Blood flow restriction as a method to elicit post activation potentiation in trained female athletes.

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Abstract

It is essential within the sporting context to be able to physically perform at the highest level possible. This demands training methods and tools that can enhance strength and power both chronically and acutely to ensure performance is maximised. Post activation potentiation (PAP) is a method that acutely enhances muscular force output and performance through performing a potentiating stimulus. While PAP has been shown to be effective in certain situations, any acute performance effects are known to be the summation of the potentiating effects and any accumulated fatigue. Blood flow restriction (BFR) is a training modality that has been shown to be effective in enhancing muscle size and strength via occlusion of the arterial flow which may enable the recruitment of high threshold motor units, create a high metabolic stress, and lead to muscular environment suited to adaptation. These physiological effects, combined with a low level of central fatigue, may combine to provide a situation where PAP is achieved. To date, only one study has investigated the effects of using BFR as a potentiation tool, and no research has been performed on female participants.

This thesis starts by evaluating and synthesizing the existing literature regarding both PAP and BFR training illustrating that there are a variety of performance benefits of using both PAP and BFR (Chapter One). Of the studies identified, 76% showed high intensity-low volume resistance exercise to be effective in inducing PAP, 86% showed WBV training to be effective, and 83% showed 'other' methods to be effective. Overall, 10 of the 42 studies identified (29%) were unsuccessful at eliciting PAP. The literature also suggests that a higher methodological quality of training characteristics, especially relating to the inclusion of female participants, is crucial to ensure the most efficient approach to using BFR to induce PAP. Specifically, of the 42 studies identified that assessed the effects of lower body PAP on sprint and jump performance in athletes, only two studies (4.8%) were conducted in female-only cohorts, and none of them reported details of the menstrual phase (Chapter One).

Chapter Two of this thesis examined the inter-session reliability of both vertical and horizontal explosive power in trained female athletes over a 3-day period utilised in the subsequent experimental chapter to inform the typical error of measurement. The reliability sessions assessed the components of the force-velocity profile for horizontal (20-m running sprint) and vertical (squat jump at body weight, 24 kg, and 48 kg), as well as power using an OptoJump™ and a StalkerATS Radar Gun. Intraclass correlation coefficients (ICC), typical error (TE) and coefficient of variation (CV) with 95% confidence intervals were calculated to compute relative and absolute reliability of measures. The force-velocity component metrics that exhibited acceptable reliability included $V0_{VERT}$ [CV:5.2%, ICC: 0.81 (good)], $F0_{VERT}$ [CV: 6.2%, ICC: 0.7 (good)], and power $Pmax_{VERT}$ [CV: 3.6%, ICC: 0.89 (good)]; while velocity $V0_{horiz)}$ exhibited a reliable CV of 9.8%. The performance metrics exhibited acceptable reliability for BW [CV: 6.9%, ICC: 0.91 (good)] with a low typical error (1.5 cm). When compared to BW jump height measures, sprint speed presented having acceptable reliability [CV: 5.5%, ICC: 0.73 (good)], however, the typical error (1.1 km/h) can be considered large. The reliability results for 24 kg weighted jump exhibited a CV slightly over acceptable range [CV: 10.2%, ICC: 0.84 (good)]; while the data collected for 48 kg weighted jump showed acceptable ICC results, but a poor CV [CV: 36.2%, ICC: 0.84 (good)]. The correlation data demonstrated that $Pmax_{VERT}$ was very strongly correlated with jump performance (r = 0.97), but the association with $F0_{VERT}$ was weak (r = 0.22). In contrast, both $Pmax_{HORIZ}$ (r = 0.71) and $F0_{HORIZ}$ (r = 0.65), were strongly related to sprint speed. $Pmax_{VERT}$ was very strongly related to sprint speed (r =0.83). Additionally, there was a strong relationship between $Pmax_{VERT}$ and $Pmax_{HORIZ}$ (r = 0.63), but the relationships between the corresponding horizontal and vertical F0 and V0 were weak. There was no indication that high levels of theoretical maximal force ($F0_{HORIZ}$ or $F0_{VERT}$) were related to a greater potentiation response.

The penultimate chapter (Chapter Three) investigated the effects of using BFR to elicit PAP in well-trained female athletes. The athletes completed the testing protocols a minimum of 2-days apart and running sprint and squat jump were assessed 4 and 8-min post the PAP intervention. The PAP intervention included completing four sets of bodyweight squats (30, 15, 15, 15 repetitions separated by 30 second rest intervals) with occlusion cuffs applied to the proximal region of the thigh inflated to 180 mmHg; whereas, the control intervention performed the same stimulus without occlusion. With the potentiating stimulus being vertically oriented, we hypothesised that this intervention would be more effective in jumping than sprinting. A 2-way (group x time) repeated-measure ANOVA used to analyse jump performance showed a negative effect of time in bodyweight ($p = 1.01 \times 10^{-7}$) and 24 kg jump ($p = 2.97 \times 10^{-6}$) conditions. An interaction effect was observed in the bodyweight jump ($p = 0.0436$), and *post hoc* analyses showed that the decrease in jump height was greater in the CON condition. Thus, while there was no evidence of potentiation in the body weight squat jump, there was a small significant difference in the decrease observed from Pre to Post 4 ($p=0.0409$) with a large effect size (ES=1.01) indicating that there was less fatigue between Pre and Post 4 for the BFR condition compared to the CON condition. The repeated-measures ANOVA used to analyse sprint potentiation reported no evidence of potentiation in sprint performance at any time point after the conditioning stimulus, results were considered unclear (Post 4: $d = 0.22 \pm 0.42$) or trivial (Post 8: $d = -0.16 \pm 0.24$).

Overall, the results did not show any significant differences in performance between the two conditions. Therefore, concluding that the BFR protocol used in this study failed to elicit potentiation in female athletes. The literature suggests that when there is an optimal balance between potentiation and fatigue it can be utilised to improve performance and low resistance exercise combined with blood flow restriction has been shown to successfully improve performance in males. However, there is very a limited amount of research done using blood flow restriction in females. Hence, the aim of this thesis was to unpack the literature regarding post activation potentiation and blood flow restriction and use it to guide our study in an attempt to potentiate an improvement in jump and sprint performance using BFR in trained females.

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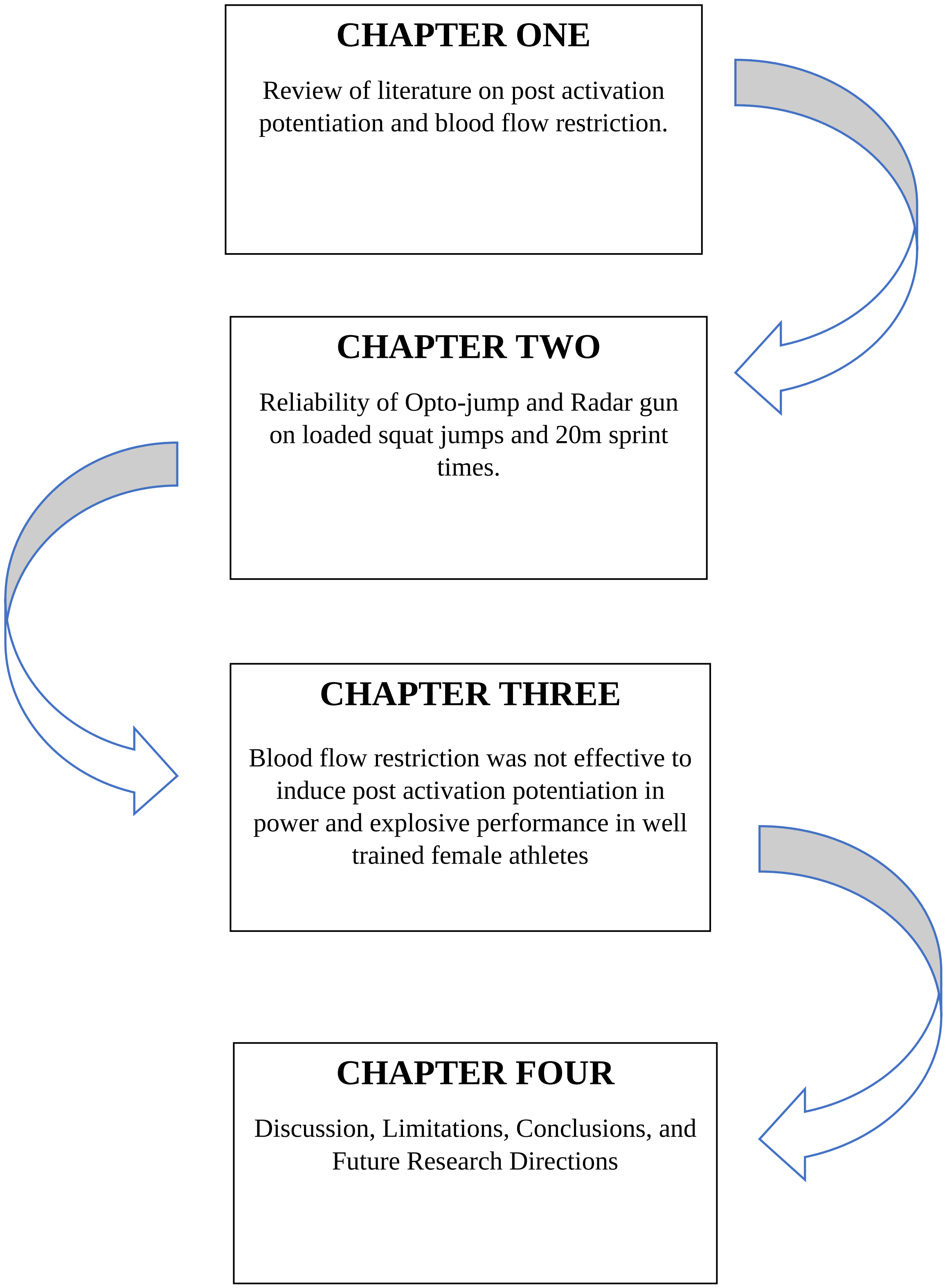
List of Abbreviations

↔ - No change/ No significant difference
↑ - Increase/Improve
↓ - Decrease
AOP - Arterial occlusion pressure.
BBP - Ballistic bench press.
BDJ – Best drop jump
BFR – Blood flow restriction
CB-RT - Combined high intensity resistance training and low intensity BFR
CMJ – Countermovement jump
COD - Change of direction
COND – Conditioning actions
CSA - Cross sectional area
CV – Coefficient of variation
DJ - Drop jump
DS – Dynamic stretching
ECC – Eccentric
EMG - Electromyography
EOL – Eccentric overload
ES - Effect size
ET - Endurance trained
F0 – Theoretical Maximal Force
FI – Functional isometric
FT – Fast twitch
F-V - Force velocity profile
GH - Growth hormone
HIGH – High-intenity, low-volume exercise
HI-RT - High intensity resistance training
HL – High load
HT - Hip thrusts
ICC – Intraclass coefficient
IRT – Individualised recovery time
ISO – Isometric
LAC - Lactate
LB – Lower body
LI-BFR - Low intensity blood flow restriction
LPT - Linear position transducers
MAPK - Mitogen-activated protein-kinase
MP - Mean power output
MRI - Magnetic resonance imaging
MVC - Maximum voluntary contraction.
NCC – No conditioning contraction

NON-BFR, No blood flow restriction
PAP – Post activation potentiation
PAPE - Post activation performance enhancement.
PC – Power cleans
PE – Plyometric exercise
PM - Pectoralis muscle
Pmax – Theoretical maximal power
PPO - Peak power output
PS – Parallel Squat
PT - Power trained
PTP - Post tetanic potentiation
QUAD - Quadricep femoris
RER - Respiratory exchange rate
rGRF – Relative ground reaction force
RM - Repetition maximum
RPE - Rate of perceived exertion
RSA - Repeated sprint times
RSI - Relative strength index
RST - Repeated sprint training
SJ - Squat jump
SJL – Standing long jump
SSJ - Static squat jumps
TB - Triceps brachii
TE – Typical error
TTF - Time to fatigue
TW – Traditional weightlifting
V0 – Theoretical maximal velocity
VCT – Complex Vibration training
VJ – Vertical jump
VL - Vastus lateralis
VO_{2MAX} - Maximum rate of oxygen consumption.
WBV – Whole body vibration

Figure 1: Thesis Outline



Background

Strength and power are key components for performance. Strength is defined as the maximal force a muscle can generate against a load (Bishop & Girard, 2013). Power can be defined as the rate of force/work over time (Lorenz, 2011; Tillin & Bishop, 2009). Having the ability to generate high levels of force against resistance and produce high work rate (power) are imperative for performance in a variety of sports (Young, 2006). Team sports are extremely popular all around the world. Most team sports require their athletes to be able to consistently make skilful and tactical decisions whilst also keeping up with the physical demands of their chosen sport (Bishop & Girard, 2013)**.** The physical demands can change depending on the sport; however, most sports require their athletes to be fast, have high levels agility, muscular strength, power, and endurance, whilst also being able to execute these skills under both fatigue and pressure (Bishop & Girard, 2013).

Post activation potentiation is a phenomenon that acutely enhances muscular force output and performance through performing a potentiating stimulus (Blazevich & Babault, 2019). Evidence has suggested that PAP can improve the muscles' ability to produce more force at a faster rate (Till & Cooke, 2009). Literature has shown that there is a variety of benefits to utilising post activation potentiation. A large portion of the literature regarding PAP investigates the effects on vertical power performance (e.g vertical jumps). Young, Jenner, and Griffiths (1998) reported an increase of 2.8% in CMJ height in ten trained males following a 5RM half squat protocol; Gourgoulis, Aggeloussis, Kasimatis, Mavromatis, and Garas (2003) reported an 2.39% increase in CMJ height in twenty trained males following a progressive half squat protocol. Nevertheless, more research is being performed on the effects PAP has on horizontal power performance (e.g. sprints). Bevan (2010) reported individual improvements in 5-m and 10-m sprint performance in sixteen professional male rugby players following a 3RM conditioning stimulus; and Rønnestad and Ellefsen (2011) reported improvements in 40 m sprints in 9 trained males following a whole body vibration protocol at 50 Hz. Ultimately, the literature emphasises that PAP can acutely improve muscular strength, power and agility in individual athletes and team sport athletes. Typically, PAP is achieved following a performance specific conditioning exercise and the mechanism is purported to be via i) myosin regulatory light chain, and ii) improved motor neuron excitability. The most common conditioning stimuli currently being used to elicit PAP include but are not limited to high intensity (HIGH); isometric (MVC); plyometric (PLYO); eccentric (ECC); whole-body vibration (WBV), and one recent paper has utilised blood flow restriction (BFR).

Research suggests that blood flow restriction (BFR) is a training method that can increase muscle mass, strength, power and improve performance with minimal fatigue (Trofa et al., 2020). It has also been shown that using BFR before exercise can amplify and enhance exercise-induce metabolic stress as decreased oxygen and electromyographic responses (Cayot, Lauver, Silette, & Scheuermann, 2016) A couple of significant appeals to BFR training is 1). the ability it has to create a build-up in hormones such as lactate, growth hormone, and testosterone with minimal fatigue (Takarada et al., 2000), 2). BFR can be used to increase muscle strength and size (B. R. Scott, J. J. Peiffer, & P. S. Goods, 2017), and 3). BFR shows promise in bone and muscle rehabilitation (Beekley, Sato, & Abe, 2005).

Physiological responses likely underpin the observed positive effects following BFR training. It is of note that lactate and testosterone responses generally require high intensity exercise to elicit a robust response. Research has also shown that BFR can activate and induce an earlier onset of fast twitch muscle fibres which is extremely beneficial when aiming to improve explosive and power related aspects of performance (Takarada et al., 2000). Training using BFR allows athletes to utilise low load resistance exercise combined with occlusion to elicit similar performance benefits of high resistance loads (Centner, Ritzmann, Schur, Gollhofer, & Konig, 2019). Currently, BFR is a relatively novel training modality and there is limited research on whether BFR can be used to elicit a conditioning stimulus to improve muscular power and velocity. To date, only one study has used BFR as a potentiating stimulus (Doma et al., 2021). These authors assessed whether twenty-four lunges using BFR would improve vertical jump performance in trained males. The results showed that the BFR effectively improved performance in vertical jump performance compared to a non- BFR control. There are currently no studies that have investigated the effects of using BFR as a conditioning stimulus to elicit potentiation in trained females.

