure, or impairment of cross-bridge cycling where neural drive is sustained) then central (a reduction in neural drive to muscle) fatigue, where isometric affected the reverse. The authors relate the findings to the reduction in blood flow and, hence, increased metabolite accumulation, in isometric as compared to dynamic action. Central fatigue would prevail in isometric conditions due to the negative effects on MU activation or firing rates caused by metabolite sensitisation of small diameter afferent neural fibres. High levels of lactate, known to sustain force production during conditions of fatigue, would, by the same analysis, reduce peripheral fatigue.

In the current study, ANOVA results presented no distinction between metabolic conditions of DYN and ISO. Conversely magnitude-based inference suggested that, as predicted by Babault et al., ISO did induce higher metabolic stress than of DYN. Though highlighting the substantial differences inferred by different approaches to statistical analysis, meaningful changes of only 4 bpm in heart rate and less than 1 mmol.L^{-1} in blood lactate, would be unlikely to account for substantial differences in fatigue response. However, the Babault et al. study examined fatigue *during* the repetitions and made no prediction or assessment of the time-course or decay of effect - which is more relevant to PAP protocols. Further, where the Babault et al. protocol involved a relatively high volume of 30 repeated contractions, the short maximal contractions in CC presents contrasting contractile conditions. Application of Babault and co's findings to acute PAP protocol outcomes may, as a result, be ill-founded.

Few studies have examined the origin of fatigue post execution of short high-resistance exercise. Two studies by Linnamo et al. may be of greater relevance in examining tests of fatigue before and after each of 5 distinct sets of leg press exercise. Most recently their research team compared a high-power and high-load protocol (Linnamo et al., 2000). Where fatigue would affect a decrease in EMG power spectrum to lower frequencies, the high-power protocol, in fact, demonstrated a shift towards higher mean power frequency and median frequency - the high-resistance protocol showing a small decline. Concentrations of blood lactate were higher in the high-load compared to power condition, being ~4.95mmol.L^{-1} and ~3.09mmol.L^{-1}, respectively – not indistinct to the isometric and dynamic conditions of the current study. While the heavier load had slightly higher indicators of metabolic stress, no correlation was found between lactate concentrations and EMG outcomes – a result directly challenging that of Babault et al.. The study established that the high-load action had elicited a somewhat higher degree of fatigue, while the high-power protocol had, in fact, facilitated the neuromuscular system.

A previous study by the same team compared the high-power condition with *maximal* load using the same protocol (Linnamo et al., 1998). Observing a greater degree of fatigue and slower recovery in the maximal load condition, the authors concluded that heavy loading affected a high degree of both peripheral and central fatigue, where the lower load-higher movement velocity condition affected central fatigue, with less involvement of fatigue peripheral in origin. An examination of isometric force-time curves during recovery revealed a marked decrease in integrated EMG (iEMG) of the early contraction (0-100 ms) phase in response to the high-power condition, where reduction in the peak force (500-1000 ms) phase during fatigue was similar in both. These conclusions may well support the established success in the DYN Post4 trial, confirming a likely central fatigue and peripheral PAP, while additionally suggesting a lower propensity for increased RFD. The combined effects of both central and peripheral fatigue following an isometric loading may, adjunct to increased metabolic stress, have induced greater overall fatigue, thereby accounting for the lack of success in ISO until the 16th minute. Following this intervention, prevailing improvements in rate of force development may have augmented performance in conditions where time available for contraction was reduced.

Without question, fatigue in response to resistance exercise is dependent on type of loading, amount of load, fast/slow fibre composition of the muscles recruited and the training background of the participant (Enoka & Duchateau, 2008). Blood lactate concentrations are further dependent on type and amount of loading as well as the timing and duration of work and rest periods (Dinsdale, et al., 2009). Insightfully, Linnamo et al. further observed that higher muscle temperature affected by increased load may be a primary contributor to differences in muscle function following high-resistance exercise. Equally Hilfiker et al. (2007) have suggested that temperature may additionally distinguish the effects of contraction type, with the production of mechanical work in the dynamic condition potentially increasing temperature beyond that of the isometric CC. One limitation of the current study design is the inability to determine the impact of temperature: certainly there may have been differences in core and muscle temperature affected by both differences in load and contraction type. In preliminary trials for the current study (unpublished data), protocols were repeated with either active or passive rest during recovery times: active rest trials were observed as producing a higher degree of performance gains following the CC stimulus. Since improvements observed were equally attributable to temperature and non-temperature related effects of the protocol, it may be supposed that temperature differences through distinct loading and contraction types may have been a contributing factor in current outcomes.

Since performance changes in response to a CC reflect a trade-off of fatigue and potentiation, the relative lack of success in both the DYN and ISO Post8 trials and ISO Post4 must certainly be accounted for by either a greater degree of fatigue or lower activation of PAP. Trends in metabolic measures cannot entirely account for this - a conclusion supported by Thatcher et al. (2012), who observed a correlation of recovery time to VO_2 during the sprint and blood lactate post-sprint, but failed to show any relationship to success or failure of the potentiation protocol. A recovery time of at least 4-minutes between each activity phase following CC would equally have been adequate for the restoration of the high energy phosphates providing the primary fuel source for the 5-6 second effort (Gaitanos et al., 1993). In each of these trial conditions, torque and power of isolated half crank cycles at the mid-way and very end of the sprint increased, though these were too few in number to affect improvement across the related segment measures. An increase in optimal cadence was also consistent through these trials suggesting that improvements in RFD were still present, though unable to affect substantial performance improvements. The consistent results of both DYN and ISO at the 8-minute time point does suggest that fatigue, whether by confounding effects of inadequate recovery following prior activity, or simply as a direct response to the CC protocol itself, clouded the beneficial effects of PAP at this point.

The balance of fatigue and potentiation affected by the dynamic intervention resulted in an overwhelmingly positive improvement in maximal dynamic force production at the 4-minute recovery time. In contrast, those following the isometric contractions affected a decline in peak isometric force at the same point. Sale (2002) described the effects of conditioning activities on the force-frequency relation, demonstrating that too severe a stimulus may, while still affecting improvement in RFD, actually affect a reduction in peak isometric force (refer to Figure 2.1). Results of ISO Post4 are indicative of this finding. However, a reduction in the change in PTA was observed at all time-points following the isometric CC. The mechanism affecting this change in biomechanical performance was, therefore, sustained throughout the full timeframe of analysis. Sinkjaer et al. (1992) determined that potentiated changes in the behaviour of intrinsic properties of the muscle could account for the ambiguity of improved MT stiffness concomitant to reductions in reflex-mediated force following a CC stimulus. The authors suggest that, even in conditions of over-riding fatigue, a potentiated increase in the intrinsic stiffness of the muscle may provide a “safety-factor” to ensure joint integrity during conditions of increased stress. In such a case, while central and peripheral mechanisms of fatigue and potentiation might be counteractive, improvements in stiffness affected by the isometric CC may well endure.

In spite of the differences in each CC mode-recovery time condition, consistent findings were improvements near the extremities of the torque- and power- cadence relationships. Sale (2002) described hypothetical effects of PAP on the force-velocity relation, concluding that it would affect an up-right shift of the central portion of the curve only: zero-cadence and zero-torque axis intersects remaining unaffected. However, unlike the classical hyperbolic force-velocity curve described by Sale, the torque-cadence relationship has commonly been reported as having a linear relationship over functional regions of operation (McCartney et al., 1983; Sargeant et al., 1981).

With performance representing the cooperative action, and fatigue/PAP response, of several muscles, such distinctions underscore the complexities of PAP in whole-body performance. The combined response characteristics will be somewhat divergent from those of isolated muscle. Current results agree that peak isometric torque, reflecting the peak force production of contributing muscles, is unaffected by PAP. On the contrary, cadence at zero torque, indicative of the integrative peak shortening velocity of combined muscle action, increased in the ISO Post16 condition. Two primary studies have been commonly cited in contending that peak unloaded shortening velocity of voluntary contraction would be unaffected by PAP: Grange et al. (1993) and Stuart et al. (1988), both of whom examined the correlation of MRLC phosphorylation to contractile function. Prior evidence has established that, in voluntary action, higher order MU activation could affect an increase in unloaded shortening velocity. While improvements in peak conditions may be unaffected by peripheral PAP mechanisms, such limitations might not apply in centrally-mediated PAP conditions.

While only a single trial condition induced improvements on the ascending limb of the power-cadence relationship, in contrast all trials affected improvements on the descending limb to some degree. Numerous studies have observed improvements in single effort explosive force production following a CC stimulus, and, as such, it may have been expected that improvements would have been more commonly observed through the early or peak portion of the curve where peak muscle force or power was produced. Few studies have examined the effects of PAP over the power-velocity relationship. However Abbate et al. (2000), examining the effects of PTP on power output of skeletal muscle, presented power-velocity results that almost exactly predict current outcomes. Magnitude of potentiation was seen to increase with shortening velocity of concentric test contractions, such that the high-velocity end of the relation showed by far the more substantial increase in power. While the extent of the potentiation was equally mediated by the content of the

CC stimulus applied, in each stimulus condition this extreme of the power-velocity relationship was consistently improved. The current study therefore confirms that electrically-evoked outcomes are equally characteristic of voluntary CC settings.