Therefore, the aim of this thesis was to investigate the effect of using BFR to elicit PAP and the impact on muscular force, power, velocity, and explosive performance in healthy, well-trained females. A secondary aim was to investigate the reliability of explosive lower-body performance measures and components of the force-velocity profile obtained from the loaded squat jump and 20-m sprint in a trained female cohort.

Chapter One: Review of literature

Review Aim

The aim of this literature review was to assess and critique the current literature on PAP methodologies, endeavouring to identify effective strategies, and uncover protocols to describe the use of BFR to elicit potentiation. A specific focus of the review was on the use of PAP protocols in healthy active females.

Post Activation Potentiation

1.0 History of Post Activation Potentiation

Potentiation has traditionally been defined as the brief increase in force observed after a muscle twitch contraction following a conditioning contraction (Ramsey & Street, 1941). There are three key forms of activity-dependent potentiation and dates back to 1871 where the first form of potentiation was labelled as staircase potentiation. In this form of potentiation, the conditioning contractions consisted of repeated, low-frequency electrical stimulations in which contractions consecutively increase in scale, implying progressive increase in twitch contractile responses (Bowditch, 1871). By the 1930s, a form of potentiation termed as post tetanic potentiation (PTP) was described. In this form, a brief high-frequency train of electrical stimulation formed the conditioning contraction (Guttman, Horton, & Wilber, 1937; D. D. O'Leary, Hope, & Sale, 1997). In 1976, Burke and colleagues (1976) used the term post activation potentiation (PAP); and it was first described in the literature as repetitive activation with natural volitional activation. Now PAP is commonly defined as the force and power improvements after completing a high intensity warm up (Blazevich & Babault, 2019), or as the acute improvements in muscle function after stimulus (Bevan et al., 2010). Current knowledge describes PAP as being induced by voluntary activation of the muscle after participation in maximal or submaximal intensities (Blazevich & Babault, 2019).

Post-activation performance enhancement (PAPE) has been a recently proposed term. Cuenca-Fernandez and colleagues (2017) suggest that this term be used when "high intensity *voluntary* conditioning contractions are performed with the intent of enhancing subsequent voluntary force production." Interestingly, PAP is traditionally used to describe the brief increases in twitch forces induced by muscle activity, whereas PAPE can be used to describe the longer lasting increases in voluntary force production (performance) elicited by muscle activity (Blazevich & Babault, 2019). As, PAPE is still a relatively recent term, and the literature currently has inconsistent use of terminology, for the purpose of this thesis we will use the term PAP to describe the improvement in performance elicited by a conditioning stimulus.

1.1 Physiological and neuromuscular mechanisms of PAP

Robbins (2005) described PAP as "a phenomenon by which the force exerted by a muscle is increased due to its previous contraction" (p.235). The mechanisms of PAP are yet to be fully determined; however, there are two key mechanisms that have been proposed to explain PAP (Jefferys, 2008). The first mechanism of PAP is associated with calcium ion handling. The sliding filament theory describes the activation of the myosin light chain kinase by calcium ions. Following the calcium-calmodulin interaction, myosin light chain kinase phosphorylates the myosin regulatory light chain to trigger the rotation of the myosin head away from the thick filament and towards the thin filament (Manning & Stull, 1979). The removal of calcium triggers separation of calmodulin, deactivation of myosin light chain kinase, and the dephosphorylation of the myosin regulatory light chain and completes a contraction cycle (Manning & Stull, 1979). An increase in calcium sensitivity of the acto-mysoin complex resulting from the potentiating stimulus is suggested to increase force output via the phosphorylation of the myosin regulatory light chain (Blazevich & Babault, 2019; Manning & Stull, 1979).

The second mechanism of PAP that has been proposed is the increased recruitment of higher order motor units (Tillin & Bishop, 2009) and enhanced neural excitability (Jefferys, 2008). The neural basis of PAP relates to the potentiated reflex response and enhanced reflex amplitudes relative to the prior stimulation (Lorenz, 2011). Research illustrates that induced tetanic isometric contractions accelerate specific afferent neural fibres and activate motoneurons which then elevates the transmission of excitation potentials across the synaptic junction at the spinal cord (Tillin & Bishop, 2009). In turn this results in an increase in post-synaptic potentials, and may explain the superior capacity to generate force following a potentiating stimulus (Lorenz, 2011).

1.2 PAP- Fatigue continuum

The relationship between the magnitude of the enhanced muscle performance and the associated fatigue following the conditioning stimulus ultimately determines the effectiveness of PAP. Hodgson and colleagues (2005) noted that PAP and fatigue co-exist, and the balance between potentiation and fatigue has been researched in several studies. Fatigue is experienced more dominantly in the early stages of recovery following an exercise stimulus which results in a decrease in performance after a stimulus (Tillin & Bishop, 2009). Of note, potentiation of performance via the mechanisms proposed above will occur later in recovery due to fatigue subsiding and the potentiating factors predominating (Hodgson et al., 2005; Tillin & Bishop, 2009).

This potentiation-fatigue continuum may help explain the lack of consensus regarding appropriate PAP stimuli, and there is limited research that assesses the time course of the competing effects of fatigue and potentiation. Differences in methodologies over several studies have caused a lack of agreement on what the optimal recovery time between the potentiating stimulus and performance. It has been reported that recovery time at which PAP is evident can range from 10-seconds to 20- minutes (Nibali, Chapman, Robergs, & Drinkwater, 2015). A review by Gouvêa and colleagues (2013) reported that rest intervals 0-3 minutes induced a detrimental effect on jump performance; 4-7 minutes and above 16 minutes elicited no changes in jump performance; and 8-12 minutes had a beneficial effect on jump performance. This meta-analysis emphasised that the window of 8-12 minutes after the conditioning stimulus is when the value of PAP generally outweighs fatigue, therefore improving performance.

Crewther and colleagues (2011) reported similar results to Gouvêa reported above. In their study of male rugby players, a reduction was observed in CMJ height after 15 s (-3.3 ± 1.5%, effect size = -0.29) following a heavy squat protocol as fatigue predominated. Improvements in CMJ height were seen at 4-minutes (3.8 ± 1.9%, effect size = 0.31), 8-minutes (3.5 ± 1.5%, effect size = 0.32), 12-minutes (3.0 ± 1.4%, effect size = 0.27), but decreases in jump performance occurred after 16-minutes (-2.9 ± 2.0%, effect size = -0.23) as the potentiating effect subsided. Turner and colleagues (2015) assessed the effects of using weighted plyometric bounding to elicit PAP, and showed that there was a reduction in sprint performance (-1.4 ± 2.5%) immediately post intervention in 23 trained males; however, at 4-minutes and 8-minutes post the conditioning stimulus, the 10-m and 20-m sprint velocity increased. Similar to above, after 12, and 16-min, the positive effects attributed to PAP had subsided, with no differences observed between the weighted plyometric group and a walking control. In contrast, in an example that utilised a 10 s isometric contraction as a potentiating stimulus, twitch characteristics of the knee extensors were potentiated to the greatest extent just 2 seconds after the contraction (Pääsuke et al., 2007). It was also noted by these authors that the magnitude and decline of the PAP was related to the training history of the participants, with a 51% enhancement in peak torque in *power-trained* athletes, 44% enhancement in *untrained* women, and only a 30% enhancement in *endurance-trained* women immediately after the isometric contraction.

It is therefore important to be aware of the effects of prior training, as well as individual differences in fatigue resistance on the outcomes and effectiveness of PAP. Thus, there are a range of physical and physiological characteristics that can affect the relative effectiveness of a conditioning stimulus and subsequent PAP. These include, but not limited to, the volume and intensity of the conditioning stimulus, training experience, fatigue resistance, and individual subject characteristics, including sex (Tillin & Bishop, 2009). Rixon and collaborators suggests that "women exhibit greater fatigue resistance due to lower twitch/tetanus ratio because pap offsets increase in fatigue, it may be seen that increased fatigue resistance may amplify PAP as an effect on power production" (p. 500). (D. D. O'Leary, Hope, & Sale, 1998; Rixon, Lamont, & Benmben, 2007)

Also of note is the range of potential conditioning stimuli and their biomechanical similarity to the performance measure. Note above that heavy back squats potentiated vertical jumping, weighted bounding potentiated horizontal sprinting, and isometric contractions can influence torque. Each of these stimuli likely have different fatigue profiles, and therefore different time courses for potentiation, in addition to individual differences in fatigue resistance and training status. Of note, a paper by Judge and colleagues (2016) that incorporated overweight implements into a warm-up of throwers, found that performance enhancement occurred despite significantly elevated *perceived* fatigue.

1.3 Training experience

As noted above, individual training experience can influence the effectiveness of inducing PAP (Hodgson et al., 2005). The relationship between fatigue, PAP, and training experience is an important consideration when prescribing a potentiating stimulus. Wilson and associates

(2013) reiterated that for PAP to be successful the increase in PAP needs to outweigh the increase in fatigue. As noted, training levels, strength, and fatigue resistances will all contribute to whether or not a given PAP will be effective (Chiu et al., 2003). Chiu and colleagues (2003) demonstrated that performance was enhanced in athletically trained individuals compared to recreationally trained individuals. The link between these factors was attributed to fatigue response, with individuals training at higher levels of resistance developing a more effective fatigue resistance.

Pääsuke and associates (2007) looked at PAP in a sample of 12 females split into three groups: power trained (PT); endurance trained (ET); untrained (UT). Ten-second isometric conditioning MVC were then applied as a conditioning stimulus to relaxed knee extensor muscles. The results showed that there was a small beneficial difference between power-trained athletes compared to endurance trained; however, there was no significant difference between the power-trained and untrained participants. Additionally, in a PAP study comparing resistance trained athletes to untrained athletes, they found a 5.1% greater increase in countermovement vertical jump after 4 minutes, and a 5.5% greater increase after 5 minutes, in the trained athletes following a 3 second functional isometric squat performed at 150% of 1RM (Berning et al., 2010).

1.4 Muscle fibre characteristics

The magnitude of PAP is influenced by the conditioning actions but also the characteristics of muscles, with fibre type being identified as being the most important characteristic (Hamada, Sale, MacDougall, & Tarnopolsky, 2000). Fast contracting muscles with a predominance of type II muscle fibres have been demonstrated to exhibit greater potentiation, implying that athletes that primarily use type II fast twitch muscle fibres such as strength and speed athletes may benefit more from PAP (G. Duthie, Young, & Aitken, 2002; Hamada et al., 2000). To this point, a study by Hamada et al., demonstrated that the four participants with the greatest magnitude of potentiation following an isometric conditioning stimulus, presented with a significantly higher percentage of type II fibres compared to a low response group. This work aligned with earlier work, suggesting that greater potentiation in type II muscle fibres is associated with greater phosphorylation of myosin regulatory light chains, and that the likely mechanism of potentiation is related to the phosphorylation of the myosin regulatory light chains (Moore & Stull, 1984). Of note, females are known to have smaller type I and type II muscle fibres compared to males (Edstrom & Nystrom, 1969).

1.5 Methods of post activation potentiation

As noted previously, a range of conditioning or potentiating stimuli have been utilised in an attempt to elicit PAP and improve performance. An exploratory review of post activation potentiation literature, conducted herein, identified three general themes for eliciting PAP:

1). high intensity, low volume heavy resistance exercise (HIGH)
e.g. 3 repetition maximum (3RM) repetitions;

2). whole body vibration applying a range of frequencies; and

3). other, including isometric and plyometric muscle actions, weighted implements, and blood flow restriction training.

1.5.1 High intensity, low volume heavy resistance exercise

Heavy resistance exercise, such as 3RM strength training is a common and reliable method for helping to improve strength, and neuromuscular qualities. A 3RM intensity requires participants to perform three repetitions at around 85% of their concentric 1 repetition maximal weight (1RM) for a specific movement such as bench press, or back squat. This type of exercise has been commonly employed to elicit PAP. Valerij Borzov, who won the men’s 100 m Olympics in 1972, reportedly lifted heavy weights immediately before his competitive races to enhance performance via what was then termed post-tetanic facilitation. The high levels of large motor unit recruitment required to lift loads close to 1RM, combined with the low volume of work, are suited to elicit PAP.

1.5.2 Whole body vibration

Whole body vibration (WBV) is a training modality that can be used to increase leg muscle force, power, and movement velocity (C. Bosco et al., 2000). Research suggests that WBV can evoke short-term and long-term neurogenic adaptations and potentially induce adaptations in mechanical behaviour of the skeletal muscles (C. Bosco et al., 2000; Ruiter, Van Raak, Schilperoort, Hollander, & De Haan, 2003). One proposed mechanism of WBV is enhanced neuromuscular activation via vibration reflexes (Bazett- Jones, Finch, & Dugan, 2008). Another proposed mechanism is the increase in muscle temperature and blood flow as well as an increase in hormone secretion due to vibration stimulus (Bazett- Jones et al., 2008). As a result, WBV has been demonstrated as an effective method to enhance explosive strength performance (Naclerio et al., 2014). These effects may also underlie the use of WBV as a tool to elicit PAP.

1.5.3 Other forms of eliciting post activation potentiation

Isometric muscle actions occur when the muscle-tendon unit remains at a constant length using either a pushing movement or a holding movement (Oranchuk, Storey, Nelson, & Cronin, 2018) The high force produced exceeds those achievable in concentric muscle actions (Aagaard, 2010). Isometric training is a method that is currently utilised in a variety of ways including rehabilitation, to improve performance, and as a tool to aid injury prevention (McNeill, Beaven, McMaster, & Gill, 2019)). Oranchuck and colleagues (2018), reported that isometric training has the potential to elicit changes in physiological qualities including but not limited to muscle architecture, strength, and tendon stiffness. A review specific to team sport athletes identified that eccentric training should be considered as an effective training strategy to improve measures of strength, speed, power and change of direction (McNeill et al., 2019)). As high forces involved in eccentric loading, and thus high levels of muscle recruitment, are purported to be requisite for eliciting PAP, eccentric muscle actions have been investigated as a conditioning stimulus.

Plyometric training can be used to improve muscular power and rate of force development (RFD), stimulating improvements in dynamic athletic performance (Lorenz, 2011). This method of training has been designed as a way to train for specific movements and is primarily related to the eccentric and concentric sequence of muscle activity (Enoka, 1994). Plyometrics is designed to take advantage of the loading and stretching of muscle fibres leading to the reflex contraction of muscle fibres (Bompa, 1993; Cross, 1997) and allows athletes to generate and utilise kinetic energy within the muscles (Adams, O'Shea, O'Shea, & Climstein, 1992). Given the reliance on large fast twitch type II motor units to produce force rapidly, it is perhaps not surprising that plyometric and ballistic exercises have been utilised as a conditioning stimulus to elicit PAP.

1.6 Search strategy: High Intensity conditioning stimulus

A search was conducted via PubMed and Google scholar using the key words, "PAP", "potentiation", "lower body", "jump", "sprint", "trained", and "athlete" and then made more specific using above key words and one of these methods "RM", "heavy resistance", "vibration", "isometric", "ballistic", and "plyometric". Abstracts were read and assessed using a criterion to ensure the relevant studies were presented in this literature review. The criterion set *a priori* were: studies that investigated: trained athletes utilising a heavy weight, low volume, (HIGH) conditioning activity as a method of potentiation (e.g. 3RM-5RM); whole-body vibration (WBV); isometric (MVC) or plyometric training; included a vertical jump test and/or a maximal sprint test within 20 minutes of the conditioning stimulus; and directly related to lower-body expressions of power. Only articles published in the English language were retrieved.

1.7 Search results: High Intensity conditioning stimulus

The initial search identified 6,370 articles that met the initial search criteria. After the duplicate references were removed, and the initial abstract screening, seventeen studies were identified and analysed as part of this literature review for heavy resistance 3RM training; thirteen for whole-body vibration training, and thirteen studies were included for other methods of PAP including isometric, plyometric training and blood flow restriction. The search highlighted that the majority (17 out of 42, or 41%) of studies utilised high intensity, low volume heavy resistance exercise (HIGH) as a conditioning stimulus to produce an acute lower body performance enhancement. These 17 identified studies are presented in Table 1, below.