In contrast the central portion of the curve was substantially *un*affected by the protocols. In assessing changes in the half crank cycle where peak power was produced, it is noted that a high-degree of inter-individualisation was present. Values of P_{i_max} were produced between half crank cycles 5 and 12, while those of P_{rev_max} were produced between half crank cycles 5 and 10, such that performance was far less consistent over this region of the curve. This may well have confounded group mean outcomes. However, no statistical relevance of either the isolated apex or overall measures of peak power was upheld. Peak power values additionally displayed high inter-individualisation in the recovery time where improvement was observed. This result is supported by Jo et al. (2010), who assessed post-CC performance of a 30-second Wingate trial and found significance in peak power only when maximum values (regardless of rest duration) were compared with baseline values. Smith et al. (2001), additionally, found improvements in average, but not peak, power. These results lend further support to the contention of Chaouachi et al. (2011), that the highly variable nature of PAP response with respect to different protocols, participants and outcome measures, confounds the ability to detect meaningful outcomes using null hypothesis statistical testing. Such evidence confirms Chaouachi et al.'s assertion that studies of potentiation require an alternative approach to statistical analysis.

In other physiological systems potentiation is experienced as a phenomenon supporting functional improvements in conditions where function is compromised or limited (Hughes, 1958). An alternative explanation for that lack of improvement in peak power suggests that the mechanisms of PAP rather supported improvement at the functional extremities of sprint performance. Further, given that all trials experienced an increase in torque production during the later stages of the sprint, it seems likely that the CC stimulus may have been additionally supplemented by the potentiating effects of the contractions themselves through the course of the sprint. In such a case, the repetitive nature of contractions in cycling will certainly have imposed substantially different conditions from that of a single explosive effort. Gossen and Sale (2000) equally acknowledged this effect, demonstrating that effects of a 10-second maximal voluntary leg extension on repeated dynamic kicks were additive: potentiated twitch torque increasing following each repeat contraction. Since termed the 'mobilisation of the PAP mechanism' (M. Hodgson, 2005), this phenomenon would undoubtedly account for the greater consistency of improvements observed over the latter stages of the sprint, and hence, descending limb of the power-cadence relationship.

Studies of sprint running concur: where performance has been assessed over intermediate splits, improvement in the final split is commonly observed (Antonopoulos, et al., 2012; Chatzopoulos, et al., 2007; Comyns, et al., 2010; McBride, et al., 2005; Yetter & Moir, 2008). The kinetic and kinematic profiles of the sprint phases show some distinction and Yetter and Moir, therefore, concluded that a CC stimulus affects functional improvements specific to the demands of maximal velocity performance (Yetter & Moir, 2008). On the contrary, Zois et al. (Zois, et al., 2011), conferring with Sale that peak velocity would be unaffected by PAP, suggests that improved RFD of PAP offers the ability to increase acceleration and decrease time to reach maximal velocity. However, results over the initial phase are less consistent, studies finding performance unchanged (Comyns, et al., 2010; Crewther, et al., 2011; McBride, et al., 2005; Yetter & Moir, 2008) or improved (Antonopoulos, et al., 2012; Bevan, et al., 2010; Chatzopoulos, et al., 2007) over this period. With sprint running commonly broken down into 4 phases (acceleration, transition, attainment of maximal velocity, maintenance of maximal velocity against the onset of fatigue (Cunha, 2005)), McFarlane (1993) describes 0-12 m as pure acceleration, 12-25 m as transition and 25-60 m as maximum velocity. The studies of

Antonopoulis et al., Chatzopoulis et al., Comyns et al., McBride et al. and Yetter and Moir, each conducted sprints over either 30 or 40 m, suggesting improvements in maximal velocity were, indeed, responsible. The consistency of results in this phase of the sprint was equally achieved in spite of differences in CC content and recovery time – a result in keeping with that of the current study. Conversely, distinctions in protocol certainly appear to affect the observation, or otherwise, of potentiation of the acceleratory phase. In support of current findings, Antonopoulis et al. and Chatzopoulis et al. both determined that improvements over the first split time of the sprint could be observed following a multiple-set, high-intensity, low-density, dynamic CC protocol, with relatively short recovery times of 6- and 5- minutes respectively. Though Bevan et al. equally observed improvements in this phase, a high-intensity but low volume protocol of 3R of 91% 1RM squats was only deemed to be successful when individualised recovery times were considered. In a final validation of current results, the Antonopoulis et al. study further critically observed that improvements in the latter phases of the sprint were more prevalent if a longer, 12-minute, recovery was considered.

Studies of cycle sprinting in response to a potentiating stimulus are less able to be reconciled with these findings (French, et al., 2003; Jo, et al., 2010; Lawrence, et al., 2010; Parry, et al., 2008; J. C. Smith, et al., 2001; Thatcher, et al., 2012). The limitations of the study designs have previously been discussed with regards to their ability, or otherwise, to observe successful outcomes. However, with respect to the current discourse, only Thatcher et al. examined performance over discrete phases, determining that mean power had increased over each of the first 5- and 10- second periods: no such change was observed over the full 30 second duration of the sprint. The authors, therefore, concluded that only sprints of up to 10-seconds would benefit from an acute PAP intervention. Existing research does not entirely support this contention (French, et al., 2003; Lawrence, et al., 2010; J. C. Smith, et al., 2001). In light of this study's findings, it may be suggested that rather the

FVP characteristics of the sprint will dictate outcomes. Where DYN Post4 highlights the potential for a CC protocol to affect an increase in maximal torque, all of the aforementioned studies conducted sprints following a rolling, rather than standing, start. Thus the torque production during the first few crank cycles would have been substantially lower. The cadences achieved by the end of the sprint were not reported in any study. While it is difficult, therefore, to compare conditions at the end of the sprints, none of the trials used trained cyclists and the inherent lack of skill in performance would likely predict their inability to produce very high cadences during the trials. In such a case, muscle shortening velocities during the final stages of the sprints may, again, be substantially less than those of the current study.

This study is, as a result, unique in being able to provide a deeper understanding of the effects of PAP on cycle sprint performance across the full range of the power-velocity relationship. Tomaras and MacIntosh (2011) have previously shown that the warm-up strategy used in the current study maximised performance when compared to a standard pre-competition warm-up. The effects of the CC protocol were, therefore, notable in further augmenting performance. While correlation of the current test protocol to field performance is yet to be established, Gardner et al. (2007) have previously demonstrated consistency of torque- and power- cadence relationships derived during a 6-second laboratory cycle sprint with those derived in field performance over 65 m. Present results may, then, support the efficacy of the high-inertia (potentiation) ergometer as an ergogenic aid. Dorel et al. (2005) concur that the characteristic sprint phases applied by Cunha to running, are equally applicable in cycling; though extended sprint times in competitive events are likely to increase the emphasis of the final, velocity maintenance phase of the sprint, and, hence, performance during the increasing presence of fatigue. Tomas et al. (2010) demonstrated that longer crank lengths supported a reduction in the number of contractions required to complete a lap, thereby increasing relaxation time, maintaining higher blood flow and reducing metabolic fatigue by the end of the sprint. However longer cranks require an increased torque production to accelerate the bike in the high-inertia conditions of the start. Potentiated ability to produce maximal torque in the first crank cycles of DYN Post4 may support the use of longer cranks as a viable option. Further, longer cranks would require higher angular velocities to achieve the same cadence, which could well be supported by an appropriate modification of the high-inertia PAP protocol.

The fixed, single gears of track bikes present a similar trade-off in performance conditions. Comparing laboratory and competitive sprint conditions, Dorel et al. (2005) observed discrepancies in the mean competitive cadence and optimal cadence predicted by the athletes' power-cadence relationships. Given the inefficiencies of this functional condition, the authors suggest that higher gearing would affect a reduction in cadence, thereby supporting an overall improvement in power delivery. However, this condition again imposes increase torque demands during acceleration. Conversely, they equally acknowledge that elite cyclists preferentially use smaller gear ratios to optimise power during the acceleratory phase, thereby increasing cadence requirements at the end of the sprint. In fact, Martin et al. (2007) conducted a review of world-class 200 m performances, observing that the majority of athletes performed the greater part of the time-trial on the descending limb of the power-cadence relationship. Whether by the preferential gains afforded by PAP at higher shortening velocities, or the mobilisation of PAP mechanism through the effects of prior contractions, it may be predicted that execution of a CC stimulus pre-sprint would benefit performance in this functional condition.

Environmental differences further distinguish the physiological demands of performance in laboratory and velodrome sprints (Bertucci, et al., 2005). During track sprinting a balance of positive and negative power terms determine changes in kinetic energy and, hence, velocity (de Groot et al., 1994). Dorel et al. (2005) observed that 200 m performance was largely dependent on the rider's ability to overcome aerodynamic drag. Accounting for up to 96% of available power in track sprint, this resistive component would not have been present in the laboratory trials, thereby allowing power production to directly affect an increase in kinetic energy (Martin, et al., 2007). Rolling resistance, related to the weight of the combined bike and rider, wheel and tyre construction and riding surface, would also be substantially reduced in ergometer sprinting - though effects of bearing resistance and other mechanical sources of friction would, to a degree, still counteract forward motion (Martin, et al., 2007). The substantial differences in final velocity of the inertial-load trials compared to those of competitive sprints, is indicative of the magnitude of resistive forces in a velodrome setting. In this environment, additional muscle power must be produced to overcome negative terms and, as such, the additional physiological demands may well distinguish response to a PAP protocol. However, Martin et al. note that, at the start of a track sprint, negative terms are near zero, such that nearly all power affects an increase in kinetic energy. With the successful DYN Post4 condition affecting potentiated improvements during this phase, these changes may equally translate to track performance.

Several authors have previously commented on the inherent difficulties in including PAP protocols in competition environments (Docherty & Hodgson, 2007; French, et al., 2003; Robbins, 2005). The high-inertia ergometer would provide the perfect solution in facilitating the execution of a CC-protocol track-side. As acknowledged by French et al. (2003), accommodation of isometric contractions may be easier yet. Indeed, in a track-setting these could be conducted by simply restricting the movement of cranks or wheels of a standard bike. However, while the 16-minute recovery time recommended by the ISO trial would be more conducive to its incorporation into competition scheduling, the ISO Post16 trial failed to affect time reduction. Though acceleratory conditions at the start of laboratory and velodrome sprints may be somewhat equivalent, the subsequent stages would be substantially less so. Having achieved peak velocity, the extended velocity maintenance phase would lengthen the period where biomechanical improvements elicited by ISO Post16 would be beneficial. Indeed, Ditroilo et al. (2011) have demonstrated that maintenance of stiffness during the fatiguing conditions at the end of the sprint is critical to performance. With a disproportionate period of the sprint spent on the descending limb of the power-cadence relationship, such augmentations of performance may well affect a more meaningful change in sprint time in track conditions.

In such cases, the performance gains elicited by DYN Post4 or ISO Post16 could each be beneficially exploited in competitive conditions. Incorporation of the appropriate protocol into the pre-sprint warm-up may assist the athlete in overcoming functional limitations, permitting a more advantageous selection of gear or pedal length. Such strategies may, therefore, allow sprint performance to be sustained over more optimal regions of the power-cadence relationship.

5.1 CONCLUSION

The current study demonstrates that executing multiple sets of short maximal contractions on a custom-built high-inertia ergometer can enhance subsequent sprint cycling performance in highly-trained sprint cyclists. The loci of observed improvements were the high-torque and high-cadence extremities of the sprint performance, with response governed by the CC mode and recovery time at which the sprint was conducted. The prevailing responses depicted DYN as being most successful at 4 minutes post-CC - dynamic contractions evoking a reduction in performance time and affecting improvements predominantly on the ascending limb of the power-cadence relationship, augmenting power during initial acceleration. In contrast, the isometric trial required a longer recovery time - performance at the 16-minute time point enhanced over the descending limb of the power-cadence relationship, augmenting performance at higher limb speeds during the maximal velocity phase of the sprint. Results imply that each CC mode elicited distinct performance outcomes likely characterised by the prevalence of different PAP mechanisms. Consistent improvements in the final stages of the sprint in each trial condition additionally suggest that PAP is augmented by the cumulative effects of repeat contraction.

While correlation of the test measure to track sprint conditions is yet to be established, results provisionally suggest the efficacy of including a high-inertia ergometer component in the sprint warm-up. Adding a dynamic CC component at a timeframe of 4 minutes out from the sprint start, would support a higher torque and power production during acceleration, facilitating choice of a higher gear and/or longer pedals, while reducing mean competitive cadence. An isometric protocol conducted 16-minutes out from the sprint start would furnish the rider with higher legs speeds towards the end of the sprint, enabling the rider to achieve the increased angular velocities demanded by longer pedal lengths or augmenting performance at the higher mean competitive cadences imposed by lower gear selection.

Selection of an appropriate PAP protocol may therefore be seen as an integral part of the wider competition strategy. In the tightly-constrained bike-rider system, potentiation of the high-torque or high-velocity extremities of performance would offer functional enhancements, where compromise in gear and pedal length selection strategies would, otherwise, impose limitations on performance.

5.2 LIMITATIONS OF THE STUDY

1. The criteria for selection of appropriate participants made for a small selection pool. Additional constraints in recruitment were imposed by trials being conducted during an Olympic year where many suitable athletes were unavailable. Though meaningful results were observed, low statistical power may have compromised the ability to observe more definitive outcomes.
2. Limited time availability of athletes further imposed the requirement for testing of multiple recovery-time conditions during a single session. Effects of repeat testing may have had an impact on fatigue levels and ability to achieve a consistent, maximal performance during each test sprint.
3. Training schedules of the participants could not be controlled during the trial period. Differences in training load and, hence, physical condition may have been present.
4. Lack of an appropriate assessment meant that the presence of post-activation potentiation could not be verified.
5. Neither core nor muscle temperature was recorded during the trials. Thus the study was unable to account for the effects of temperature on results.
6. Design and construction of the high-inertia ergometer meant that control of loading was limited. Inability to individualise CC load would have, therefore, affected the relative load experienced by athletes of different maximal strength.
7. In ergometer cycling, velocity and cadence should be related by a fixed constant reflecting the gear ratio used. Slight differences in the ratio of velocity to cadence suggested inefficiencies may have been present in the drive-train mechanism.
8. The novel design of both ergometers meant these were unfamiliar to the athletes. While a familiarisation time was provided, the athletes would have been unlikely to have achieved absolute maximal performance on each.

9. Correlation of the inertial-load ergometer to track sprint performance is yet to be established. Only limited inference on the possible carry-over of benefit to competitive performance may be made.

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH

1. Repeating trials with an extended sample size would ensure results are more representative of true (population) outcomes and would provide the opportunity to more closely inspect the effects of participant characteristics. Increasing sample size while maintaining selection criteria may confirm or refute current assertions of limited inter-individual variations in performance. Extending sample selection to accommodate athletes of different training status would facilitate comparison of the effects of skilled performance, relative strength, and fibre type distribution. Ensuring the participant sample has an equal number of female athletes would facilitate assessment of sex differences on PAP response.
2. Including additional neurophysiological measures in repeat trials to assess the effects of temperature and establish, or otherwise, the presence of potentiation.
3. Compare different high-inertia ergometer protocols, while testing at the same time points, to distinguish the effects of loading, volume and inter-set rest.
4. Conduct repeat trials during a training phase or training camp where the athlete’s schedules and training environment are controlled. Such conditions would permit the timetabling of extended testing sessions to accommodate assessment of a single, isolated CC protocol within each session. A controlled environment would further ensure athletes arrive at the testing days in optimal and equivalent physical condition.
5. Combine the laboratory trials with a field study at a velodrome to establish whether results are transferable to track sprint performance.

6. Repeat testing using a longitudinal study design to determine the influence of learning effects in achieving excitation through the novel CC-stimulus. A longitudinal design could equally be conducted to assess of the impact of training on potentiation response.
7. Modify the high-inertia to allow control and quantification of loading such that the CC protocol can be individualised for each participant.
8. Determine an ‘optimal’ protocol that maximises performance improvements for each athlete.

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APPENDICES

Appendix 1 – Participant Information Sheet

Appendix 2 – Pre-exercise Health Screening Questionnaire

Appendix 3 – Participant Consent Form

Appendix 4 – Ethics Approval from Massey University Human Ethics Committee

Appendix 5 – Supplementary Results

Appendix 6 – Summary of Trial Outcomes

APPENDIX 1 – PARTICIPANT INFORMATION SHEET

Institute of Food, Nutrition, and Human Health
Massey University
Albany
New Zealand

The Effect of High-Inertia Ergometer Warm-Up on Sprint Cycling Performance

INFORMATION SHEET

Researcher Introduction

Ms. Lynne A. Munro, Master of Science (Sport and Exercise Science) candidate,
Institute of Food, Nutrition, and Human Health

The study is intended to examine the effects on sprint cycling performance of including a high-resistance conditioning protocol in pre-exercise warm-up. The experiment will involve physiological assessment, performance measurement and analysis.

Project Description and Invitation

You are invited to take part in a study looking at optimising warm-up routine for sprint cycling performance.

In elite level sprint cycling, where fractions of a second separate rankings, small percentage improvements in performance critically benefit outcome. Previous studies have suggested that execution of maximal muscle contractions prior to explosive exercise movement can improve performance in the goal movement. This study aims to determine whether inclusion of these so-called “conditioning contractions” in the warm-up activities will lead to improvements in sprint performance and in such case determine whether an optimal protocol exists for each athlete.