Table 1: Review of the literature using 3RM as a method post activation potentiation

Author	Year	Sex	Training Status	Conditioning Stimulus	Variables Measured	Time	Results
(Ah Sue, Adams, & DeBeliso)	2016	9 F	T – Collegiate	5RM Squat	Standing long jumps	2, 6, 10, 14, 18 min	SJL after PAP was greater at 2, 6, & 10 min
(Arias, Coburn, Brown, & Galpin)	2016	15 M	UT	5 x deadlifts @85% 1RM	Maximal vertical jump; countermovement jump	15 s, 2, 4, 6, 8, 10, 12, 14, 16 min	VJ height: ↓ 15 s after DL. Results suggest that 5 reps of DL did not induce PAP.
(Bevan et al.)	2010	16 M	T - Professional	3x Squat @ 91%	10-m sprint	4, 8, 12, 16 min	For 5-m sprints 47% of participants performed best 8 min post intervention; 27% after 12 min and 13% at 4 min and 16 min compared to baseline. 10 m similar to 5 m results.
(L. Carbone et al.)	2020	17 M	T - Amateur	3RM of Hip thrusts or 3RM of Back squat	10-m sprint	8 min	↔ in 5 m or 10 m sprint times after both PAPE conditions with no difference between HT or BS.
(Chatzopoulos et al.)	2007	15 M	T - Amateur	10 single reps at 90% of 1RM	30-m sprint (0-10 m and 0-30 m) x 3	3, 5 min	↑ running phases 5 min after HRS. Emphasising that HRS can ↑ 10-m and 30-m sprints
(Crewther et al.)	2011	9 M	T - Sub elite	3RM Squat	CMJ; 5-10 m sprints; 3 m horizontal sled pushes	15 s, 4, 8, 12, 16 min	↓in CMJ height @ 15 s and 16 min. ↑in CMJ height @ 4, 8. and 12 min post stimulus. No effect for 3 m sled push and 5-10 m sprint.
(Comyns, Harrison, & Hennessey)	2010	11 M	T - Rugby union players	3RM Squat	10-, 20-, 30-m sprints	4 min	No effect

(Evetovich, Conley, & McCawley)	2015	12 M, 8 F	T - Collegiate	3RM Squat	Vertical jumps and standing long jumps	8 min	↑ VJP and HJP Men and women responded similarly
(Kilduff et al.)	2008	20 M	T - Professional	3RM Squat	CMJ	15 s, 4, 8, 12, 16, 20, 24 min	↓ CMJ power 15 s. ↑ CMJ power 8 min. ↓ in RFD 15 s. ↑ RFD 8 min ↓ Jump height 15 s ↑ Jump height 8 min
(Kilduff et al.)	2007	23 M	T - Professional	3RM Squat	CMJ	15 s, 4, 8, 12, 16, 20 min	↓ CMJ power 15 s ↑ CMJ power 8 & 12 min No effect 4, 16, or 20
(Kobal et al.)	2019	18 M	T – Collegiate	First set: 5 x 3RM @ 50%, 10 x 5RM @ 50% Second set – 3 x 1 & 3RM @ 70%, reps, 5 x 5RM @ 70% Third set: 5 attempts to obtain 1, 3 and 5RM loads in HS exercise	CMJ	3 min	↓ in CMJ 1RM, 3RM, 5RM, & 1RM @60%. Control condition: ↑ in CMJ in 2 people 1RM condition: ↑ in CMJ observed in 6 people. 3RM condition: ↑ in CMJ in 5 people. 5RM condition: ↑ in CMJ in 5 people. 60% 1RM condition: ↑ in CMJ in 4 people.
(Lowery et al.)	2012	13 M	T - Resistance	Squat @56%, 70% and 93% of 1RM	Vertical jumps	Immediately, 2, 4, 8, 12 min	MD (70%): VJ height ↑ at 4 min returned to baseline at 8 min. HI (93%): VJ height ↑ from 4 - 8 min returned to baseline by 12 min. No effects found for low intensity condition.

(Mola, Bruce-Low, & Burnet)	2014	22 M (2 groups PAP and CON)	T - Professional	3RM Squat	CMJ	15 s, 4, 8, 12, 16, 20 min	↔ time effect. ↓ in CMJ peak power immediately post ↔ in peak power for baseline compared to 4 min. ↓ in peak power at 8 min and 12 min.
(Rouissi et al.)	2018	20 M	T - Elite	1, 2 or 3 half squats at 90% 1RM	10 m, 20 m, 30 m	PAP1 (1 x 90% 1RM), PAP2 (2 x 90% 1RM) PAP3 (3 x 90% 1RM)	↑ in RSA at PAP1 and PAP2. ↔ effect at PAP3 or controlled. ↑ in overall (0-30 m) performance and initial acceleration (0-10 m).
(Scott, Ditroilo, & Marshall)	2017	20 M	10 x T (pro); 10 x amateur	3x HBD or BS	CMJ	Pre, 2, 4, 6, 8, 10, 12, 14, 16 min	HBD improved PPO @ 2, 4, and 6 min. ↔ following BS. HBD had greater ↑ than BS at 2, 6, 10, 12, 14 and 16 min. Control group showed significant ↓ in PPO at 16 min.
(L. P. Seitz, De Villarreal, & Haff)	2014	18 M	T- Elite junior	3RM squats @ 90% 1RM	Single unloaded squats	15 s, 3, 6, 9, 12 min	↓ in SJ PPO 15 s post stimulus. ↑ in SJ PPO 3, 6, 9 12 min post for the strong group. ↑ in SJ PPO 6, 9, 12 min post for the weak group.
(Sygulla)	2014	29 F	T- Collegiate	3RM Squat	Static squat jumps	3, 5 min	↓ in power from pre to post test in the volleyball players. PAP protocol 3 reps @ 90%1RM with 5-minute rest did not potentiate jump height in the female players. No mention of the menstrual cycle.

Note: F, Female. M, Male. T, Trained. UT, Untrained. 1RM, 1 repetition maximum. 5RM, five repetition maximum. 3RM, three repetition maximum. HS, Half squats. BS, Back squats. HR, Heavy resistance. HBD, Hex bar deadlift. CMJ, Countermovement jump. SJ, Squat jump. PAP, Post activation potentiation. SLJ, Standing Long Jump. VJP, Vertical jump. RSA, Repeated sprint times. HJP, Horizontal jump. PAPE, Post activation performance enhancement. HT, Hip thrusts. SSJ, Static squat jumps. PPO, Peak power output. BBP, Ballistic bench press. ↔ no significant change. ↑, Improvement/increase. ↓, Decrease.

1.8 Table 1. Discussion

Sex

The summation of the data presented in Table 1 show that there was a total of 295 participants. Of these participants, 84% were males-only cohorts; 13%, were female-only cohorts and 3% were a mixed cohort with females combined with males. The 13% of female- only cohorts (38 participants) were split across (Ah Sue et al., 2016; Sygulla, 2014).

Training Status

Of the 17 studies, 16 studies (94.1%) included trained participants (Ah Sue et al., 2016; Bevan et al., 2010; L. Carbone et al., 2020; Chatzopoulos et al., 2007; Comyns et al., 2010; Crewther et al., 2011; Evetovich et al., 2015; Kilduff et al., 2007; Kilduff et al., 2008; Kobal et al., 2019; Lowery et al., 2012; Mola et al., 2014; Rouissi et al., 2018; D. J. Scott et al., 2017; L. P. Seitz et al., 2014; Sygulla, 2014). One study (5.9%) included untrained participants (Arias et al., 2016) this study showed that vertical jump height decreased after the conditioning stimulus. Indicating that a 5RM deadlift protocol is ineffective for inducing potentiation in untrained participants. Thus, it appears that the use of HIGH as a conditioning stimulus to produce an acute lower body performance enhancement is typically reserved for trained participants.

Conditioning Stimulus

The same 16 studies that included trained participants used 3RM-5RM back squats as a preload stimulus, and Arias and colleagues (2016) used 3RM deadlifts as a preload stimulus. Of the 17 studies, 76% showed that 3RM is an effective potentiation tool and showed improvements in the identified lower-body performance measures. The remaining 23% of studies that indicated no improvement in performance which could be related to a variety of variables including, female-only population, untrained participants, and using vertical stimulus to try and improve horizontal performance.

Variables Measured

- Nine of the 17 studies (53%) measured vertical jump performance. Seventy percent showed success following a HIGH conditioning stimulus and 30% (Arias et al., 2016; Mola et al., 2014; Sygulla, 2014) showed no improvements in vertical jumps following a 3RM-5RM conditioning stimulus.
- Five of the 17 studies (29%) measured 5 - 30 m sprints using 3RM (85-91%) back squats as a preload stimulus. Three studies measured sprint performance at different time points or intensities. Bevan and colleagues measured 10 m sprint performance at 4, 8, 12, and 16 min. Chatzopoulos and colleagues measured 30 m sprint performance at 3 and 5 min and Rouissi and colleagues measured 10, 20 and 30 m sprints at different PAP levels (1 x 90% 1RM; 2 x 90% 1RM and 3 x 90%1RM) (Bevan et al., 2010; Chatzopoulos et al., 2007; Rouissi et al., 2018). All of these studies showed improvements in sprint performance at different time points and or different intensities.
- One study (6%) (Crewther et al., 2011) investigated the effects of using 3RM back squat stimulus for improving CMJ, 5-10 m sprints and 3 m sled pushes, and found improvements in CMJ but not in sprint performance or 3 m sled pushes.
- One study (6%) (Ah Sue et al., 2016) measured standing long jump (SLJ) following a 5RM back squat preload stimulus and found SLJ improved following the potentiation condition.
- One study (6%) (L. P. Seitz et al., 2014) measured unloaded squat performance following a 3RM back squat at 90% preload stimulus and found improvements in performance at different time points in both the strong and weak participants.
- Overall, of the studies that reported using a *vertical* 3RM-5RM stimulus to improve vertical jump performance, 70% were successful. Of the studies that reported using a vertical stimulus to improve horizontal performance, 60% were successful. One study

reported using vertical 3RM stimulus to improve vertical and horizontal performance and found improvements in vertical performance but not horizontal, and one study measured vertical 3RM performance on unloaded squat performance.

Time

Six studies (35.3%) (Arias et al., 2016; Crewther et al., 2011; Kilduff et al., 2007; Kilduff et al., 2008; Mola et al., 2014; L. P. Seitz et al., 2014) reported a decrease in performance immediately post (15 s) post PAP protocol. Individual variability was noted by some authors including Kobal et al. (2019) who compared the effects of performing half squats under four different experimental conditions, with distinct numbers of repetitions and loading intensities (1RM, 3RM, 5RM, and 60% 1RM) on vertical jump ability in eighteen trained males. A key finding of this study highlighted worthwhile changes in individual performance emphasising that the use of PAP is subject dependent. Mola et al. (2014), investigated optimal recovery time following a 3RM conditioning stimulus in eleven trained males (intervention group), and their results showed that some participants responded to the stimulus, and some didn't, emphasising that PAP is individualised and complex.

The three most common time points where success occurred was 4 min, 8 min and 12 min post conditioning stimulus.

- Four studies (Bevan et al., 2010; Crewther et al., 2011; Lowery et al., 2012; D. J. Scott et al., 2017) showed performance improvements 4-min post conditioning stimulus.
- Six studies (Bevan et al., 2010; Crewther et al., 2011; Evetovich et al., 2015; Kilduff et al., 2007; Kilduff et al., 2008; Lowery et al., 2012) showed performance improvements 8-min post conditioning stimulus.

- Four studies (Bevan et al., 2010; Crewther et al., 2011; Kilduff et al., 2007; L. P. Seitz et al., 2014) showed performance improvements 12-min post conditioning stimulus.

1.9 Table. 1 Summary

Percentage effective (with number of participants)

76% of the studies in the table above showed HIGH resistance training to be effective in inducing PAP. There was a total of 295 participants of those participants, HIGH resistance training (3RM-5RM) training was effective in 223 participants.

Percentage not effective (with number of participants)

26% of studies in the table showed that HIGH resistance training was ineffective in inducing PAP. Out of the 295 participants, HIGH resistance training was ineffective in 72 participants.

Potential reasons for not being effective

One study that was ineffective was in untrained participants and used deadlifts in an attempt to improve vertical jump performance. Two studies used back squats (vertical stimulus) to try and improve 10-m sprint (horizontal performance). The final study that failed to demonstrate improved performance was in female participants

Percentage of studies in females/males (with number of participants)

Out of the 17 studies included, 82% included male participants, a total of 245; 12% included female participants, a total of 38; and 6% included a combination of male and female participants, 12 males and 8 females.

Percentage of studies where PAP effective in females (with number of participants)

Out of the two studies that investigated whether PAP was effective in females, only one was ineffective for inducing PAP. Of the 38 participants identified, PAP was ineffective in 29 (76%) of them.

Menstrual phase data

None of the studies that exclusively investigated females reported on any menstrual phase data. Also, there was no mention of menstrual phase data in the study that combined male and females.

Interesting take aways

Overall, there was no clear indication that a horizontal stimulus would not improve vertical performance or vice versa. There was also no clear indication that using a vertical stimulus would only improve vertical performance and vice versa with horizontal performance. The literature also showed that HIGH resistance is an effective tool for eliciting PAP and improving lower-body sprint and jump performance most commonly at 4, 8, and 12-minute time points. Only one study (Ah Sue et al., 2016), demonstrated a positive effect in females following a high resistance 5RM back squat conditioning stimulus. An overall potential weakness that has been identified is the lack of data reported on the menstrual phase.

1.10 Search results: Vibration as a conditioning stimulus

As part of this literature review the search highlighted that (13 out of 42, or 33%) of studies utilised whole body vibration as a conditioning stimulus to produce an acute lower body performance enhancement. These 13 identified studies are presented in Table 2 below.

Table 2: Review of literature using whole body vibration as a method of post activation potentiation

Author	Year	Sex	Training Status	Conditioning Stimulus	Variables Measured	Time	Results
(Armstrong, Grinnell, & Warren)	2010	90 total: 30 M & 60 F	UT	CONT, 30, 35, 40, 50 Hz high and low amplitude for 1 min	CMJ	Before, 1, 5 min for 30 min	↑ in CMJ at all time points ↑ were significant at 5 and 10 min post. ↔ at the other time points.
(Bazett- Jones et al.)	2008	40 M 18 F	UT	5 different vibration sessions 1: 0 Hz 2: 30 Hz 3: 40 Hz 4: 35 Hz 5: 50 Hz	CMJ	Immediately, 5, 10 min	↑ CMJ performance in short WBV. Results were not seen in men. Woman: ↑ of 9% and 8.3% No mention of menstrual cycle
(Bullock et al.)	2008	7 total: 1 M & 6 F	T - Olympians, 1 world cup	30Hz (3 x 60 s)	CMJ; 30-m sprints	5 min	CONT condition: Second 30-m sprint was slower. ↓ 5-10 m after CONT compared to WBV. ↑ Mean velocity after WBV ↔ were found for peak velocity, height, or peak acceleration in the SQJ. ↔ were found in all parameters measured for the CMJs
(Z. R. Chen, Lo, Wang, Yu, & Peng)	2017	10 M	T- Collegiate	30 Hz (3 x 10 s)	Vertical Jump	Pre and post	↑ in all the results when comparing post-test to pre-test. Individual changes were found for VJ performance. CT and VCT failed to ↑ individual PAP for every athlete. Failed to ↑ VJ performance.
(Dabbs, Munoz, Tran, Brown, & Bottaro)	2011	30 people; 15 M, 15 F	T - Recreational	6 WBV conditions: One control condition WBV entailed 4 bouts of 30 s (2 min vibration) Squat protocol (quarter squats every 5 s while stimulating arm swing)	CMJ	Immediately, 30 s, 1, 2, 4 min	↔ interaction of sex by condition. Greater values for men compared to women. ↑ VJ height at different individual rest intervals, ↔ in PV or rGRF.