Participant Identification and Recruitment

Volunteers from local and national sprint cycling teams will be asked to take part in the study. Selection criteria will ensure participants have competed at national or international level in track sprint and have participated in regular (> 2 times per week) strength training for at least 1 year. The study will utilise 6 participants in order to ensure statistical validity of the study while accommodating an acceptable timeframe for scheduling of the trials.

Participants will be subject to the normal risks involved in participation in the sport. Measures of blood lactate will be taken at 5 points during each trial. This will be done using finger-prick sampling, which will involve a moderate degree of discomfort at the time of sampling only. Due to the very small sample volume that will be taken it is unlikely that there will be any blood remaining after testing. In such case there will be no opportunity for return of samples taken to participants.

Project Procedures

Trials will be conducted in the sports science laboratory of Massey University (Albany) using an inertial ergometer for warm-up and sprint performance, and a higher-inertia ergometer for conditioning contractions. Participation will entail performing a set warm-up (17 minute duration), followed by two pre-conditioning 5-second maximal efforts on the inertial ergometer. Conditioning contractions will then be performed, consisting of a short number of crank cycles under maximum load on the high-inertia ergometer. Following a set recovery period the participant will then execute two post-conditioning maximal efforts on the inertial ergometer. Performance data will be captured at the cranks of both ergometers throughout all efforts.

Trial conditions will vary the volume and intensity of the conditioning set. One trial will be conducted each day with 3-4 trial days initially planned as athlete time and availability allows over the forthcoming weeks. Participation time for each day will be approximately 1.5 hours.

Participants will be allowed familiarisation time on both ergometers to ensure they are comfortable in executing maximal efforts on each. No time limit will be placed on familiarisation, however it is expected that the participants will not experience either ergometer as unduly different from ergometers they will have used in training or standard athlete testing.

Data Management

The data will be transferred to a computer and analyzed. It will be stored on a single computer, and backed up on a removable drive; data access to both devices will be password protected. After the analysis is complete, the data will be removed from the computer and backup drive. The data files will not be identified with the participants' names during analysis and any association between a participant's name and data will be confined to communication with the participant themselves. Confidentiality of participants' names and the data obtained will be preserved at all times and only researchers and supervisors of this study will have access to this information.

Results will be made available to the participants on completion of the thesis report.

Participant's Rights

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- decline to answer any particular question;
- withdraw from the study at any time;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded.

Project Contacts

Researcher: Lynne A. Munro
Phone: 0272790894
Email: lynne.munro@northshorecity.govt.nz

Supervisor: Dr Andrew Foskett
School of Sport and Exercise
Massey University
New Zealand

Phone: +64 9 443-9770 x41104
Email: A.Foskett@massey.ac.nz

Participants are invited to contact the researcher, Lynne Munro, or supervisor, Dr Andrew Foskett, if they have any questions about the project.

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 11/14. If you have any concerns about the conduct of this research, please contact Professor Julie Boddy, Chair, Massey University Human Ethics Committee: Southern A, telephone 06 350 5799 x 2541, email humanethicsoutha@massey.ac.nz.

If physical injury results from your participation in this study, you should visit a treatment provider to make a claim to ACC as soon as possible. ACC cover and entitlements are not automatic and your claim will be assessed by ACC in accordance with the Injury Prevention, Rehabilitation and Compensation Act 2001. If your claim is accepted, ACC must inform you of your entitlements, and must help you access those entitlements. Entitlements may include, but not be limited to, treatment costs, travel costs for rehabilitation, loss of earnings, and/or lump sum for permanent impairment. Compensation for mental trauma may also be included, but only if this is incurred as a result of physical injury.If your ACC claim is not accepted you should immediately contact the researcher. The researcher will initiate processes to ensure you receive compensation equivalent to that to which you would have been entitled had ACC accepted your claim.

APPENDIX 2 – HEALTH SCREENING QUESTIONNAIRE

MASSEY UNIVERSITY

Institute of Food, Nutrition, and Human Health
Massey University
Albany
New Zealand

The Effect of High-Inertia Ergometer Warm-Up on Sprint Cycling Performance

Pre-Exercise Health Screening Questionnaire

Name:____

Address: ____

Phone: _______________________________

Age: ________________ Height:_______________ Weight:_______________

Number of years experience sprint cycling:_____________

Number of years experience resistance training:___________

Record of Caffeine intake in 24 hour period prior to testing:

Caffeine-Containing Substance	Total Quantity/Volume Ingested	Caffeine dose per 100ml or grams ingested (if available)	Date/Time Ingested

This questionnaire has been designed to inform the exercise specialist conducting the exercise test of any health or medical issues that may be of concern in executing the test and to identify the small number of persons for whom the exercise test might be inappropriate. The questions are based upon the Physical Activity Readiness Questionnaire (PAR-Q), originally devised by the British Columbia Dept of Health (Canada), as revised by [1]Thomas *et al.* (1992) and [2]Cardinal *et al.* (1996), and with added requirements of the Massey University Human Ethics Committee. The information provided by you on this form will be treated with the strictest confidentiality.

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Institute of Food, Nutrition, and Human Health
Massey University
Albany
New Zealand

Please read the following questions carefully. If you have any difficulty, please advise the exercise specialist who is conducting the exercise test.

Please answer all of the following questions by ticking only one box for each question:

Q 1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes ☐ No ☐

Q 2. Do you feel a pain in your chest when you do physical activity?

Yes ☐ No ☐

Q 3. In the past month have you had chest pain when you were not doing physical activity?

Yes ☐ No ☐

Q 4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes ☐ No ☐

Q 5. Are you currently using prescription medication?

Yes ☐ No ☐

Q 6. Do you have a bone or joint problem that could be made worse by vigorous exercise, particular in the lower back and/or legs?

Yes ☐ No ☐

Q 7. Do you know of any other reason why you should not do physical activity?

Yes ☐ No ☐

Q 8. Have any immediate family members had heart problems prior to the age of 50?

Yes ☐ No ☐

Q 10. Have you been hospitalised recently?

Yes ☐ No ☐

Q 11. Are you diabetic?

Yes ☐ No ☐

Q 12. Do you have any infectious disease that may be transmitted in blood?

Yes ☐ No ☐

Q 13. This experiment includes the taking of blood for measuring levels of lactate present. Do you have any objection to this?

Yes ☐ No ☐

Q 14. Are you currently suffering from the effects of any injury, illness or other condition which may affect or impair your performance in this test?

Yes ☐ No ☐

You should be aware that even amongst healthy persons who undertake regular physical activity there is a risk of sudden death during exercise. Though extremely rare, such cases can occur in people with an undiagnosed heart condition. If you have any reason to suspect that you may have a heart condition that will put you at risk during exercise, you should seek advice from a medical practitioner before undertaking an exercise test.

I have read, understood and completed this questionnaire.

Signature: ____ Date: ____________________

References

1. Thomas S, Reading J and Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci* 17(4): 338-345.
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APPENDIX 3 – PARTICIPANT CONSENT FORM

MASSEY UNIVERSITY

Institute of Food, Nutrition, and Human Health
Massey University
Albany
New Zealand

The Effects of High-Inertia Ergometer Warm-Up on Sprint Cycling Performance

PARTICIPANT CONSENT FORM - INDIVIDUAL

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction and I understand that I may ask further questions at any time.

I agree/do not agree to crank data of the sprint performance being recorded.