(Guggenheimer, Dickin, Reyes, & Dolny)	2009	14 M in WBV group; 9 M in PC group	T- Collegiate	WBV: (0, 30, 40, 50 Hz). 5 s of high knees @ each WBV level PC: Consisted of 2 separate sessions 3 x PC @ 90%1RM	WBV: 10, 20, & 40 m sprint. PC: 5, 10 & 40 m sprints	Different frequencies	WBV: ↔ between first and second sprints 10, 20 & 40 m for all frequencies. PC: ↔ between control & treatment for any of the recordings @ 5, 10 & 40 m
(Kavanaugh et al.)	2014	21 M	T – Collegiate	WBV: 30 s 50Hz	15, 30, 45 m sprint		↔ between conditions. ↔ interaction effect found for sprint distance by treatment. WBV: ↔ on sprint times for the 30 m fly or at 15, 30, and 45 m
(Lamont et al.)	2010	21 M	T – Recreational	4 vibration conditions: Frequency either 30 or 50 Hz	CMJ	Pre, 2 min – 17 min with 1 min between jumps.	↔ difference between condition x height. Higher WBV suggests greater PAP. 50 Hz showed 2% ↑ in CMJ height. ↓ in higher condition
(Miller et al.)	2018	20 M	T- Recreational	1) CONT 2) WBV and WBV + BFR, 3) MVC and MVC + BFR (160 mmHg).	CMJ	Pre, 10, 30 min.	↔ time x condition interaction for jump power. ↑ differences between PRE and POST values for 3 conditions ↑ jump height
(Naclerio et al.)	2014	15 M (8 American Football, 7 Baseball)	T- Collegiate	3 different conditions: 1) Parallel squats @80% 1RM 2) PS @ 80% 1RM with WBV 3) CONT Each condition was performed using low volume (LV) and high volume (HV) protocols.	CMJ and Best drop jump	Short: 1 min Long: 4 min	4 min recovery was adequate for CMJ or BDJ performance after NV-PS and WBV-PS with both LV and HV
(Rønnestad & Ellefsen)	2011	9 M	T - Amateur soccer	6 Separate test sessions: 30 s of half squats @ WBV50, WBV30 or No WBV	40 m Sprints	Pre and post	↑ 40 m sprint @ WBV50 compared to no WBV. ↔ in 40 m sprint time @ WBV30 compared to no WBV

(A. P. Turner, Sanderson, & Attwood)	2011	12M	T - Recreational	Four randomised testing vibrations 1) 30 Hz 2) 35 Hz 3) 40 Hz 4) 0 Hz (CONT). 30 s of WBV in a half squat position.	CMJ	Pre and post	↔ main effect for vibration frequencies. ↔ 40 Hz from pre to post. ↑ in CMJ performance.
(Washif)	2019	12 total: 8 Ms & 4 Fs	T - Sprinters	WBV: 2 x 30 s 40 Hz. 10 x squats 10 x calf raises	Drop Jump	15 s	Competitive athletes: Did better during WBV compared to CONT. Elite athletes responded poorer during WBV compared to CONT.

Note: M, Male. F, Female. UT, Untrained. T, Trained. CONT, Control. WBV, Whole body vibration. 1RM, one repetition maximum. 5RM, five repetition maximum. BFR, Blood flow restriction. MVC, Maximum voluntary contraction. PS, Parallel squats. LV, Low volume. HV, High volume. L, Low. H, High. CMJ, Countermovement jump. PC, Power cleans. SQJ Squat jump. CT, Complex training. VCT, Complex vibration. PAP, Post activation potentiation. RE, Resistance exercises. NV – PS, No volume parallel squat. PE, Plyometric exercises. BDJ, Best drop jump. ↔. No significant difference/change. ↑, Improvement/increase. ↓, Decrease.

1.11 Table 2. Discussion

Sex

There was a total of 328 participants 69% were male-only cohorts and 31% were females however none of the studies researched females exclusively. Of the 31% of female participants only one study (14.9%) reported on female data separately, the remaining five studies (86.1%) of the female data collected was combined with male data for analysis.

Training Status

Of the 13 studies, 11 studies (84.6%) included trained participants (Bullock et al., 2008; Z. R. Chen et al., 2017; Dabbs et al., 2011; Guggenheimer et al., 2009; Kavanaugh et al., 2014; Lamont et al., 2010; Miller et al., 2018; Naclerio et al., 2014; Rønnestad & Ellefsen, 2011; A. P. Turner et al., 2011; Washif, 2019). Of the 11 studies that included trained participants, two studies that represented 13% of the total participants, failed to improve performance following WBV stimulus. Two studies (15.4%) included untrained participants. Of the total number of participants in the untrained studies 73% were successful for improving performance following a WBV stimulus. (Armstrong et al., 2010; Bazett- Jones et al., 2008).

Conditioning Stimulus

Eleven studies (84.6%) only used WBV as a preload stimulus, two studies (15.4%) looked at WBV against other different methods including BFR, MVC, resistance exercises, plyometric exercises, and complex training as well as some of these methods combined with WBV.

There were four common vibration pressures; (0, 30, 35, 40, and 50 Hz) and amplitude ranged between 2 to 6 mm.

- Six studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; Guggenheimer et al., 2009; Kavanaugh et al., 2014; Rønnestad & Ellefsen, 2011; A. P. Turner et al., 2011) all used control (0hz) as a WBV stimulus.

- Eight studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; Bullock et al., 2008; Z. R. Chen et al., 2017; Guggenheimer et al., 2009; Lamont et al., 2010; Rønnestad & Ellefsen, 2011; A. P. Turner et al., 2011) used 30 Hz as a WBV stimulus.
- Three studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; A. P. Turner et al., 2011) used 35 Hz as a WBV stimulus.
- Three studies (Guggenheimer et al., 2009; A. P. Turner et al., 2011; Washif, 2019) used 40 Hz as a WBV stimulus.
- Six studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; Guggenheimer et al., 2009; Kavanaugh et al., 2014; Lamont et al., 2010; Rønnestad & Ellefsen, 2011) used 50 Hz as a WBV stimulus.
- Overall, vibrations of 30 and 50 Hz were shown to have the most success in eliciting PAP and improving specific performance measures.

Variables Measured

- Nine of the thirteen (69%) studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; Z. R. Chen et al., 2017; Dabbs et al., 2011; Lamont et al., 2010; Miller et al., 2018; Naclerio et al., 2014; A. P. Turner et al., 2011; Washif, 2019) measured the effects WBV had on vertical jumps. All the studies reported improvements in vertical jumps (CMJ, drop jumps) following different WBV stimuli.
- Three of the thirteen (23%) studies (Guggenheimer et al., 2009; Kavanaugh et al., 2014; Rønnestad & Ellefsen, 2011) measured the effects WBV had on sprints ranging from (5 to45 m). Two of the three studies (67%) showed no improvement in sprint performance and one study (27%) showed improvements following WBV50.
- One study (Bullock et al., 2008) measured the effects of WBV on both vertical (CMJ) and horizontal performance (30 m sprint). Results showed that 5-10 m splits were faster

in the WBV condition compared to the CON condition and there were no improvements in CMJs reported.

- Overall, of the studies that reported using a vertical stimulus to improve vertical performance 69% were successful. Of the studies that reported using a vertical (WBV) stimulus to improve horizontal performance 33% were successful. Interestingly, the one study that measured both vertical and horizontal performance, showed success improving horizontal performance but not vertical performance following a vertical (WBV) stimulus.

Time

Two studies (15.4%) (Dabbs et al., 2011; Washif, 2019) took measures immediately (15 s) post WBV stimulus. Three studies (23.1%) (Armstrong et al., 2010; Bazett- Jones et al., 2008; Bullock et al., 2008) took measures 5 min post WBV stimulus. Three (23.1%) studies (Armstrong et al., 2010; Bazett- Jones et al., 2008; Miller et al., 2018) took measures 10 min post WBV stimulus. Five (38.5%) studies (Armstrong et al., 2010; Z. R. Chen, Wang, Peng, Yu, & Wang, 2013; Miller et al., 2018; Rønnestad & Ellefsen, 2011; A. P. Turner et al., 2011) took measures either pre intervetion, post intervention, or both. The remaining studies (Kavanaugh et al., 2014) and (Naclerio et al., 2014) took measures at 1-minute periods but Naclerio also took measures at 4-minutes . Guggenheimer and colleagues (2019), compared the different frequences rather than time. Post measures were generally seen as having improved performance compared to pre measures, and the time period between 4 and 10 min was suggested to be best for performance.

1.12 Table. 2 Summary

Percentage effective (with number of participants)

86% of the studies in the table above showed WBV training to be effective in inducing PAP. There was a total of 328 participants, and of those participants, WBV training was effective for 284 participants.

Percentage not effective (with number of participants)

14% of studies in the table showed that WBV training was ineffective in inducing PAP. Out of the 328 participants, WBV was ineffective in 44 participants.

Potential reasons for not being effective

Both studies that were ineffective used different vibration frequencies and attempted to improve horizontal sprint performance in trained collegiate males.

Percentage of studies in females/males (with number of participants)

Out of the 14 studies, 64% included male participants (a total of 131 participants), and 36% included a combination of male and female participants: 94 males (48%) and 103 females (52%).

Percentage of studies where PAP effective in females (with number of participants)

Out of the five studies that used female participants within their study, 85% showed that WBV was effective for improving performance and inducing PAP. Of the 103 total female participants, it was shown to be effective in 88 participants. Interestingly, only one study explicitly mentioned how females differed to males.

Comment on menstrual phases data

There was no mention of menstrual cycle in any of the studies that included female participants.

Interesting take aways

Overall, the literature showed 85% of the studies showed an improvement in performance following WBV exposure and 15% of the literature identified found that WBV was ineffective for eliciting a PAP response. When broken down into training status and gender the literature showed that WBV was effective in improving performance in 48% of trained males; 30% trained female athletes; 28% in untrained males and 72% of untrained females. Interestingly, in the study by Bazett-Jones and colleagues (2008), the results showed that short WBV improved CMJ performance in untrained female participants; however not in untrained male participants. An overall potential weakness of the literature reporting on WBV as a potentiating stimulus is again, the failure to report on menstrual phase data.

1.13 Search results: Other conditioning stimuli

As part of this literature review the search highlighted that (12 out of 42, or 33%) of studies utilised other methods of PAP including isometric training, plyometric training, and blood flow restriction as a conditioning stimulus to produce an acute lower body performance enhancement. These 12 identified studies are presented in Table 3, below.

Table 3: Review of literature involving other methods of PAP

Author	Year	Sex	Training Status	Conditioning Stimulus	Variables Measured	Time	Results
(Berning et al.)	2010	21 M	13 T; 8 UT	3-second FI squat with 150% 1RM.	CMJ	4 min	↔ in CMJ in the untrained group. ↑ in CMJ heights 4 min after FI
(Beato et al.)	2019	10 M	T- Amateur	EOL half squat vs TW half squat.	Standing long jump; CMJ; 5m sprint	1, 3, 7 min	↔ between conditions for CMJ, SLJ, 5 m. ↑ SLJ and CMJ following EOL at 3 and 7 min ↑ SLJ and CMJ following TW at CMJ 3 and 7 min
(Bogdanis, Tsoukos, Veligekas, & Terzis)	2014	14 M	T - Track and field	Four conditions: Isometric (ISO) eccentric (ECC); conditioning load (CON) load was set at 90% 1RM; control (CTRL) half squats	CMJ	Every 2-3 min for 21 min	↑ in number of reps in ECC ↓ in average force in ECC compared to CON and ISO. ↑ in CMJ performance in ISO than CTRL from 2 -10 min. ↓ in CMJ performance 10 min post for all conditions. ISO was more effective than ECC and CON for inducing PAP.
(Boyd, Donald, & Balshaw)	2014	10 M	T - Strength	FI or DYN half squats loaded with 150% of full back squats 1RM	Kinematic and Kinetic CMJs	2 min, 11 min	↑ in peak force and ↓ in peak power occurred after squat protocols combined condition CMJ data. ↔ in percentage change were detected for peak displacement, velocity, force, or power. FI did not produce acute CMJ responses.
(Doma, Leicht, Boullosa, & Woods)	2020	18 M	T – Anaerobically	3 x 8 reps of lunges 130% of individuals' systolic blood pressure.	Drop Jump	Baseline, 3, 6, 9, 12, 15 min	BFR ↑ in FT, MJH, and power @DJ-15. Power ↑ @ DJ-6, DJ-9 & DJ-15 vs DJ-base. BFR showed a greater effect size for VJH, FT, MJH and power @ DJ-6, DJ-9, DJ-15. RPE, Lactate heart rate, all ↑ during BFR.
(Golas, Maszczyk, Zajac, Mikolajec, & Stastny)	2016	31 M	T - 3 disciplines (Basketball, Athletic throws,	Basketball players: 4 x 4 Keiser squats @ 80% 1RM 90 s rest. Athletic throws: IRT test: 3 x 8 @75% 1RM.	CMJ	2, 4, 6, 8 min	↑ power performance for all three sport disciplines at 6 min.

			Luge athletes)	Luge athlete: 3 x 4 dumbbell row at 80% 1RM IRT post-conditioning (2 Latissimus pull down repetitions on Keiser Power Rack at 50% 1RM).			
(Lim & Kong)	2013	12 M	T - Track athletes	4 protocols: Control Isometric MVC knee extension - 3 x 3 s maximal bilateral knee extension. Isometric MVC back squats - 3 x 3 s, Dynamic squats - 1RM back squats, 3 reps @ 90% 1RM	10 m, 20 m, 30m sprints	Not relevant	↔ difference in sprint performance between CON, ISO knee extension, ISO squat and DYN squat.
(Pojskic et al.)	2015	21 M	T - Collegiate	4 conditions: 1) No conditioning contraction (NCC). 2) DS: 7 exercises x 7mins 3) FI: 5 x per minute 4) ST with external 30% BW load. .	CMJ; 20 m sprint, T agility test	2, 3.5, 5 min	↑ in CMJ after DS and ST ↑ in speed in DS Agility test showed that time in NCC was higher than DS and ST +30% BW.
(A. Turner et al.)	2015	23 M	T- Plyometric	3 conditions: Control- Walking ©. P - 3 x 10 plyometric bounds. WP - 3 x 10 plyometric bounds with 10% body mass	10 + 20 m sprint	15s, 4, 8, 12, 16 min	↑ 10m sprint velocities during P at 4 min and WP at 8 min. WP at 8 min sprint velocity was greater than P and C. ↔ between P and C, ↑ in 20 m sprint velocities during P @ 4 min. ↑ in 20 m sprint velocity 4 min and 8 min post WP ↑ 4 min and 8 min post WP.
(Till & Cooke)	2009	12 M	T - Soccer players	1) control: No PAP treatment. 2) Weight exercise (DL): 5 x 5RM 3) Plyometric exercise: 5 x double legged tuck jumps 4) Isometric MVCs: MVC 3 x 3 s	20 m sprints, CMJ	4, 5, 6, 7, 8, 9 min	10 m and 20 m sprint performance changes occurred at 4, 5, 6 min and VJ at 7, 8, 9 min. ↑ sprint and jump after DL and tuck jumps ↔ between PAP conditions ↑ VJ performance at 7 min post deadlift Average sprint and VJ performance ↑ after deadlift for all 3 tests

(Tsolakis, Bogdanis, Nikolaou, & Zacharogiannis)	2011	13 M, 10 F	T - International fencers	3 x 5 Isometric push ups 3 x 5 Isometric double legged tuck jumps.	CMJ; Ballistic Bench throws	15 s, 4, 8, 12 min	Men performed better than women. ↓ in peak leg power output over time. ↓ time x type interaction for peak leg power after 8, 12 min in men after iso protocol. ↑ in bench press throw test. ↓ peak leg power output.
(Vargas- Molina et al.)	2021	18 M	T	1) ISOMS: 2 x 4 s of submaximal (75% of 1RM) 2) ISOTS: 2 x 3 reps at 75% 1RM.	CMJ	Baseline, 4 min post	↑ in CMJ height after set one in both protocols. ↔ after set 2. ↔ differences were found between the isometric and isotonic conditions

Note: M, Male. F, Female. T, Trained. UT, Untrained. FI, Functional isometric. 1RM, One Repetition Maximum. EOL, Eccentric overload. TW, Traditional weightlifting. ISO, Isometric. ECC, Eccentric. CON, Conditioning actions. CTRL, Control. DYN, Dynamic.IRT, Individualised recovery time. NCC, No conditioning contraction. DS, Dynamic stretching. ST, Isometric static squat. BW, Body weight. P, Preload stimulus. WP, Weighted preload stimulus. PAP, Post activation potentiation. 5RM, 5 Repetition Maximum. ISOMS, Isometric squat. ISOTS, Isotonic squats. UP, Upper body. LB, Lower body. CMJ, Countermovement jump. SJL, Standing long jump. CS, Cluster sets. Plyo, Plyometric. VJ, Vertical jump. ↔, No change/ No significant difference. ↓, Decrease. ↑, Increase/Improve.

1.14 Table 3. Discussion

Sex

There was a total of 213 participants. 95% of which were male-only cohorts and 5% were a mixed cohort with females combined with male.

Training status

Eleven of the twelve studies (91.7%) included trained participants (Beato et al., 2019; Bogdanis et al., 2014; Boyd et al., 2014; Doma et al., 2020; Golas et al., 2016; Lim & Kong, 2013; Pojskic et al., 2015; Till & Cooke, 2009; Tsolakis et al., 2011; A. Turner et al., 2015; Vargas-Molina et al., 2021); whereas the last study included trained participants but also included some untrained participants as a comparison (Berning et al., 2010).