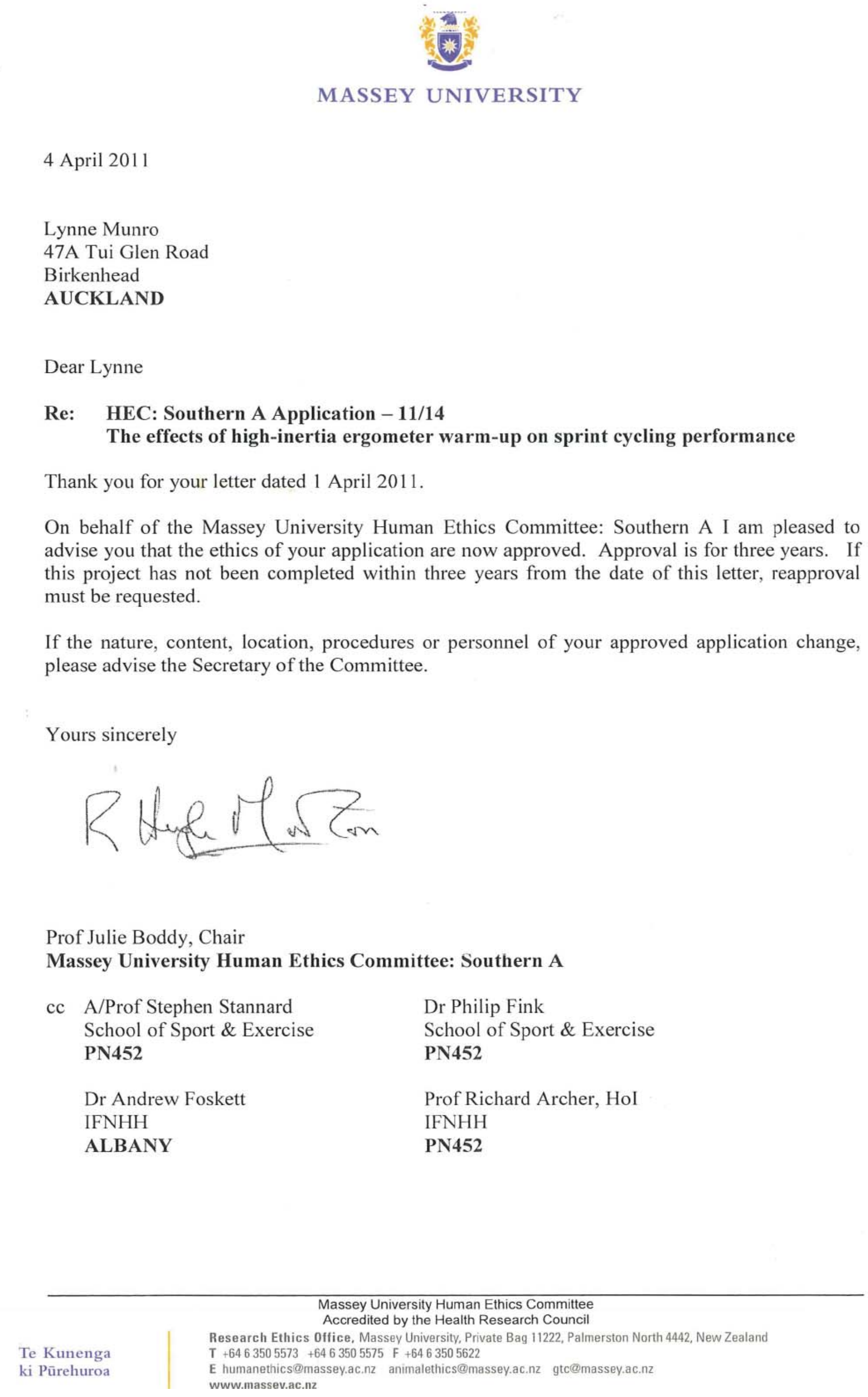
I wish/do not wish to have access to my data on completion of the study.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name - printed ....

APPENDIX 4 – ETHICS APPROVAL



MASSEY UNIVERSITY

4 April 2011

Lynne Munro
47A Tui Glen Road
Birkenhead
AUCKLAND

Dear Lynne

Re: HEC: Southern A Application – 11/14
The effects of high-inertia ergometer warm-up on sprint cycling performance

Thank you for your letter dated 1 April 2011.

On behalf of the Massey University Human Ethics Committee: Southern A I am pleased to advise you that the ethics of your application are now approved. Approval is for three years. If this project has not been completed within three years from the date of this letter, reapproval must be requested.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee.

Yours sincerely

Prof Julie Boddy, Chair
Massey University Human Ethics Committee: Southern A

cc A/Prof Stephen Stannard
School of Sport & Exercise
PN452

Dr Philip Fink
School of Sport & Exercise
PN452

Dr Andrew Foskett
IFNHH
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APPENDIX 5 – SUPPLEMENTARY RESULTS

Tables A5.1 to A5.4 depict measures showing main effect for time in ANOVA analysis.

Table A5.1 Segment and Overall Measures Showing Significant Decline from Pre to Post4 and Post4 to Post8 Time Points.

Measure (* units)	**p-value**	**Pre**	**Post4**	**Post8**	**Post16**	**Significant differences**
Acceleration	S3, p=0.000	5.73 ± 0.57	5.60 ± 0.58	5.53 ± 0.57	5.51 ± 0.61	Post4,8,16 < Pre, P=0.000 Post4 > Post8 p=0.003
Ave Power	S3, p=0.000	1279.65±197.59	1238.44±196.53	1216.31±190.17	1215.10±198.19	Post4, 8, 16 < Pre, p=0.000 Post4 > Post8, p=0.001
	S1-4, p=0.001	1035.20±159.23	1018.01±162.11	1002.23±156.33	999.57±158.52	Post4, 8, 16 < Pre, p=0.02,0.001,0,001 Post4 > Post8, p=0.003
Ave Torque	S3, p=0.000	92.70 ± 8.93	90.45 ± 8.90	89.40 ± 8.77	88.88 ± 9.18	Post4, 8, 16 < Pre, p=0.0001, 0.000,0.000 Post4 > Post8, p=0.0014
Ave Velocity	S4, p=0.001	103.95 ± 5.60	103.17 ± 5.81	102.77 ± 5.69	102.73 ± 5.89	Post4,8,16 < Pre, p=0.01, 0.000,0.000 Post4 > Post8, p=0.018
Peak Power	p=0.000	1354.14±221.21	1314.29±221.27	1282.15±211.61	1281.71±223.47	Post4, 8, 16 < Pre, p=0.003, 0.000,0.000 Post4 > Post8, p=0.001
Work Done	S3, p=0.000	1767.04±178.94	1724.32±171.26	1704.13±170.01	1696.57±179.05	Post4, 8, 16 < Pre, p=0.000 Post 4 > Post8, p=0.025

** acceleration – $m.s^{-2}$; power - watts; torque - Nm; velocity – $m.s^{-1}$; work done - joules*

Table A5.2 Segment and Overall Measures Showing Significant Decline from Post4 to Post8 Time Points.

Measure (* units)	**p-value**	**Pre**	**Post4**	**Post8**	**Post16**	**Significant differences**
Ave Cadence	S3, p=0.045	132.56 ± 8.13	131.67 ± 8.45	130.95 ± 8.30	131.5 ± 8.37	Post8,16 < Pre, p=0.002,0.025 Post4 > Post8, p=0.01
Ave Velocity	S3, p=0.037	78.8 ± 4.86	78.32 ± 5.05	77.89 ± 4.89	78.144 ± 4.98	Post8, 16 < Pre, p=0.001, 0.015 Post4 > Post8, p=0.006
Performance Time	S3, p=0.037	1.38 ± 0.09	1.39 ± 0.09	1.41 ± 0.09	1.40 ± 0.09	Post8, 16 > Pre, P=0.001, 0.031 Post4 < Post8, p=0.007

** acceleration – $m.s^{-2}$; velocity – $m.s^{-1}$; time - s*

Table A5.3 Segment and Overall Measures Showing Significantly Lower Post- Versus Pre- CC Values.

Measure **(* units)**	**p-value**	**Pre**	**Post4**	**Post8**	**Post16**	**Significant differences**
Ave Cadence	S4, p=0.005	174.67 ± 9.40	173.39 ± 9.94	172.83 ± 9.49	172.72 ± 9.94	Post4,8,16 < Pre, p=0.018,0.000,0.002
Ave Power	S4, p=0.024	1031.89±144.18	1006.89±133.83	1008.78±128.38	992.56±129.36	Post4, 8, 16 < Pre, p=0.011, 0.021,0.01
Performance Time	S4, p=0.001	1.75 ± 0.10	1.76 ± 0.11	1.77 ± 0.10	1.77 ± 0.10	Post4,8,16 > Pre, P=0.004,0.000,0.000
Velocity Change	S3, p=0.002	24.49 ± 0.93	24.14 ± 0.89	24.00 ± 0.91	23.80 ± 1.07	Post4, 8, 16 < Pre, p=0.01, 0.0001,0.000

** cadence – rpm; power - watts; velocity – m.s^{-1}; time - s*

Table A5.4 Instantaneous Power Measures Showing Significant Main Effect for Time.

Measure (watts)	**p-value**	**Pre**	**Post4**	**Post8**	**Post16**	**Significant differences**
P_{rev_max}	0.000	1385.2±225.5	1344.0±218.3	1309.3±212.2	1314.7±222.6	Post4, 8, 16 < Pre, p=0.001, 0.000,0.000 Post4 > Post8, p=0.000
P_{qrev_max}	0.000	1311.7±211.2	1278.1±213.0	1257.5±203.1	1259.9±212.6	Post4, 8, 16 < Pre, p=0.004, 0.000,0.000 Post4 > Post8, p=0.003
P_{i_max}	0.000	2245.2±401.0	2169.5±401.5	2116.2±376.8	2111.7±394.3	Post4, 8, 16 < Pre, p=0.001, 0.000,0.000 Post4 > Post8, p=0.01
P_{qi_max}	0.001	2126.2±361.6	2074.3±373.2	2035.9±346.6	2028.6±352.8	Post4, 8, 16 < Pre, p=0.01, 0.000,0.000 Post 4 > Post8, p=0.003

Tables A5.5 to A5.16 presents outcomes from within subjects contrasts analysis of individual half crank cycles.

Tables A5.5 to A5.7 depict meaningful changes in T_i and f_i from Pre-CC to Post-CC trial at each time point.

Tables A5.8 to A5.10 depict meaningful changes in T_{rev} and f_{rev} from Pre-CC to Post-CC trial at each time point.

Tables A5.11 to A5.13 depict meaningful changes in P_i and f_{qi} from Pre-CC to Post-CC trial at each time point.

Tables A5.14 to A5.16 depict meaningful changes in P_{rev} and f_{qrev} from Pre-CC to Post-CC trial at each time point.

Table A5.5 Meaningful Changes in T_i for Post4 Trials.

		Post-CC measure (Nm)		**Change in Measure from Pre-CC value (%)**		**Cohen's d**	**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Ti1	DYN Post4	303.29±32.82	286.66±46.28	7.58±2.22	1.69±4.75	0.46	0.13	0.79	91	likely
Ti2	DYN Post4	262.56±35.07	246.58±37.20	5.96±2.33	-0.59±2.27	0.41	0.19	0.62	95	likely
Ti3	DYN Post4	216.40±31.33	207.42±31.48	0.45±6.61	-4.11±7.94	0.30	0.08	0.51	79	likely
Ti9	ISO Post4	140.79±12.89	131.69±13.47	2.37±2.17	-4.01±3.38	0.59	0.30	0.88	98	very likely
Ti10	ISO Post4	125.32±8.33	117.77±5.39	0.34±4.31	-5.75±2.89	0.97	0.30	1.65	97	very likely
Ti15	DYN Post4	88.92±10.10	82.71±5.50	0.00±9.91	-7.86±3.99	0.73	0.09	1.38	94	likely
	ISO Post4	86.51±4.04	82.71±5.50	1.77±6.70	-7.86±3.99	0.90	0.58	1.22	100	almost certainly
Ti17	ISO Post4	82.23±10.29	76.91±4.98	4.60±5.78	- 4.29±8.02	0.75	-0.01	1.51	92	likely
Ti19	DYN Post4	66.64±6.82	65.57±6.90	-0.48±11.61	-11.96±8.09	0.79	-0.19	1.77	86	likely
	ISO Post4	72.46±13.28	65.57±6.90	3.87±12.64	-11.96±8.09	1.08	0.15	2.01	95	likely

Table A5.6 Meaningful Changes in T_i for Post8 Trials.

		Post-CC measure (Nm)		**Change in Measure from Pre-CC value (%)**		**Cohen's d**	**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Ti15	DYN Post8	87.62±5.27	87.00±7.22	2.98±9.40	-2.91±7.25	0.55	-0.13	1.23	83	likely
Ti18	ISO Post8	81.58±9.90	74.84±11.28	3.69±4.82	-7.07±7.79	0.85	0.10	1.59	93	likely
Ti19	DYN Post8	70.25±6.52	68.25±9.91	4.84±6.60	-8.34±6.20	0.91	0.32	1.51	97	very likely

Table A5.7 Meaningful Changes in T_i for Post16 Trials.

		Post-CC measure (Nm)		**Change in Measure from Pre-CC value (%)**		**Cohen's d**	**90% Confidence Limits**		**Likelihood of exceeding SWC**	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Ti9	ISO Post16	134.70±15.24	128.65±14.19	-2.25±4.41	-6.42±2.27	0.39	-0.05	0.83	81	likely
Ti10	ISO Post16	123.14±8.48	116.16±7.68	-1.43±7.22	-7.22±5.67	0.93	0.34	1.51	97	very likely
Ti11	ISO Post16	118.14±12.25	111.36±9.36	0.60±4.96	-6.44±4.93	0.86	0.06	1.66	93	likely
Ti13	DYN Post16	97.36±8.21	94.29±7.50	-3.74±3.72	-7.99±2.66	0.44	0.31	0.56	99	very likely
	ISO Post16	104.22±12.63	94.29±7.50	0.34±7.77	-7.99±2.66	1.04	0.08	2.01	93	likely
Ti15	DYN Post16	87.09±7.20	88.13±9.64	2.25±8.62	-1.81±8.49	0.38	-0.10	0.85	76	likely
	ISO Post16	90.20±10.48	88.13±9.64	1.42±9.12	-1.81±8.49	0.30	0.00	0.61	75	likely
Ti19	DYN Post16	69.22±8.05	71.68±7.68	3.17±5.72	-3.07±7.77	0.43	-0.22	1.09	75	likely
	ISO Post16	71.56±13.02	71.68±7.68	2.64±14.02	-3.07±7.77	0.39	-0.39	1.17	72	possibly

Table A5.8 Meaningful Changes in T_{rev} for Post4 Trials.

Measure	Trial/Time	Post-CC measure (Nm)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Trev2	DYN Post4	144.71±18.47	138.02±17.70	3.55±2.81	-2.28±5.24	0.45	0.23	0.68	96	very likely
Trev3	DYN Post4	125.03±17.00	120.39±15.50	3.28±4.73	-2.36±4.33	0.43	0.09	0.77	90	likely
Trev9	DYN Post4	85.69±9.21	82.96±9.59	0.17±4.89	-4.06±5.04	0.35	-0.04	0.73	76	likely
Trev10	DYN Post4	78.62±5.65	77.37±6.04	-3.85±3.77	-7.17±5.76	0.39	-0.17	0.95	75	likely
	ISO Post4	79.93±6.14	77.37±6.04	-1.10±3.66	-7.17±5.76	0.78	0.15	1.41	94	likely
Trev15	DYN Post4	57.71±5.45	55.32±5.79	3.35±4.62	-4.30±8.10	0.52	0.02	1.01	87	likely
Trev18	DYN Post4	51.83±4.16	52.15±4.58	-0.07±7.57	-6.11±7.93	0.64	-0.53	1.80	77	likely
	ISO Post4	52.22±3.55	52.15±4.58	0.20±3.99	-6.11±7.93	0.64	-0.12	1.39	85	likely

Table A5.9 Meaningful Changes in T_{rev} for Post8 Trials.

Measure	Trial/Time	Post-CC measure		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Trev7 (lower)	ISO Post8	90.50±9.93	94.95±12.61	-7.59±2.79	-2.63±3.23	-0.41	-0.59	-0.23	97	very likely
Trev10	DYN Post8	80.50±6.69	77.41±7.38	-1.55±2.58	-7.24±6.90	0.66	-0.04	1.37	88	likely
	ISO Post8	78.36±7.25	77.41±7.38	-3.20±3.72	-7.24±6.90	0.52	-0.26	1.30	78	likely
Trev14	DYN Post8	64.64±6.28	63.01±6.19	1.82±6.46	-2.71±10.44	0.50	-0.38	1.38	76	likely
Trev18	DYN Post8	52.26±5.33	52.07±3.75	0.61±9.38	-6.15±6.71	0.71	-0.33	1.76	83	likely
	ISO Post8	52.38±7.63	52.07±3.75	-0.28±10.41	-6.15±6.71	0.59	-0.55	1.74	75	likely
Trev19	DYN Post8	47.40±5.53	44.48±5.89	5.04±4.63	-6.35±9.46	0.66	0.17	1.15	94	likely
	ISO Post8	47.56±6.72	44.48±5.89	6.74±10.81	-6.35±9.46	0.81	0.01	1.60	91	likely

Table A5.10 Meaningful Changes in T_{rev} for Post16 Trials.

Measure	Trial/Time	Post-CC measure (Nm)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Trev10	ISO Post16	78.14±7.06	77.20±6.45	-3.45±5.57	-7.43±2.67	0.51	-0.02	1.04	86	likely
Trev11	ISO Post16	75.42±7.49	71.92±7.27	1.19±4.24	-4.69±4.75	0.61	0.01	1.20	89	likely
Trev13	ISO Post16	67.03±3.94	62.16±5.67	4.30±5.40	-4.53±6.27	0.86	0.35	1.36	98	very likely
Trev14	DYN Post16	62.61±4.12	61.01±6.07	-1.16±4.47	-5.94±7.90	0.53	0.11	0.95	92	likely

Table A5.11 Meaningful Changes in P_i for Post4 Trials.

Measure	Trial/Time	Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Pi2	DYN Post4	1787.71± 339.90	1657.38± 342.46	5.36±4.06	-2.90±7.21	0.35	0.13	0.57	91	Likely
Pi9	ISO Post4	2100.59± 325.78	1993.32± 329.14	0.13±3.05	-4.70±4.09	0.28	0.05	0.52	81	Likely
Pi10	ISO Post4	1967.73± 239.86	1849.90± 199.38	-0.68±4.90	-6.61±3.46	0.52	0.11	0.93	93	Likely
Pi15	DYN Post4	1611.54± 270.28	1494.35± 177.55	-0.85±10.62	-8.75±3.91	0.54	0.03	1.05	88	likely
	ISO Post4	1569.07± 151.34	1494.35± 1777.55	1.15±7.83	-8.75±3.91	0.64	0.36	0.93	99	very likely
Pi17	ISO Post4	1551.64± 275.79	1445.05± 168.35	3.90±6.47	-5.10±8.84	0.57	-0.05	1.19	89	likely
Pi19	DYN Post4	1300.93± 193.32	1271.72± 193.60	-0.94±12.26	-12.98±8.96	0.63	-0.16	1.43	86	likely
	ISO Post4	1414.80± 338.05	1271.72± 193.60	3.08±13.52	-12.98±8.96	0.83	0.07	1.60	94	likely

Table A5.12 Meaningful Changes in P_i for Post8 Trials.