Conditioning stimulus

- Nine studies (75%) (Berning et al., 2010; Bogdanis et al., 2014; Boyd et al., 2014; Golas et al., 2016; Lim & Kong, 2013; Pojskic et al., 2015; Till & Cooke, 2009; Tsolakis et al., 2011; Vargas- Molina et al., 2021) used isometric (FI or MVC) training as a conditioning stimulus. Four of the nine (44%) studies that investigated isometric training also included dynamic training as a conditioning stimulus (Berning et al., 2010; Boyd et al., 2014; Lim & Kong, 2013; Pojskic et al., 2015).
- Two (17%) studies (Beato et al., 2019; Bogdanis et al., 2014) investigated eccentric training as a conditioning stimulus, and one of these studies also investigated isometric training as well as eccentric.
- Two (17%) studies (Till & Cooke, 2009; A. Turner et al., 2015) investigated plyometric training and one also investigated isometric training.
- One (8%) study (Doma et al 2020) investigated blood flow restriction as a conditioning stimulus.

Variables Measured

- Seven studies (54%) (Berning et al., 2010; Bogdanis et al., 2014; Boyd et al., 2014; Doma et al., 2020; Golas et al., 2016; Tsolakis et al., 2011; Vargas- Molina et al., 2021) measured vertical jump. Six of the seven studies (86%) showed performance improvements ranging when utilising isometric, eccentric, blood flow restriction, plyometric, and dynamic conditioning stimuli. One study (14%) failed to improve performance following isometric training stimulus. This study included a combination of male and female international fencers and used 3 sets of 5 double legged tuck jumps to try and improve vertical jump (CMJ) performance. Unfortunately, this method failed to acutely improve performance, and it could be due to the conditioning stimulus used.
- Two studies (17%) (Lim & Kong, 2013; A. Turner et al., 2015), measured sprints ranging between 10 to 30 m and one study showed improvements in sprinting performance following plyometric and weight preloading stimulus while one failed to show improvements following vertical isometric conditioning stimulus.
- Beato and colleagues (2019) measured horizontal jump; vertical jump and 5-m sprints and showed improvements in horizontal and vertical jumps but not 5 m sprints. Pojskic and colleagues (Pojskic et al., 2015) measured vertical jump, sprints, and a agility test and showed improvements in all performance measures. Till and Cooke (2009), measured vertical jump and sprints and showed an increase in jump and sprints after 5RM deadlifts and a plyometric potentiating stimulus, however not after an isometric stimulus.
- Overall, of the studies that reported using a vertical stimulus to improve vertical performance, 86% was successful. Of the studies that reported using vertical stimulus to improve horizontal performance 50% was successful. Of the three studies measured vertical jump and horizontal sprint performance, 67% showed success when using a

vertical stimulus to improve both horizontal and vertical performance, and 33% were successful for improving vertical performance but not horizontal.

Time

Improvements in performance were reported ranging between 2 to 15 minutes. Two studies (17%) showed improvements 4-minutes post intervention. Nine studies (75%) took measures at two or more post intervention time points ranging between 1-minute and 21 minutes. The most successful time points in regard to sprints were 4-minutes and 8-minutes. The most successful time points regarding vertical jump performance were between 4-minutes and 15-minutes. Some studies showed an early improvement in performance, whereas some had a delayed response.

1.15 Table. 3 Summary

Percentage effective (with number of participants)

Of the studies above, 83% showed other methods of PAP to be effective in inducing PAP. There were a total of 213 participants and of those participants 178 (84%) were deemed to have a good response to other methods of PAP and identified an improvement in sprint or jump performance.

Percentage not effective

Out of the 213 participants, other methods of PAP failed to improve performance in 35 (16%) of the participants. Two studies (17%) shown in the table above were ineffective in inducing PAP.

Potential reasons for not being effective

One study (Tsolakis et al., 2011) had a combination of male and female trained fencers and used isometric tuck jumps in an attempt to improve vertical jump performance. The combination of male and females may have played a part in the effectiveness in the method as well as the type of exercise used. The other study that reported a lack of potentiation (Lim & Kong, 2013), attempted to improve horizontal sprint performance by using vertical based variations of isometric and dynamic exercises such as knee extensions and squats in trained male track athletes.

Percentage of studies in males/females

Out of the twelve studies included, 95% included male participants (a total of 203 participants), and 5% included a combination of male (n=13) and female (n=10) participants.

Percentage of studies where PAP effective in females

The study one (8%) that included female participants (n=10) in combination with male (n=13) participants failed to improve vertical jump performance using isometric potentiation in all of the 23 participants included.

Comment on menstrual phases data

There was no data collected or reported regarding the menstrual phase in the one study that included female participants.

Interesting take aways

Interestingly, the study that incorporated female participants showed that, while the males performed overall better than females, the rate of decrease in leg peak power was more predominant in males. This assertion supports work by O'Leary and colleagues (1998) which who showed that the women have a higher fatigue resistance, and in in turn, a slower decay of potentiation. Overall, the literature showed that other methods of PAP including isometric, plyometric, BFR, and eccentric stimuli can be an effective tool for eliciting PAP in 85% of trained males and 93.8% in untrained males. However, these methods proved ineffective for eliciting PAP in 6.2% of trained males and 5% of trained females. Currently, the work by Doma and co-workers in 2020 has been the only study identified in this review to explicitly focus on using BFR to induce potentiation (Doma et al. (2020). The result of this study leads us to believe that BFR may be effective in eliciting PAP. A limitation of this table is the lack of data reported on the menstrual cycle.

1.16 Overall summary

Overall, there were a total of 836 participants that met the inclusion criteria. Of those, just 19% of them were females. No studies have reported or attempted to account for the potential impact of menstrual phase in PAP research. Thirty-eight females were exclusively researched across two studies and 121 were researched in combination with male participants across seven studies with majority of the research in females being done in whole body vibration. Of the total number of participants included in this literature review, 20% of them were untrained, 78 (46%) were untrained females, 93 (54%) were untrained males. Three studies primarily investigated the effects of different conditioning stimulus in untrained participants; however, one study used a combination of trained and untrained participants.

Of the 42 studies included in this literature review:

- 22 studies (52%) showed success with improving vertical performance when using a vertical conditioning stimulus;
- 5 studies (12%) showed success with improving horizontal performance when using a vertical stimulus;
- 2 studies (5%) showed improvements in vertical and horizontal performance after a vertical stimulus;
- 2 studies (5%) showed improvements in vertical performance, but not horizontal performance after a vertical stimulus; and
- 1 study (2%) showed improvements in unloaded squats after a vertical stimulus.
- The remaining 29% failed to improve either horizontal or vertical performance.

From the literature in Table 1 regarding HIGH (3RM-5RM) potentiating stimuli, the three most common time points where there was improvement in performance was 4-, 8- and 12-min post intervention. From the literature in Table 2 regarding WBV interventions, the most successful time range for improving different performance aspects occurred between 4- and 10-min post intervention. From the literature in Table 3 regarding other methods of PAP, the most successful time points when trying to improve sprint performance was evident between 4 and 8 minutes. Whereas the most successful time points for improving vertical jump performance ranged between 4 to 15 minutes.

Blood Flow Restriction

Blood flow restriction (BFR) training is an intervention being used to enhance mechanical and metabolic stress by occluding blood flow to the selected muscles region using occlusion tourniquet cuffs (Doma et al., 2020). Thus, BFR restricts the muscles ability to attain oxygen which causes a build-up of signalling molecules such as lactate, growth hormone, and testosterone (Takarada et al., 2000). Further, this restriction leads to an increase in the recruitment of fast twitch (type II) muscle fibres which respond directly to reduced oxygen and an build-up of carbon dioxide (Hamada et al., 2000; T. Yasuda et al., 2010). As a result, BFR has been used to augment or replace training in a variety of different ways including: improving performance, increasing muscle strength and hypertrophy (Abe, Kearns, & Sato, 2006; T. Yasuda, Brechue, Fujita, Sato, & Abe, 2008), as a rehabilitation tool (Beekley et al., 2005; Lambert, Hedt, Moreno, Harris, & McCulloch, 2018), to enhance aerobic capacity (Bennett & Slattery, 2019), and recently, as a conditioning stimulus to elicit PAP (Doma et al., 2020). Research has also shown BFR can be used in combination with low-load resistance training to stimulate similar muscular adaptations to those detected during high resistance training (Centner et al., 2019; Kawada, 2005; T. Yasuda et al., 2008).

2.0 Mechanism of BFR

Blood flow restriction training aims to restrict the venous blood flow and limit the arterial blood flow by applying a tourniquet cuff to the proximal region of the upper or lower extremities (Wilk et al., 2018). There is only limited restriction of the arterial blood flow due to the thick muscular arterial wall, the high pressure of arterial blood flow, and the fact that the arteries are located deeper than the superficial veins. The key effect of BFR includes increased mechanical tension and elevated metabolic stress. As the tourniquet restricts the muscles’ ability to attain oxygen and results in the pooling of venous blood, there is an increase in signalling of anabolic and catabolic pathways (C. J. Cook, Kilduff, & Beaven, 2014). This signalling in turn leads to an intensification of muscle protein synthesis (Fujita et al., 2007; Wilk et al., 2018), which has been related to the increase of circulating IGF-1 (Abe et al., 2006; Abe, Yasuda, et al., 2005). There is also an elevation of metabolic stress, activating and inducing an earlier onset of fast twitch muscle fibres (Kawada, 2005; Takarada et al., 2000), increasing cell swelling, and post-exercise growth hormone levels (Suga et al., 2009; Wilk et al., 2018). Abe and colleagues (2006) showed that a 3-weeks of Kaatsu-walk training not only increased muscle CSA and volume, muscle-bone CSA, and relative strength but also a single bout of Kaatsu-walk exercise can significantly increase serum growth hormone concentration.

2.1 BFR and Hormones

Heavy resistance exercise commonly leads to neuromuscular responses, including muscle fatigue and elevations in hormone signalling (Ahtiainen, Pakarinen, Kraemer, & Hakkinen, 2004). Hormones are an integral part of the body's adaptive response to exercise, and the production of hormones is influenced by volume and intensity of exercise and recover (Ahtiainen et al., 2004). Increases in hormones can offer short-term training and performance benefits and long-term adaptations (Ahtiainen et al., 2004; Gaviglio, Osborne, Kelly, Kilduff, & Cook, 2015). In a study by Goto and colleagues, who compared the effects of two different exercise regimens without or with rest period, the no rest regimen caused larger increases in blood lactate, growth hormone, and norephinephrine as well as larger increases in muscle CSA and strength (Goto, Ishii, Kizuka, & Takamatsu, 2005). Kim and colleagues (2014) also investigated the hormonal effects of two different exercise regimens, a low intensity blood flow restriction (BFR) group and a traditional high intensity (HI) resistance training group on thirteen trained females. The results showed an increase in growth hormones and cortisol levels post exercise after both conditions (Kim et al., 2014). Literature has indicated that BFR in combination with resistance exercise can influence the promotion of a variety of different hormonal responses and systemic adaptations (C. J. Cook, Kilduff, & Beaven, 2013). Increases in lactate and systemic hormones such as plasma growth hormones (GH), insulin-like growth factor-1 (IGF-1), norepinephrine (NE), and testosterone have all been reported after low-intensity exercise training with blood flow restriction (Abe, Yasuda, et al., 2005; C. J. Cook, Kilduff, & Beaven, 2013; Kawada, 2005; Loenneke, Abe, Wilson, Ugrinowitsch, & Bemben, 2012; Loenneke, Fahs, Rossow, Abe, & Bemben, 2012; West, Cunningham, Crewther, Cook, & Kilduff, 2013).

2.1.1 Growth hormone

Growth hormone (GH) is an anabolic polypeptide hormone that influences all body systems and stimulates the generation of IGF-I and its binding proteins which is the primary mediator of many GH functions. One key mechanism of GH is to mobilise fat by direct lipolytic action therefore diverting nutritional calories into protein synthesis (Sonksen, 2001). The second key outcome of GH release is to stimulate protein synthesis through mobilising amino acid transporters (Sonksen, 2001). Growth hormone is released from the anterior pituitary gland in response to a variety of stimuli such as exercise, sleep, stress and others, and is especially important for muscle growth (Macintyre, 1987). Goto et al. (2005), reported a significant increase in GH during resistance training in participants that performed a no rest (NR) regimen, and the results showed that the value of GH in the NR regimen was about threefold higher than the same regimen with rest.

Previous studies have shown the beneficial effects of using occlusion training to increase growth hormone in participants. Takarada and colleagues investigated the effects of low intensity resistance training with occlusion on the increase in plasma hormones in male athletes, they found that there were increases in lactate, growth hormones and norepinephrine. Interestingly GH reached peak levels about 15 minutes after exercise and increased up to a concentration ~290 times as high as that before exercise (Takarada et al., 2000). Another study showed greater GH response following low intensity occlusion compared to moderate resistance in males (Reeves et al., 2006). These studies emphasise that blood flow restriction training can be used as a tool to increase hormonal responses, that may in turn influence adaptations and specific performance measures.

2.1.2 Lactate

Lactate is a product of glycolysis that is formed when there is a lack of oxygen to contracting skeletal muscles (Brooks, 2007). While the build-up of lactate was once looked at as a consequence of a lack in oxygen to muscle causing muscular fatigue, research has now shown that it can have force-restoring effects and can be utilised as a tool during aerobic conditioning (Bandschapp, Soule, & Iaizzo, 2012; Brooks, 2007). Bandschapp and colleagues (2012) reported that elevated lactic acid may impede the voltage-gated chloride channels, thus regenerating excitability of the muscle cell sarcolemma more effectively (p.1019). Therefore, lactate has the potential to offset peripheral fatigue which in turn can restore power and force capabilities (Thomas, Sirvent, Perrey, Raynaud, & Mercier, 2004). In fact, *in vitro* data has shown positive effects on muscle power and isometric force as a result of extracellular acidification (20 mm lactic acid) in fatigued muscle (Overgaard, Højfeldt, & Nielsen, 2010). Research has shown that BFR can elevate lactate. In a study by Yasuda and colleagues, the authors showed that blood lactate concentration and muscle activation increased in the bicep flexion and triceps extension following BFR exercise (T. Yasuda et al., 2014). Overall, it may be postulated that higher levels of lactate generated by BFR might help to protect against peripheral fatigue (and thus enhance PAP) via the fatigue-potentiation continuum.

2.1.3 Testosterone

Testosterone is the primary androgenic hormone that is produced in the Ledig cells in the testes and the adrenal glands (Freeman, Bloom, & McGuire, 2001). Testosterone is known to stimulate the synthesis of specific proteins through crossing cell membrane and binding receptors in the nucleus encouraging activations of particular genes (Cardinale & Stone, 2006). The use of testosterone has been widely studied due to the variety of benefits including increase in muscle strength and size, increase in type I and II fibres and an increase in the myonuclear number (Cardinale & Stone, 2006). Studies dating back to the 1990s have shown how testosterone and cortisol can influence performance. In C. Bosco, Tihanyit, and Viru (1996), they investigated the levels of testosterone and cortisol against results of vertical jumps and speed and reported that higher levels of testosterone were apparent in athletes who possed better strength and sprint running performance. Thus the authors speculated that there was aa relationship between testosterone and the development of fast twitch muscle fibres (C. Bosco et al., 1996). In a later study (C. Bosco & Viru, 1998) compared testosterone and cortisol levels in male sprinters, soccer players, and cross-country skiers. The authors reported that higher levels of testosterone were found in sprinters, again indicating a relationship between testosterone and fast twitch muscle fibres. It also leads us to hypothesise that increased testosterone generated by BFR may be linked with explosive actions such as CMJ and sprints.

2.2 Hormonal priming

The concept of hormonal priming has been suggested as a preparation strategy for improving game day performance (Kilduff, Finn, Baker, Cook, & West, 2013). Literature has identified that there is a likely connection between hormones such as endogenous testosterone and behaviour related aspects including motivation and confidence (Kilduff et al., 2013). Evidence has shown that video presentations can acutely alter male testosterone (T) concentrations (C. J. Cook & Crewther, 2014). In a study by Cook and colleagues, they examined the effects of watching a post-match presentation on hormonal responses (stress-test, pre-match levels) and match performance in males. Participants watched the video presentations within different social environments (1) strangers who were bigger (SB), (2) strangers who were smaller (SS),

(3) friends who were bigger (FB) and (4) friends who were smaller (FS). All treatments showed elevations T responses. Interestingly though, on match day the FB protocol was linked to higher T concentrations and better match day performance than any other condition (C. J. Cook & Crewther, 2014). Another study examined whether a morning training session would influence hormonal responses (testosterone and cortisol concentrations) and alter afternoon physical performance in eighteen semi-professional males. The results showed greater T concentrations following the weight and sprint protocols which lead to better performance in CMJ, 3RM, squat and 40 m sprint in the afternoon (C. J. Cook, Kilduff, & Beaven, 2013). Thus, there is a range of data showing how testosterone can be affected by different activities and how it can influence subsequent performance. Cook and colleagues also showed how three weeks of chronic BFR training leads to improvements in bench press, squats, maximum sprint time and leg power in trained males. Of note, these improvements were associated with greater acute exercise-induced salivary testosterone (C. J. Cook et al., 2014).

2.3 Fast twitch muscle fibres

Fast twitch muscle fibres, also known as type II fibres, are recruited as the intensity of an exercise increases, they are generally larger than slow twitch fibres, and are responsible for contracting muscle rapidly and powerfully (Maglischo, 2015). Fast twitch muscle fibres have a greater supply of myosin ATPase, which is the enzyme that prompts are faster release of ATP (Bogdanis, 2009). Fast twitch muscle fibres are best suited for anaerobic metabolism and exercises such as sprint and power exercises. Unfortunately, fast twitch muscle fibres fatigue more rapidly than slow twitch muscle fibres. (Maglischo, 2015). When oxygen is severely reduced, such as during blood flow restriction a larger recruitment of motor units is required to compensate for the lack of force development (Loenneke, Wilson, & Wilson, 2010). Studies have shown that reducing oxygen and an elevated metabolic build-up can create an increased recruitment of high threshold fibres, maintain the requisite force (Loenneke, Fahs, et al., 2012).

2.4 BFR and Proteins

Muscle hypertrophy is key for performance and is generally induced via resistance training. Literature suggests that the activation of cell signalling leads to the activation of proteins such as mammalian target of rapamycin (mTOR) and mitogen-activated protein-kinase (MAPK) (Drummond et al., 2009; Mahoney, Dempsey, & Blenis, 2009; Schoenfeld, 2013) which are responsible for sending signals that promote an increase in protein synthesis leading to muscle growth (Bodine et al., 2001; Loenneke, Fahs, et al., 2012). Some research has shown that low resistance blood flow restriction exercise increases muscle protein synthesis through activation of the mTOR and MAPK signalling pathways (Fry et al., 2010; Fujita et al., 2007; Ozaki et al., 2014), acute muscle cell swelling (Yasuda et al. 2012), increased type II fibre recruitment (T. Yasuda et al., 2010; T. Yasuda et al., 2009), and proliferation of satellite cells (Nielsen et al., 2012).

2.5 BFR and adaptation

Blood flow restriction training has been shown to enhance muscle fibre recruitment and systemic hormone production as well as increasing muscle strength and hypertrophy (Abe et al., 2006; Bennett & Slattery, 2019; T. Yasuda et al., 2008). Research has also shown that BFR training is effective to enhance muscle hypertrophy and increase the development of muscular strength and size using low loads (B. R. Scott et al., 2017). A combination of BFR and aerobic exercise has the potential to improve cardiorespiratory fitness whilst also allowing maintenance and improvement of aerobic performance during low load off season training intensity (Bennett & Slattery, 2019). In addition, BFR training has shown performance benefits such as improvements in $VO2_{max}$ (Amani-Shalamzari et al., 2020); improvements in bench press strength, bench press peak power, and bench press mean power (C. J. Cook et al., 2014; Wilk, Krzysztofik, Filip, Szkudlarek, et al., 2020; Tomohiro. Yasuda et al., 2011), and improvements in squat strength and CMJ (Beaven, Cook, Kilduff, & Drawer, 2012; C. J. Cook et al., 2014).

2.6 Search Strategy

A search was conducted via PubMed and Google scholar (169) using the key words “BFR”, “KAATSU”, “occlusion”, “lower-body”, “jump”, “sprint”, “trained”, “strength, “power”, and “athlete”. Duplicate references were removed, and abstracts were read and assessed using a criterion to ensure the relevant studies were presented in this literature review. The criterion set *a priori* were: studies that investigated: trained athletes utilising a blood flow restriction as a method of training; included a measure of lower-body expression of power. Only articles published in English language were retrieved. Twelve studies were identified and analysed as part of this literature review.

Table 4: Review of mechanism used in blood flow restriction in lower body performance

Author	*Year*	*Participants*	*BFR Intervention*	*Measured*	*Time*	*Results*	*Cuff Type/Pressure*	*Hormonal responses*
(Abe, Yasuda, et al.)	2005	T – Male Track and field (n = 15)	Squat and leg curl 3 x 15 (30 s inter-set rest, 20% 1RM)	Maximal strength, muscle-bone CSA, mid-thigh muscle thickness (MTH), and sprint/jump performance	Baseline; day 8	↑ muscle-bone CSA (BFR). ↑ in quad and ham MTH. ↑ in leg press strength. Overall ↑in 30-m dash. No improvements in jump.	Day 1: 160 mmHg increase in 20 mmHg each day. Day 8: 240 mmHg	↑ IGF-1
(Behringer, Behlau, Montag, McCourt, & Mester)	2017	T – Male Sport students (n=25)	6-week low intensity sprint training with or without BFR. Participants performed 6 x 100-m sprints at 60–70% of their maximal 100-m twice a week.	100-m sprint performance,	Pre, 1min, 20 min, 120 min, 24 h	The 100-m dash time significantly ↓ more in the intervention group (IG) than in the control group (CG)	Elastic wraps	↔ GH, IGF-1, & C
(Bjørnsen et al.)	2018	T – Male and female Resistance trained (n=16 + 3)	BFRRE: 2 x 5 front squats and four sets (30, 8, 15, 12) (first and last set to voluntary failure) at ~30% of 1RM.	Maximal voluntary isokinetic torque (MVIT) in knee extension 1RM front squat	Pre and Post	↑ in VL CSA in BFRRE ↑ in MVIT but not 1RM front squat in BFRRE ↑ in 1RM front squat in CON	Elastic Wraps	Not assessed
(C. J. Cook et al.)	2014	T – Male Semi-professional rugby union players (n=20)	BFR training - 5 sets of 5 reps of leg squat, bench press and weighted pull ups.	Bench press. Leg squat. Maximal and Repeated sprint times. CMJ power	Pre and post	↑ in bench press, leg squat over the 8-week training program. BFR showed greater ↑ in bench press, squat, maximal sprint and CMJ power. ↑ in performance maintenance in repeated sprint test compared to non-BFR condition.	180 mmHg.	↑ salivary TST & C
(Davids et al.)	2021	T – Male and female Resistance (n=21)	Nine weeks of training 3 x p/w (barbell back squat; leg press; knee	Resting muscle biopsies Quadricep cross sectional area (CSA),	Pre and Post	↑ in muscular strength in both groups, superior gains in 1RM squat in HL-RT. ↑ in CSA in both groups	60% AOP	Not assessed

			extension and Bulgarian split squats) with low load BFR: 30-40% 1RM LL-BFR.	muscular strength and power were measured CMJ Squat jumps				
(Elgammal, Hassan, Eltanahi, & Ibrahim)	2020	T – Male basketball players (n=24)	12 on court sessions consisting of 3 sets of 8 reps of 20 s and 4 min rest.	Bench press, Half squats	Pre and Post	↑ in upper maximum strength (bench press) and anaerobic (suicides) in training group (TG with BFR) compared to control group (CG). ↑ in lower body maximum strength (half-squat) and aerobic capacity (VO2max) in TG.	100 mmHg	Not assessed
(Horiuchi, Endo, Sato, & Okita)	2018	Trained males (n=20)	Jump training with BFR: 5 x 10 with one-minute intervals of half-squat jumps (SJ) at maximal effort, four days a week for four weeks.	SJ, CMJ, Knee ext, Knee flexion	Pre and post	Knee flexion strength ↑ after BFR jump training. Knee extension and flexion strength ↑ after CON. BFR training did not ↑ SJ or counter-movement jumps (CMJ), whereas training without BFR (CON) ↑ the performance of both jumps.	200 mmHg	Not assessed
(Hosseini Kakhak, Kianigul, Haghighi, Nooghabi, & Scott)	2020	T – Male semipro soccer players (n=19)	STBFR: Soccer training with BFR (n=10). 6-week preseason.	Leg extension strength and endurance, CMJ, 40yd sprint, COD ability, aerobic endurance, and soccer specific endurance	Pre and post	Large ↑ were observed in STBFR compared with ST for tests of muscular endurance, COD, aerobic and soccer-specific endurance.	Day 1: 160 mmHg increase by 10 mmHg until reached 210 mmHg	Not assessed
(Korkmaz, Uzuner, Babayeva, Torgutalp, & Özçakar, 2020)	2022	T – Male youth soccer players (n=23)	BFR: 30%1RM 4 x 30, 15, 15, 15 reps) unilateral knee extension exercises	Muscle strength. Muscle thickness; Pennation angle and fascicle length	Pre and Post	↑ in bilateral knee flexor and extensor for both groups ↑ in dominant side extensor muscle strength and RF thickness after BFR	Constant range between 130 – 150 mmHg	Not assessed
(Luebbers, Witte, Oshel, & Butler)	2019	T – Male and females (n=22+ 3)	Bench press and squat: 30, 20, 20, 20 reps (45 s rest) 20%1RM	1RM back squat	Pre and post	Significant ↑ in leg strength for the LO + BFR group but not for the HI or LO groups.	Elastic wraps	Not assessed

(Manimmanakorn, Hamlin, Ross, Taylor, & Manimmanakorn)	2013	T – Female netball (n=30)	5-week training of knee flexor and extensor muscles 3 x 3 ext + 3 flex to failure with 30 s rest (20%1RM).	MVC3, MVC30, Reps201RM. 5 m and 10 m sprints; 505 agility test; vertical jump; 20-MST; MAS; VO2Max	Pre and Post	↑ in CT; KT; HT in MVC3 ↑ in CSA in KT, HT, CT ↑ in 5 m; 10 m; agility test; vertical jump; 20-MS; MAS; VO2max after KT	160 mmHg increase by 10 mmHg 230 mmHg	Not assessed
(B. R. Scott et al.)	2017	T – Male football players (n=21)	LLBFR - Low load blood flow (4 x squats 30, 15, 15, 15 reps 30 s rest between sets). 5-week (3 x p/w).	CMJ and Sprinting	Pre and Post	↑ in 3RM from pretraining levels in LL and LLBFR. ↔ in CMJ height between training groups pre and post assessment. 0-10m sprint ↑ from pretraining levels in LLBFR.	Elastic wraps	Not assessed
(Takarada, Sato, & Ishii)	2002	T – Male elite rugby players (n=17)	Low intensity occlusion (LIO) 50%1RM knee extension in seated position (4 x 30 s)	Knee extension torque Muscle CSA Muscle endurance	Pre and post	↑ isokinetic knee extension torque in LIO. ↑ in CSA of knee-extensors in LIO ↑ in muscle strength, size and endurance in LIO	200 mmHg	Not assessed
(Wilk, Krzysztofik, Filip, Zajac, et al.)	2020	T – Males (n=14)	BFRnarrow BFRwide 1 x 3 bench press @70% 1RM	Peak power; Mean power; Peak velocity; Mean velocity of bench press	Pre and post	↑ in PP; MP; PV; MV in BFRwide ↔ in any of the variables for BFRnarrow and no BFR	90% AOP pressure	Not assessed

Note: M, Male. F, Female. T, Trained. BFR, Blood flow restriction. LL, Low load unrestricted training group. LLBFR, Low load blood flow restriction group. RM, Repetition Max. CMJ, Countermovement jump. Min, Minutes, m, Meters. ↓, Decrease. ↑, Increase/Improve. ↔ No difference/No change. HI, High load. LO, Low load. LO + BFR, Low load with blood flow restriction. Plyo, Plyometric. ST, Normal soccer training. STBFR, Soccer training with blood flow restriction. COD, Change of direction. Yd, Yards. CON, Control. SJ, Squat jump. mmHg, Millimetres of mercury. N, Number. Reps, Repetitions. Ext, Extension. VJH, Vertical jump height. CT, contact time. FT, flight time, MJH, measure jump height. RSI, Relative strength index. DJ, Drop jump. RPE, Rate of perceived exertion. LAC, Lactate. HR, Heart rate. QUAD, Quadricep femoris. EMG, Electromyography. VO2, Maximum rate of oxygen. WU, Warm up. W, Max power. RST, Repeated sprint training. RST + BFR, Repeated sprint training with blood flow restriction. HL, High load. AOP, Arterial occlusion pressure. CG, Control group. IG, Intervention group. NON-BFR, No blood flow restriction. TST, testosterone. C, cortisol

2.7 Table 4 Discussion

Sex

There were a total of 293 participants; 88% were male-only cohorts; 10% were exclusively female cohorts and 2% were females combined with males.

BFR Intervention

- All studies had a minimum of two conditions. Ten studies (71%) (Abe, Kawamoto, et al., 2005; Behringer et al., 2017; Bjørnsen et al., 2018; C. J. Cook et al., 2014; Davids et al., 2021; Elgammal et al., 2020; Horiuchi et al., 2018; Hosseini Kakhak et al., 2020; Korkmaz et al., 2020; B. R. Scott et al., 2017) had a control condition and a BFR condition.
- Four studies (29%) (Luebbers et al., 2019; Manimmanakorn et al., 2013; Takarada et al., 2002; Wilk, Krzysztofik, Filip, Zajac, et al., 2020) had three conditions. Luebbers and colleagues had a control condition; traditional high load condition and a low load with BFR condition and Manimmanakorn and colleagues had a control training group, a hypoxic training group, and a katsu training group. Takarada and colleagues had a low-intensity exercise combined with an occlusion group, a low intensity group and an untrained group. Finally, Wilk and colleagues had a control condition (No-BFR) and two different conditions with blood flow restriction but different cuff sizes (BFRwide and BFRnarrow).

BFR Intervention

Eleven studies reported on different resistance levels. Three studies (Abe, Kawamoto, et al., 2005; Luebbers et al., 2019; Manimmanakorn et al., 2013) reported using 20% 1RM. Two studies (Bjørnsen et al., 2018; Korkmaz et al., 2020) reported using 30% 1RM. One study (Davids et al., 2021) reported between 30-40% 1RM. One study (B. R. Scott, J. J. Peiffer, & P.

S. Goods, 2017) reported using 40% 1RM. One study (Takarada et al., 2002) reported using 50% 1RM. One study (Behringer et al., 2017) reported using between 60-70% 1RM and two studies (C. J. Cook et al., 2014; Wilk, Krzysztofik, Filip, Zajac, et al., 2020) reported using 70% 1RM. The remaining three studies did not report using different resistance against predicted 1RM strength. 12 out of the 14 studies reported using repetition in an attempt to improve performance. One study (Behringer et al., 2017) reported doing 6 sets of 100 m; two studies reported using sets of 5 (C. J. Cook et al., 2014; Horiuchi et al., 2018); Five studies reported doing sets of 4 (Bjørnsen et al., 2018; Korkmaz et al., 2020; Luebbers et al., 2019; B. R. Scott et al., 2017; Takarada et al., 2002); Three studies reported using sets of 3 (Abe, Kawamoto, et al., 2005; Elgammal et al., 2020; Manimmanakorn et al., 2013); and one study reported using sets of 1 (Wilk, Krzysztofik, Filip, Zajac, et al., 2020). The remaining two studies did not report on sets or repetitions.

Performance measures

Eight studies measured different aspects of performance.

- One study (Horiuchi et al., 2018) measured vertical jumps and showed that BFR intervention failed to improve performance.
- One study measured 100-m sprint performance (Behringer et al., 2017) and showed that 100-m dash time decrease following the BFR intervention group emphasising that there was an improvement in performance.
- Four studies measured vertical jump and sprint performance (Abe, Kawamoto, et al., 2005; C. J. Cook et al., 2014; Hosseini Kakhak et al., 2020; B. R. Scott et al., 2017). Two of the studies (Abe, Kawamoto, et al., 2005) and (B. R. Scott et al., 2017) showed improvements in sprint performance but not jump performance after a BFR intervention. The other two studies (C. J. Cook et al., 2014) and (Hosseini Kakhak et al., 2020) both showed improvements in vertical jump and sprint performance.

- The final two studies that measured performance aspects (Elgammal et al., 2020; Luebbers et al., 2019) measured whether BFR improved back squat strength and showed improvements in lower body strength after intervention.