Measure	Trial/Time	Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Pi15	DYN Post8	1583.74± 161.29	1568.09± 210.50	2.04±10.34	-4.09±7.42	0.40	-0.09	0.89	77	likely
Pi18	ISO Post8	1557.22± 260.35	1427.79± 273.78	2.60±4.17	-8.32±8.15	0.61	0.07	1.14	91	likely
Pi19	DYN Post8	1366.61± 185.19	1322.07± 250.64	4.13±6.86	-9.58±6.18	0.72	0.24	1.21	96	very likely
	ISO Post8	1498.53± 410.32	1322.07± 250.64	7.84±17.11	-9.58±6.18	0.90	0.01	1.80	92	likely

Table A5.13 Meaningful Changes in P_i for Post16 Trials.

Measure	Trial/Time	Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	Control Mean ± SD	Experiment Mean ± SD	Control Mean ± SD		lower	upper	%	Qualitative Inference
Pi2	DYN Post16	1725.55± 316.56	1625.94± 326.76	1.96±4.62	-4.62±9.21	0.28	0.03	0.53	76	likely
Pi10	ISO Post16	1929.71± 267.06	1821.72± 225.24	-2.78±8.51	-8.28±6.37	0.48	0.11	0.86	91	likely
Pi11	ISO Post16	1922.29± 330.65	1809.21± 248.24	-0.66±5.97	-7.49±5.56	0.50	0.01	0.99	88	likely
Pi13	ISO Post16	1796.73± 330.45	1621.11± 205.59	-1.12±9.10	-9.19±3.03	0.61	-0.03	1.26	87	likely
Pi19	DYN Post16	1342.52± 213.83	1385.65± 221.87	2.05±6.14	-4.52±8.92	0.35	-0.21	0.90	70	possibly
	ISO Post16	1394.45± 335.96	1385.65± 221.87	1.66±15.03	-4.52±8.92	0.32	-0.28	0.92	71	possibly

Table A5.14 Meaningful Changes in P_{rev} for Post4 Trials.

		Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Prev2	DYN Post4	1009.56± 204.13	949.89± 191.66	4.47±5.98	-2.37±7.60	0.35	0.01	0.68	83	Likely
Prev9	DYN Post4	1326.78± 208.81	1256.95± 226.61	1.59±6.57	-4.76±6.21	0.34	0.05	0.64	81	Likely
Prev10	DYN Post4	1251.44± 146.26	1216.56± 165.83	-2.71±6.07	-8.03±6.48	0.34	0.03	0.65	80	Likely
	ISO Post4	1256.09± 174.27	1216.56± 165.83	-2.12±4.28	-8.03±6.48	0.43	0.03	0.82	87	Likely
Prev15	DYN Post4	1043± 156.60	1001.90± 160.85	1.45±6.36	-5.18±7.48	0.34	-0.10	0.77	75	Likely
Prev18	DYN Post4	1001.07± 103.03	995.30± 126.05	0.90±8.30	-7.08±8.06	0.53	-0.20	1.27	81	Likely
	ISO Post4	999.30± 128.79	995.30± 126.05	-0.55±4.24	-7.08±8.06	0.42	-0.10	0.95	80	Likely
Prev19	DYN Post4	889.68± 141.55	832.19± 126.19	-0.43±9.01	-10.69±11.51	0.46	-0.15	1.08	85	Likely
	ISO Post4	875.23± 160.33	832.19± 126.19	0.33±9.82	-10.69±11.51	0.51	-0.14	1.15	81	Likely

Table A5.15 Meaningful Changes in P_{rev} for Post8 Trials.

		Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
Measure	**Trial/Time**	**Experiment Mean ± SD**	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Prev10	DYN Post8	1265.92± 170.44	1210.19± 182.57	-1.78±3.03	-8.72±7.51	0.44	0.06	0.82	85	likely
	ISO Post8	1229.46± 173.42	1210.19± 182.57	-4.31±3.22	-8.72±7.51	0.32	-0.12	0.76	75	likely
Prev14	DYN Post8	1144.30± 165.01	1110.19± 161.11	0.95±7.06	-3.93±11.10	0.33	-0.22	0.87	71	possibly
Prev18	DYN Post8	1001.59± 140.27	991.06± 117.81	0.60±10.21	-7.39±7.09	0.53	-0.11	1.28	84	likely
	ISO Post8	1000.77± 188.98	991.06± 117.81	-1.37±9.93	-7.39±7.09	0.39	-0.35	1.13	80	likely
Prev19	DYN Post8	923.50± 150.19	862.23± 154.08	3.31±4.43	-7.58±9.43	0.49	0.08	0.91	90	likely
	ISO Post8	924.29± 178.67	862.23± 154.08	5.77±11.56	-7.58±9.43	0.61	0.02	1.20	90	likely

Table A5.16 Meaningful Changes in P_{rev} for Post16 Trials.

Measure	Trial/Time	Post-CC measure (Watts)		Change in Measure from Pre-CC value (%)		Cohen's d	90% Confidence Limits		Likelihood of exceeding SWC	
		Experiment Mean ± SD	**Control Mean ± SD**	**Experiment Mean ± SD**	**Control Mean ± SD**		**lower**	**upper**	**%**	**Qualitative Inference**
Prev10	ISO Post16	1225.48± 192.93	1211.96± 170.84	-4.79±6.94	-8.49±3.26	0.27	-0.06	0.60	71	possibly
Prev12	ISO Post16	1194± 143.55	1139.47± 154.70	-1.11±4.16	-5.69±5.02	0.32	0.04	0.60	78	likely
Prev14	ISO Post16	1103.22± 130.41	1075.71± 155.68	-2.41±4.79	-7.11±8.42	0.31	0.03	0.59	78	likely
Prev15	ISO Post16	1020.45± 170.93	1017.47± 191.44	1.40±7.94	-3.96±7.67	0.29	-0.07	0.64	75	likely
Prev16	DYN Post16	1075.45± 155.41	1021.23± 152.69	-1.45±7.54	-6.31±6.72	0.32	-0.08	0.71	75	likely
Prev17	DYN Post16	977.76± 145.73	912.97± 163.44	3.46±10.16	-4.77±13.30	0.36	-0.09	0.82	75	likely
	ISO Post16	976.92± 164.60	912.97± 163.44	1.88±5.06	-4.77±13.30	0.32	-0.15	0.82	75	likely
Prev18	DYN Post16	975.24± 121.11	940.24± 136.89	-1.90±7.59	-13.00±10.48	0.74	0.05	1.43	91	likely
	ISO Post16	975.51± 91.67	940.24± 136.89	-2.63±7.41	-13.00±10.48	0.67	0.33	1.02	98	very likely
Prev19	DYN Post16	920.21± 145.37	870.96± 186.25	3.06±4.80	-6.93±17.42	0.45	-0.09	0.99	82	likely
	ISO Post16	936.58± 173.54	870.96± 186.25	2.79±8.03	-6.93±17.42	0.45	-0.15	1.06	79	likely

Table A5.17 presents metabolic measures showing main effect for time in ANOVA analysis.

Table A5.17 Metabolic Measures Showing Main Effects for Time.