The remaining six studies showed:

- Increases in muscle CSA following BFR training by (Bjørnsen et al., 2018; Davids et al., 2021; Manimmanakorn et al., 2013; Takarada et al., 2002).
- Increases in muscle strength (Davids et al., 2021; Korkmaz et al., 2020; Takarada et al., 2002).
- One study (Manimmanakorn et al., 2013) measured (MVC; 5 m, 10 m agility test, vertical jumps, shuttle runs) as well as muscle CSA and reported improvements in all measures after a BFR protocol.
- Finally, one study (Wilk, Krzysztofik, Filip, Zajac, et al., 2020) which was upper body-based measured power and velocity measures and showed improvements after the BFR condition that utilised wide cuffs.

Time

Twelve studies reported taking measures pre and post intervention (Bjørnsen et al., 2018; C. J. Cook et al., 2014; Davids et al., 2021; Elgammal et al., 2020; Horiuchi et al., 2018; Hosseini Kakhak et al., 2020; Korkmaz et al., 2020; Luebbers et al., 2019; Manimmanakorn et al., 2013; B. R. Scott et al., 2017; Takarada et al., 2002; Wilk, Krzysztofik, Filip, Zajac, et al., 2020). The final two studies took measures at more than one time point. (Behringer et al., 2017) measures at four different time points ranging between 1 minute to 24 hours post intervention and (Abe, Kawamoto, et al., 2005) reported taking post measures at the end of the training period 8 days after taking baseline measures.

Cuff type and pressure

- Four studies (Behringer et al., 2017; Bjørnsen et al., 2018; Luebbers et al., 2019; B. R. Scott et al., 2017) all reported using elastic cuffs. B. R. Scott et al. (2017) showed improvements in sprint performance but not jump performance. Luebbers et al. (2019) showed improvement in overall performance and Behringer et al. (2017) showed no improvements in sprint performance.
- Two studies (Abe, Kawamoto, et al., 2005) and (Hosseini Kakhak et al., 2020) both had a gradual increase in cuff pressure. Abe, Kawamoto, et al. (2005) started at a pressure of 160 mmHg and increased by 20 mmHg until reaching 240 mmHg; Hosseini Kakhak et al. (2020) started at a pressure of 160 mmHg and increase by 10 mmHg until reaching final pressure of 210 mmHg. Both studies showed improvements in sprint performance however only (Hosseini Kakhak et al., 2020) showed improvements in vertical jump performance.
- Elgammal et al. (2020) used a pressure of 100 mmHg and was successful in improving upper and lower body performance; C. J. Cook et al. (2014) used a pressure of 180 mmHg and also showed improvements in upper and lower body performance and Horiuchi et al. (2018) used a pressure of 200 mmHg and showed improvements in vertical jump performance.

Hormonal responses

Eleven studies (Bjørnsen et al., 2018; Davids et al., 2021; Elgammal et al., 2020; Horiuchi et al., 2018; Hosseini Kakhak et al., 2020; Korkmaz et al., 2020; Luebbers et al., 2019; Manimmanakorn et al., 2013; B. R. Scott et al., 2017; Takarada et al., 2002; Wilk, Krzysztofik, Filip, Zajac, et al., 2020) did not take any hormonal measures therefore did not report on any change or effect on performance. Three studies did report on different hormonal responses. Abe, Kawamoto, et al. (2005) reported an increase in IGF-1 after completing training 3 x 15 repetition of squats and leg curls twice daily with occlusion cuffs and C. J. Cook et al. (2014) reported increases in salivary testosterone and cortisol after performing 5 sets of 5 repetition of leg squat, bench press and weighted pull ups with occlusion cuffs. However, one study failed to improve hormonal responses. Behringer et al. (2017) reported no change in growth hormones, IGF-1 or cortisol after performing 6 x 100-m sprints at 60–70% of their maximal 100-m twice a week with occlusion cuffs.

2.8 Table. 4 Summary

The results from Table 4 showed that BFR is a growing intervention that can improve performance measures, muscle strength and size and influence changes in hormonal responses. The literature shows that BFR training has been an effective tool for improving performance measures in 84% of the participants included in Table 4. Of the 12 studies that were effective, 69% of them were male participants; 10% were female participants and 5% were a mixed male and female cohort. The remaining two studies (15% of participants) failed to acutely improve performance measures after BFR intervention in males. Interestingly, there was one study that primarily used female participants and showed improvements in all measurements including 5-10 m sprints; vertical jumps; shuttle runs and other measures following blood flow restriction training (Manimmanakorn et al., 2013). Unfortunately, there was no data reported on the menstrual phase in this study or the other studies that included female participants.

2.9 BFR as a form of post activation potentiation

As noted previously, there is currently only one study that has investigated the effects of using BFR to induce lower body PAP (Doma et al., 2020). Doma and colleagues found overall improvements in drop jump measures when using BFR. Eighteen anaerobically trained males participated in a study assessing whether 3 sets of 8 lunges with BFR (130% of systolic BP) or without BFR would induce PAP. The results compared two key variables 1) the differences in drop jump height measures following the BFR intervention versus no intervention, and 2) the differences in results for the different time points (at 3, 6-, 9-, 12-, and 15-min post intervention). Two measures of jump height were taken, one using a vertical jump apparatus (VJH) and one using a jump mat (MJH). Overall, the results showed that lunges with BFR improved jump height, flight time, and power within 6-minutes to 15-minutes post intervention. Specifically, flight time (FT); mat jump height (MJH) and power were significantly greater following the BFR condition at 15-minutes. Jump height measured by a timing mat showed a number of additional significant results at 15-minutes versus using a Vertec device. The study suggests that occlusion of the lower limbs induced an effective PAP stimulus (Doma et al., 2020).

2.10 Conclusion

In conclusion, PAP has been shown as a method to maximise power and explosive development (Lorenz, 2011)**.** Whilst BFR also has a variety of benefits, the key component is the increase in muscular size and strength (Lambert et al., 2018). Although there are no specific guidelines for BFR, it is important to consider factors like recovery times, cuff width, overall strength, fibre-type, and training experience when prescribing BFR. Currently, there is limited research investigating the acute effects of BFR in females and, to the best of our knowledge, there does not appear to be any research regarding using BFR to induce PAP in trained females.

3.0 Research Question

It is apparent that there is a lack of research in trained female athletes that has assessed a range of conditioning stimuli to elicit a performance enhancement via post activation potentiation. The literature assessed identified the 4-8 min time period as the window where performance enhancements are likely to be observable, as PAP is a summation of potentiation and fatigue. Currently, there is only one study that has looked at lower-body BFR as a conditioning stimulus to elicit PAP. Thus, our research aim was to assess the effectiveness of BFR as a conditioning stimulus to enhance sprint and jump performance in trained female athletes. A secondary aim was to assess the effectiveness of a BFR conditioning stimulus on components of the horizontal and vertical force-velocity profiles. A cohort-specific reliability study was also run over three sessions that aimed to inform our smallest worthwhile change and matched the time course of the intervention study.

4.0 Hypotheses

Based on observations from Doma, we hypothesised that:

- **Hypothesis One**. BFR would potentiate jump performance via enhanced muscle activation of lower body expression.
- **Hypothesis Two.** BFR would potentiate sprint running via enhanced muscle activation; however, the potentiation would be lesser than jump potentiation due to lack of movement specificity.
- **Hypothesis Three**. Jump-derived components of vertical force-velocity profiles would be reliable, although the weighted jumps would be less reliable due to the lesser familiarity of the athletes and use of absolute (as opposed to relative) loads.
- **Hypothesis Four**. The force-velocity metrics derived from the 20-m sprint would be less reliable than the jump metrics due to the increased reliance on technique and complexity of the movement.

Chapter Two: Inter-day reliability of force, speed, and power measures in trained female athletes.

Abstract

Purpose: Many sports rely on an athletes' ability to produce large amounts of force, speed, and power. An integral part of training and monitoring progression is the ability to be able to reliably measure identified variables. This study aimed to examine the reliability of the jump and sprint performance, as well as components of the horizontal and vertical force-velocity profile derived from a series of loaded squat jumps and a 20 m sprint test in trained females.

Methods: 15 trained females completed three sessions separated by 3 days. Each session consisted of six loaded squat jumps (2 x body weight, 2 x 24 kg, 2 x 48 kg) and a maximal 20-m sprint to enable the calculation of individual horizontal and vertical force-velocity profiles. Specifically, the squat jump variables assessed were jump height, and theoretical maximal force ($F0_{VERT}$), velocity ($V0_{VERT}$), and power ($Pmax_{VERT}$) recorded with the use of an OptoJump™ (Microgate, Bolzano, Italy). For the 20-m sprint and sprint speed, and theoretical maximal force ($F0_{HORIZ}$), velocity ($V0_{HORIZ}$), and power ($Pmax_{HORIZ}$), were recorded using a StalkerATS, radar Gun. Reliability was assessed using intraclass coefficients (ICC), typical error (TE), and coefficient of variation (CV) statistics.

Results: In the vertical profiling, $F0_{VERT}$ (TE = 1.19, ICC = 0.71, CV = 5.4%); $V0_{VERT}$ (TE = 0.10, ICC = 0.84, CV = 4.7%), and $Pmax_{VERT}$ (TE = 0.39, ICC = 0.87, CV = 3.8%) were deemed to be reliable based on previously reported thresholds. Sprinting $V0_{HORIZ}$ (TE = 0.43, ICC = 0.63, CV = 7.3%) was also found to be reliable; however, the reliability measures from the 20 m sprint data found that $F0_{HORIZ}$ (TE = 0.55, ICC = 0.51, CV = 10.8%) and $Pmax_{HORIZ}$ (TE = 0.96, ICC = 0.73, CV = 13.1%) were not deemed to be reliable in this cohort. The performance metrics exhibited acceptable reliability for BW (TE = 1.5 cm, CV: 6.9%, ICC: 0.91) and sprint speed (TE = 1.1 km/h, CV: 5.5%, ICC: 0.73).

Conclusion: All the variables from the vertical power profile were considered to have acceptable reliability, but only the theoretical maximal velocity was reliable using the radar gun. When monitoring power profiles in trained female athletes, or assessing progression, the identified typical errors should be used to define smallest worthwhile changes.

Introduction

Power, force, and velocity are crucial for athletic ability and overall performance. Having the ability to produce large amounts of force and velocity are essential in an athlete's ability to produce power and execute movements more explosively (Cormie, McBride, & McCaulley, 2008; Harrison, Keane, & Coglan, 2004). As technology in the sporting environment continues to develop and become more accessible, more portable and cost-efficient options to assess strength and power are becoming widely used in more sport-specific settings (Pereira & Gomes, 2003). The reliability of the measures and tools of relevance to sporting performance are essential for providing accurate results to inform decision making (Pereira & Gomes, 2003). Being able to reproduce outcomes is essential for being able to monitor progression, adaptations, recovery, or even over-training (Murray, Beaven, & Hebert-Loiser, 2019).

The ability to produce an optimal combination of force and velocity has been shown to be an important contributing factor to jump and sprint performance (P. Jimenez-Reyes et al., 2018). Ballistic performance such as jumping and sprinting is determined by an individual's capacity to produce optimal combinations of force at low and high velocities, as can be accessed via force-velocity profiling (P. Jimenez-Reyes, Samozino, & Morin, 2019). A force-velocity profile relates to force, power, and velocity relationship describing the capability of the lower limbs neuromuscular systems. For an optimal F-v performance an optimal balance between force and velocity has been identified Assessment of the F-v profile can provide individuals with information on the magnitude and directions of the imbalances between force and velocity qualities, and training programs designed to target specific aspects of the F-v curve has been shown to be an effective method for improving performance measures (P. Jimenez-Reyes et al., 2019).

By measuring jumps such as squat jumps (SJ), countermovement jumps (CMJ), and drop jumps (DJ) as well as assessing jumping profiles, we are able to gauge information on the capacity of the lower limbs to produce force in a vertical direction (P. Jimenez-Reyes et al., 2018). Loaded squat jumps are a commonly used exercise to assess lower limb strength and muscular power without a contribution from the stretch-shortening cycle (Writz, Zinner, Doermann, Kleinoeder, & Mester, 2016). Squat jumps require each participant to start in a 90-degree, semi squat position and hold at the bottom before jumping as high as possible. This protocol prevents participants from gaining any momentum and the musculotendinous unit is unable to store high levels of force prior to the movement (Bobbert, Gerritsen, Litjens, & Van Soest, 1996)

Typically, force plates (FP) are considered as the gold standard used to assess vertical jump performance; however, the cost and accessibility of FP can prove quite challenging (Glatthorn et al., 2011; O'Donnell, Tavares, McMaster, Chambers, & Driller, 2018). Other research-grade equipment commonly used to measure vertical jumps include GymAware, photoelectric cells, contact mats, and linear position transducers (LPT) (Glatthorn et al., 2011; Markovic, Dizdar, Jukic, & Cardinale, 2004; O'Donnell et al., 2018). The OptoJump utilises an array of high-density photoelectric cells positioned at floor level and is cost efficient (relative to FP) and easily transportable, allowing for field-based assessments. While the Optojump has been shown to be valid (ICC = 0.997 relative to FP) and reliable with respect to squat jump height in 'healthy' volunteers with an ICC of 0.982 and CV of 3.1% (Glatthorn et al., 2011), no typical error or reliability data is available in trained female athletes. These authors did however note that the Optojump tended to underreport jump height by ↔1.1 cm compared to the FP in a test of concurrent validity (Glatthorn et al., 2011).

Sprint speed is also a key component of performance across a range of sports, although attaining maximal velocity in many sports is uncommon; hence, concentrating on acceleration of the first 20-m is crucial (K. D. Simperingham, Cronin, & Ross, 2016). Sprint profiles provide us with information on the lower limbs ability to produce force in a horizontal direction specific to sprinting (P. Jimenez-Reyes et al., 2018). Photoelectric cells (or timing lights) are promoted as the gold standard used in sprint testing (Altmann et al., 2017); however, a radar gun can provide additional information regarding instantaneous velocity. Radar guns emit high frequency radio waves and measure the change in frequency as the waves bounce off the participant who is sprinting (K. D. Simperingham et al., 2016). The validity of the radar guns has previously been assessed against photoelectric cells and was described as "essentially identical" with an r^2 of 0.99 in male sprinters (di Prampero et al., 2005). Further, radar guns have previously been reported to inform individual biomechanical models to estimate the horizontal force-velocity profile of elite male athletes (Mendiguchia et al., 2016) and the inter-session (7 day) reliability has been reported for male rugby players (K. D. Simperingham et al., 2016). Specifically, Simperingham and colleagues (2016) reported acceptable inter-session reliability for the majority of radar-derived measures, although lower reliability was seen in relative F0. However, literature describing the reliability of radar guns to assess inter-session reliability of components of the force-velocity profile in female athletes is lacking. Thus, the aim of this study was to assess the reliability of the Optojump and a radar gun in trained females. In particular, we examined the inter-session reliability of components of both the horizontal and vertical force-velocity profile, in addition to the performance outcomes (sprint speed and jump height) using loaded squat jumps and 20-m maximal running sprints.

Determining the reliability of these measures will help to inform worthwhile changes in these metrics in a population of trained female athletes.

Methods

Participants

Fifteen resistance trained team sport females (age = 20.0 ± 5.0 y, height = 167.2 ± 7.3 cm, body mass = 75.1 ± 13.3 kg; mean ± standard deviation [SD]) participated in this study. All participants were competing at regional level in sports such as rugby, rugby league, and netball that required lower body power. Participants were recruited via word-of-mouth and social media platforms and provided written consent form before participating in the study. Ethics was approved by the University of Waikato Human Research Ethics Review Board [HREC(Health)] and in accordance with the Declaration of Helsinki.

Study Design

A repeated measures design was used to examine the reliability of the force, velocity, and performance variables collected over three sessions separated by three days. Each session consisted of a standardised warm-up (see Table 5) followed by six loaded squat jumps (two repetitions each at body weight, 24, and 48 kg) and a maximal 20-m sprint.

Reliability Sessions

Participants arrived at a climate-controlled gymnasium (19 ±1 ºC) and completed a menstrual phase questionnaire. After collecting height and body mass, the participants performed a 5-minute standardised warm up including jogging and dynamic stretches (leg swings, lunges, squats). Participants then moved on to performing two rounds of 30 seconds pogo jumps and squat jumps and then three sub maximal 20-m sprints at 70%, 80% and 90% of their perceived maximal intensity. After completing the warmup participants had a 4-minute rest before completing 6 squat jumps (2 repetitions at body weight, 2 at 24 kg and 2 at 48 kg). After a further 2 minutes rest, the participants performed one 20 m maximal sprint.