Measure (* units)	**p-value**	**Pre**	**Post4**	**Post8**	**Post16**	**Significant differences**
Heart Rate	0.000 (significant)	133.3±11.7	114.3±13.4	113.9±13.8	111.3±10.7	Post4, 8, 16 < Pre, p=0.000
Blood Lactate	0.056 (trend)	6.0±1.9	4.6±1.8	5.9±1.8	5.3±1.6	Post4, 8, 16 < Pre, p=0.006 Post8 > Post4, 16, p=0.000, 0.006

** Heart rate – bpm; blood lactate - mmol.L^{-1}*

APPENDIX 6 – SUMMARY OF TRIAL OUTCOMES

DYN Post4

DYN Post8

DYN Post16

ISO Post4

ISO Post8

ISO Post16

DYN Post4

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**	**Measure**	**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max	✔		Time to Peak Power	✔	
Ti0, Trev0, Ti_max, Trev_max	Ti_max, Trev_max		Peak Torque	✔	
			Time to Peak Torque	✔	
fi0, frev0			Final Cadence	✔	
fqi_opt, fqrev_opt					
			Final Velocity	✔	✔
			Average Cadence S1-4		
			Average Power S1-4	✔	
			Average Torque S1-4	✔	
			Average Velocity S1-4	✔	
			Change in PTA S1-4		
			Performance Time S1-4	✔	
HCC Pi_max, HCC Prev_max	✔		RPD S1-peak		
			Work Done S1-4	✔	
			Average Cadence S1	✔	
Pi 1-2, Prev 2	Pi 2, Prev 2		Average Power S1	✔	
Ti 1-2, Trev 2	Ti 1,2, Trev 2		Average Torque S1	✔	
			Average Velocity S1	✔	
			Change in PTA S1		
			Performance Time S1	✔	
HCC Pi_max, HCC Prev_max			RPD S1	✔	
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4	Ti3, Trev 3		Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10	Prev 9,10		Average Power S3		
Ti 5-10, Trev 5-10	Trev 9,10		Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3		
			Work Done S3		
			Average Cadence S4		
Pi 11-20, Prev 11-20	Pi 15,19, Prev 15,18,19		Average Power S4		
Ti 11-20, Trev 11-20	Ti 15, 19, Trev15,18,19		Average Torque S4		
			Average Velocity S4		
			Change in PTA S4		
			Performance Time S4		
			Work Done S4	✔	

DYN Post8

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**	**Measure**	**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max			Time to Peak Power		
Ti0, Trev0, Ti_max, Trev_max			Peak Torque		
			Time to Peak Torque		
fi0, frev0			Final Cadence		lower
fqi_opt, fqrev_opt	fqi_opt				
			Final Velocity		lower
			Average Cadence S1-4		
			Average Power S1-4		
			Average Torque S1-4		
			Average Velocity S1-4		
			Change in PTA S1-4		
			Performance Time S1-4		
HCC Pi_max, HCC Prev_max			RPD S1-peak		
			Work Done S1-4		
			Average Cadence S1		
Pi 1-2, Prev 2			Average Power S1		
Ti 1-2, Trev 2			Average Torque S1		
			Average Velocity S1		
			Change in PTA S1		
			Performance Time S1		
HCC Pi_max, HCC Prev_max			RPD S1		
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4			Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10	Prev 10		Average Power S3		
Ti 5-10, Trev 5-10	Trev 10		Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3		
			Velocity Change S3		
			Work Done S3		
			Average Cadence S4		
Pi 11-20, Prev 11-20	Pi 15,19, Prev 14,18,19		Average Power S4		
Ti 11-20, Trev 11-20	Ti 15,19, Trev 14,18,19		Average Torque S4		
			Average Velocity S4		
			Change in PTA S4		
			Performance Time S4		
			Work Done S4		

DYN Post16

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**	**Measure**	**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max			Time to Peak Power		
Ti0, Trev0, Ti_max, Trev_max			Peak Torque		
			Time to Peak Torque		
fi0, frev0			Final Cadence	✔	
fqi_opt, fqrev_opt	fqrev_opt				
			Final Velocity	✔	
			Average Cadence S1-4		
			Average Power S1-4		
			Average Torque S1-4		
			Average Velocity S1-4		
			Change in PTA S1-4		
			Performance Time S1-4		
HCC Pi_max, HCC Prev_max			RPD S1-peak		
			Work Done S1-4		
			Average Cadence S1	✔	
Pi 1-2, Prev 2	Pi 2		Average Power S1		
Ti 1-2, Trev 2			Average Torque S1		
			Average Velocity S1		
			Change in PTA S1		
			Performance Time S1		
HCC Pi_max, HCC Prev_max			RPD S1		
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4			Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10			Average Power S3		
Ti 5-10, Trev 5-10			Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3		
			Work Done S3		
			Average Cadence S4		
Pi 11-20, Prev 11-20	Pi 19, Prev 16-19		Average Power S4		
Ti 11-20, Trev 11-20	Ti 13,15,19, Trev 14-19		Average Torque S4	✔	
			Average Velocity S4		
			Change in PTA S4		
			Performance Time S4		
			Work Done S4	✔	

ISO Post4

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**	**Measure**	**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max			Time to Peak Power		
Ti0, Trev0, Ti_max, Trev_max	Trev0 (lower)		Peak Torque		
			Time to Peak Torque		
fi0, frev0			Final Cadence		Trial fx
fqi_opt, fqrev_opt	fqi_opt, fqrev_opt				
			Final Velocity		
			Average Cadence S1-4		
			Average Power S1-4		
			Average Torque S1-4		
			Average Velocity S1-4		
			Change in PTA S1-4		Trial fx
			Performance Time S1-4		
HCC Pi_max, HCC Prev_max			RPD S1-peak		
			Work Done S1-4		
			Average Cadence S1		
Pi 1-2, Prev 2			Average Power S1		
Ti 1-2, Trev 2			Average Torque S1		
			Average Velocity S1		
			Change in PTA S1		
			Performance Time S1		
HCC Pi_max, HCC Prev_max			RPD S1		
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4			Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10	Pi 9,10, Prev 10		Average Power S3		
Ti 5-10, Trev 5-10	Ti 9,10, Trev 10		Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3		
			Work Done S3		
			Average Cadence S4		
Pi 11-20, Prev 11-20	Pi 15,17,19, Prev 18,19		Average Power S4		
Ti 11-20, Trev 11-20	Ti 15,17,19, Trev 18,19		Average Torque S4		
			Average Velocity S4		
			Change in PTA S4	✔	Trial fx
			Performance Time S4		
			Work Done S4		

ISO Post8

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**	**Measure**	**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max			Time to Peak Power		
Ti0, Trev0, Ti_max, Trev_max			Peak Torque		
			Time to Peak Torque		
fi0, frev0			Final Cadence		Trial fx
fqi_opt, fqrev_opt	fqi_opt				
			Final Velocity		
			Average Cadence S1-4		
			Average Power S1-4		
			Average Torque S1-4		
			Average Velocity S1-4		
			Change in PTA S1-4	✔	Trial fx
			Performance Time S1-4		
HCC Pi_max, HCC Prev_max			RPD S1-peak		
			Work Done S1-4		
			Average Cadence S1		
Pi 1-2, Prev 2			Average Power S1		
Ti 1-2, Trev 2			Average Torque S1		
			Average Velocity S1		
			Change in PTA S1		
			Performance Time S1		
HCC Pi_max, HCC Prev_max			RPD S1		
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4			Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10	Prev 10		Average Power S3		
Ti 5-10, Trev 5-10	Trev 7 (lower), 10		Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3		
			Work Done S3		
			Average Cadence S4		
Pi 11-20, Prev 11-20	Pi 18, 19, Prev 18,19		Average Power S4		
Ti 11-20, Trev 11-20	Ti 18, Trev 18, 19		Average Torque S4		
			Average Velocity S4		
			Change in PTA S4	✔	Trial fx
			Performance Time S4		
			Work Done S4		

ISO Post16

Instantaneous Measures			Segment/Overall Measures		
Measure	**Mag-based Inference**	**ANOVA**		**Mag-based Inference**	**ANOVA**
Pi_max, Pqi_max, Prev_max, Pqrev_max			Peak Power		
HCC Pi_max, HCC Prev_max			Time to Peak Power		
Ti0, Trev0, Ti_max, Trev_max			Peak Torque		
			Time to Peak Torque		
fi0, frev0	✔		Final Cadence	✔	✔
fqi_opt, fqrev_opt	fqrev_opt				
			Final Velocity	✔	✔
			Average Cadence S1-4		
			Average Power S1-4		
			Average Torque S1-4		
			Average Velocity S1-4		
			Change in PTA S1-4	✔	Trial fx
			Performance Time S1-4		
HCC Pi_max, HCC Prev_max			RPD S1-peak		
			Work Done S1-4		
			Average Cadence S1		
Pi 1-2, Prev 2			Average Power S1		
Ti 1-2, Trev 2			Average Torque S1		
			Average Velocity S1		
			Change in PTA S1		
			Performance Time S1		
HCC Pi_max, HCC Prev_max			RPD S1		
			Work Done S1		
			Average Cadence S2		
Pi 3-4, Prev 3-4			Average Power S2		
Ti 3-4, Trev 3-4			Average Torque S2		
			Average Velocity S2		
			Change in PTA S2		
			Performance Time S2		
HCC Pi_max, HCC Prev_max			RPD S2		
			Work Done S2		
			Average Cadence S3		
Pi 5-10, Prev 5-10	Pi 10, Prev 10		Average Power S3		
Ti 5-10, Trev 5-10	Ti 9,10, Trev 10		Average Torque S3		
			Average Velocity S3		
			Change in PTA S3		
			Performance Time S3		
HCC Pi_max, HCC Prev_max			RPD S3	✔	
			Work Done S3		
			Average Cadence S4	✔	
Pi 11-20, Prev 11-20	Pi 11,13,19 Prev 12,14, 15,17-19		Average Power S4	✔	
Ti 11-20, Trev 11-20	Ti 11,13,15,19 Trev 11,13,15,17-19		Average Torque S4	✔	
			Average Velocity S4		
			Change in PTA S4	✔	Trial fx
			Performance Time S4		
			Work Done S4	✔	