Table 5. Warm-up protocol

Exercise	Sets/Laps	Time	Rest (s)
Jog	4	__	__
High Knees	2	__	__
Butt Kicks	2	__	__
Pogo Jumps	2	30s	20
Squat Jumps	2	30s	20
20m Sprint (70%)	1	__	10
20m Sprint (80%)	1	__	10
20m Sprint (90%)	1	__	10

Loaded squat jumps

Participants were instructed to squat in a 90-degree angle, hold at the bottom for approximately two seconds before jumping up as high as they could without using the momentum of their arms. Two jumps were performed with bodyweight, and with 12 kg and 24 kg dumbbells in each hand. Each jump was separated by 30 seconds recovery. Flight time data was recorded using OptoJump (Microgate, Bolzano, Italy) and analysed using Microsoft Excel. Initial metrics collected included jump height (m) and later these measurements were used to calculate a vertical force-velocity profile using the methods described by (P. Samozino, Morin, Hintzy, & Belli, 2008). The maximal theoretical force output ($F0_{VERT}$), maximal theoretical velocity output ($V0_{VERT}$), and maximal power ($Pmax_{VERT}$) were derived from the force-velocity profile, and the inter-session reliability was assessed by calculating the typical error, ICC, and CV for all measures (Hopkins, 2000).

20-m Sprint

Individuals completed one maximal 20 m sprint on an indoor track in athletic clothing. Participants were given appropriate cueing and verbal encouragement and instructed to sprint from a standing start as fast as they could without decelerating until after a cone positioned at the 20 m mark. Instantaneous sprint velocity was recorded at 46.8 Hz using a radar gun (Stalker ATS II, Texas, USA) securely placed 1 m behind the participant at a height of 1 m above the ground. Raw data files were manually processed after export into Microsoft Excel and a validated customised spreadsheet was used to attain the horizontal force-velocity profile (P. Samozino et al., 2008). Initial metrics derived were speed (km/h), maximal theoretical force output (F0), maximal theoretical velocity output ($V0_{HORIZ}$), and maximal power ($Pmax_{HORIZ}$). Inter-session reliability was assessed using the same approach described above.

Statistical analyses

Descriptive data are presented as means, standard deviation and range. Intraclass correlation coefficients (ICC), typical error (TE) and coefficient of variation (CV) with 95% confidence intervals were calculated to compute the relative and absolute reliability of measures. Inter-class correlations were interpreted as: poor (ICC < 0.40), fair (0.40 ≥ ICC < 0.75), good (0.75 ≥ ICC < 0.90), and excellent (ICC ≥ 0.90). Absolute reliability was deemed acceptable when the CV was < 10% (Atkinson & Nevill, 1998). Statistical differences between the data points collected three days apart was calculated via a paired t-test, with an *a priori alpha* set at p ≤ 0.05.

Results

Loaded squat jumps

Inter-session relative reliability for the jump height measures was good for the bodyweight, 24 kg, and 48 kg squat jumps (all ICC ≥ 0.78); although only the bodyweight jump presented with acceptable absolute reliability (CV < 10%). The reliability measures for the loaded squat jumps, components of the vertical force-velocity profile, and $Pmax_{VERT}$ are presented in Table 6. The relative reliability of these vertical force-velocity measures ranged from fair to excellent. All jump measures demonstrated acceptable absolute reliability except the 48 kg loaded squat jump height. The only significant difference between sessions was between Session 1 and Session 2 in $Pmax_{VERT}$.

20-m Sprint

Inter-session relative reliability for sprint speed, was observed to be lower than the jump measures (ICC = 0.72; fair); however, the absolute reliability was acceptable (CV < 10%). The reliability measures for the 20 m sprint speed, components of the horizontal force-velocity profile, and $Pmax_{HORIZ}$ are presented in Table 7. The relative reliability of these measures ranged from poor to good. Only sprint speed and $V0_{HORIZ}$ demonstrated acceptable absolute reliability. No significant differences between sessions were observed between any sprint variables, although the p-value difference between $Pmax_{HORIZ}$ in Session 2 and Session 3 was <0.1.

Table 6*:* Raw units, typical error (TE), intraclass coefficient (ICC), and coefficient of variation (CV) with 95% confidence limits [lower, upper] in jump F0, V0 and Pmax (n=15). Mean and standard deviations (mean ± SD) provided

	Comparison				Reliability Statistics			
	S1	**S2**	**S3**	**Δ in mean**	**TE (Raw Units)**	**CV %**	**ICC**	**p-value**
Jump F0 (N/kg)	22.8 ± 2.5	22.6 ± 1.7	23.0 ± 3.0					
S2 vs S1				-0.26	1.19 [0.87, 1.88]	5.4 [3.9, 8.7]	0.71 [0.33, 0.89]	0.559
S3 vs S2				0.39	1.62 [1.18, 2.55]	6.9 [5.0, 11.1]	0.59 [0.14, 0.84]	0.516
Overall					1.42	6.2	0.7	
Jump V0 (m/s)	2.09 ± 0.25	2.04 ± 0.22	2.03 ± 0.22					
S2 vs S1				-0.05	0.10 [0.07, 0.16]	4.7 [3.4, 7.6]	0.84 [0.59, 0.94]	0.199
S3 vs S2				-0.01	0.11 [0.08, 0.18]	5.5 [4.0, 8.9]	0.77 [0.44, 0.92]	0.785
Overall					0.11	5.2	0.81	
Jump (Pmax)	11.77 ± 0.89	11.46 ± 1.10	11.53 ± 1.23					
S2 vs S1				-0.31	0.39 [0.29, 0.62]	3.8 [2.8, 6.0]	0.87 [0.65, 0.95]	0.046
S3 vs S2				0.07	0.38 [0.28, 0.60]	3.4 [2.5, 5.4]	0.91 [0.75, 0.97]	0.605
Overall					0.39	3.6	0.89	

F0: Force output, V0: Velocity output, Pmax: Maximum power, TE: Typical error, CV: Coefficient of variation, ICC: Intraclass correlation coefficient, p-value: Statistical significance (p <0.05). S1, Session one. S2, Session two. S3, Session three. Δ, Change.

Table 7: Raw units, typical error (TE), intraclass coefficient (ICC), and coefficient of variation (CV) with 95% confidence limits [lower, upper] in sprint F0, V0 and Pmax (n=15). Mean and standard deviations (mean ± SD) provided.

	Comparison				Reliability Statistics			
	S1	**S2**	**S3**	**Δ in mean**	**TE (Raw Units)**	**CV %**	**ICC**	**p-value**
Sprint F0 (N/kg)	5.55 ± 0.65	5.29 ± 0.85	5.37 ± 0.9					
S2 vs S1				-0.26	0.55 [0.40, 0.86]	10.8 [7.8, 17.6]	0.51 [0.02, 0.80]	0.216
S3 vs S2				0.08	0.59 [0.43, 0.94]	13.2 [9.5, 21.5]	0.59 [0.13, 0.84]	0.704
Overall					0.57	12	0.55	
Sprint V0 (m/s)	6.27 ± 0.61	6.33 ± 0.72	6.8 ± 0.9					
S2 vs S1				0.06	0.43 [0.31, 0.67]	7.3 [5.3, 11.8]	0.63 [0.19, 0.86]	0.696
S3 vs S2				0.47	0.76 [0.56, 1.20]	11.9 [8.6, 19.3]	0.18 [-0.35, 0.62]	0.116
Overall					0.62	9.8	0.38	
Sprint Pmax (W/kg)	8.74 ± 1.58	8.43 ± 1.91	9.2 ± 2.5					
S2 vs S1				-0.31	0.96 [0.71, 1.52]	13.1 [9.4, 21.4]	0.73 [0.36, 0.90]	0.389
S3 vs S2				0.77	1.09 [0.80, 1.72]	11.6 [8.4, 18.9]	0.79 [0.48, 0.92]	0.072
Overall					1.03	12.4	0.77	

F0: Force output, V0: Velocity output, Pmax: Maximum power, TE: Typical error, CV: Coefficient of variation, ICC: Intraclass correlation coefficient, p-value: Statistical significance (p <0.05). S1, Session one. S2, Session two. S3, Session three. Δ, Change.

Table 8: Raw units, typical error (TE), intraclass coefficient (ICC), and coefficient of variation (CV) with 95% confidence limits [lower, upper] in Body Weight loaded squat jumps and Sprint time (n=15). Mean and standard deviations (mean ± SD) provided

	Comparison				**Reliability Statistics**			
	S1	**S2**	**S3**	**Δ in mean**	**TE (Raw Units)**	**CV %**	**ICC**	**p-value**
Body Weight (kg)	25.8 ± 4.01	25.2 ± 4.63	25.2 ± 5.1					
S2 vs S1				-0.57	1.58 [1.16, 2.49]	7.8 [5.7, 12.6]	0.88 [0.69, 0.96]	0.337
S3 vs S2				-0.05	1.41 [1.03, 2.22]	5.9 [4.3, 9.4]	0.93 [0.80, 0.98]	0.929
Overall					1.5	6.9	0.91	
24 (kg)	17.1 ± 2.9	16.1 ± 3.0	16.1 ± 4.2					
S2 vs S1				-0.97	1.35 [0.99, 2.12]	9.1 [6.6, 14.8]	0.82 [0.55, 0.94]	0.068
S3 vs S2				-0.03	1.60 [1.17, 2.52]	11.1 [8.0, 18.0]	0.83 [0.58, 0.94]	0.964
Overall					1.48	10.2	0.84	
48 (kg)	6.3 ± 3.7	6.0 ± 2.8	6.6 ± 3.5					
S2 vs S1				-0.32	1.41 [1.03, 2.23]	39.4 [27.5, 68.9]	0.84 [0.58, 0.94]	0.540
S3 vs S2				0.60	1.47 [1.07, 2.31]	32.8 [23.1, 56.5]	0.81 [0.52, 0.93]	0.319
Overall					1.44	36.2	0.84	
Sprint Speed (km/h)	21.6 ± 1.9	21.4 ± 2.2	21.9 ± 1.9					
S2 vs S1				-0.19	1.09 [0.80, 1.72]	5.5 [4.0, 8.8]	0.75 [0.40, 0.91]	0.643
S3 vs S2				0.50	1.10 [0.81, 1.74]	5.5 [4.0, 8.8]	0.74 [0.38, 0.90]	0.208
Overall					1.1	5.5	0.73	

F0: Force output, V0: Velocity output, Pmax: Maximum power, TE: Typical error, CV: Coefficient of variation, ICC: Intraclass correlation coefficient, p-value: Statistical significance (p <0.05). S1, Session one. S2, Session two. S3, Session three. Δ, Change.

Discussion

The findings from this study indicated that, in the current context, the overall inter-session reliability for vertical force-velocity measures have acceptable reliability in a trained female cohort when sessions are separated by three days; however, horizontal metrics were less reliable. Specifically, when using the OptoJump to assess the loaded squat jumps and construct a 3-point vertical force-velocity profile, the relative reliability of the derived theoretical maximal vertical force output, velocity output, and power ranged from fair to excellent with acceptable absolute reliability. The radar gun derived components of the horizontal force-velocity profile, tended to be less reliable than their vertical counterparts. Specifically, only the V0 data collected from the 20-m sprint exhibited a reliable CV under 10% (9.8%); however, the ICC was interpreted as having poor relative reliability.

Loaded squat jumps

Vertical jump testing is important for both the training and testing of the lower body (Cuk et al., 2014; P. Jimenez-Reyes et al., 2015; Perez- Castilla, Comfort, McMahon, Pestana- Melero, & Garcia-Ramos, 2018; Perez-Castilla, Ramirez-Campillo, Fernandes, & Garcia-Ramos, 2021). The literature shows that vertical power is an important physical performance measure for testing the lower body power due to the strong correlation between jump capacity and performance in a variety of sports (Mandic, Jakovljevic, & Jaric, 2015; Markovic et al., 2004; Perez- Castilla et al., 2018). Loaded jumps are currently implemented in jump testing to assess how athletes manage against different loading conditions (Garcia-Ramos, Jaric, Perez- Castilla, Padial, & Feriche, 2017; Loturco et al., 2017; Perez- Castilla et al., 2018). The aim of our study was to assess whether loaded squat jumps could be provide a reliable representation of force-velocity profiles in female athletes, and our results showed that the measures taken from loaded squat jump were reliable measures of force, velocity, and power.

Samozino and colleagues (2008) identified that loaded squat jumps can be used to determine an individual F-v profile and Pmax. In a study by Moir and colleagues (2004), the authors reported that familiarisation session were unnecessary for loaded (10 kg) and unloaded squats in trained males (Moir, Button, Glaister, & Stone, 2004). Another study by Moir and colleagues reported high levels of reliability can be achieved with loaded (30% and 60% 1RM) squats in active men without the need for familiarisation when recording kinetic and kinematic variables of CMJ (Moir, Sanders, Button, & Glaister, 2005). These authors have also reported that there was little difference between male and females, emphasising that familarisation was not required in physically active male and female participants (Moir, Garcia, & Dwyer, 2009). Similarly, our data showed no evidence for improved reliability across the three sessions, also supporting the assertion that familiarisation is not required in a trained female population.

20-m sprint

Measuring lower body power via jumping is essential; however, it is just as important to assess lower body power via sprinting. Jimenez-Reyes and colleagues (2018) emphasise that jumping, and sprint acceleration represent two related, but distinct physical capabilities. Evaluating both jumping and sprinting can ensure more specific and comprehensive representation of individual physical capabilities (P. Jimenez-Reyes et al., 2018). Enhancing athletes' capabilities to sprint over short distances is vital in a variety of sports (Shahab, Steendahl, Ruf, Meyer, & Van Hooren, 2021). For example, in male rugby players, sprint speed over 10, 20, and 30 m was related to potentially match-defining efforts including line breaks and tries scored (Smart, Hopkins, Quarrie, & Gill, 2014).

A sprint is commonly divided into four phases, initial take off phase; acceleration phase; maximum velocity phase; and the deceleration phase (G. Duthie, Grant, Pyne, Marsh, & Hooper, 2006; Rumpf & Cronin, 2011). In general, the two most valuable phases of a sprint in team sports, are the initial take off (first-step quickness) and the acceleration phase or the ability to get up to maximum velocity quicker (Cronin & Hansen, 2005). However, horizontal velocity can be impacted by variability during the initial steps of a sprint which can interfere with the reliability of the measures (K. D. Simperingham, Cronin, Pearson, & Ross, 2017). Participants in this study were required to start in a static start position. According to (Buchheit et al., 2014; K. D. Simperingham et al., 2017) static starts potentially causes greater variability in F0 and V0 measures, which may explain the lower reliability metrics attained . Which concur within this the current study.

Moderate CVs were reported for two of the three variables for inter-day reliability; F0 $_{HORIZ}$ (12.0%) and Pmax $_{HORIZ}$ (12.4%) similar to (Talukdar & McGuigan, 2021), who reported on intra and inter-day reliability in 29 young female athletes using a radar gun showing moderate CV (11.2%) for F0 results. In contrast the ICC values reported in Talukdar and colleagues (2021) reported acceptable reliability for all of the variables except V0 (ICC=0.79) whereas our results showed that all of the variables were deemed unacceptable with Pmax $_{HORIZ}$ being closest to having acceptable reliability (ICC = 0.77). Studies by (Buchheit et al., 2014) and (K. D. Simperingham et al., 2017), reported acceptable inter-day reliability (ICC = 0.75 and CV = 10%) using a radar gun; however, these studies were done on highly trained male-only cohorts. Research has also suggested that there is a potential for greater bias and higher level of error in the early stages of a sprint when using a radar gun (Bezodis, Salo, & Trewartha, 2012). Overall, testing and monitoring short sprint acceleration is very important for comparing athlete performances; assessing training efficacy; talent identification; and for monitoring overtraining and long-term development (Rumpf & Cronin, 2011). Literature suggest that it takes at least three sessions for a learning effect to occur, therefore we can be confident that there was no learning effect that could comprise the results (Hopker, Coleman, Wiles, & Galbraith, 2009; K. D. Simperingham et al., 2016). Of note, the participants in this study only completed one familiarisation session but our data showed no evidence for improved reliability across the three sessions.

Meaningful difference

Improvements in force, velocity, and power against a load are valuable especially when matching the movement demands of sport, and allow for the assessment of training adaptations (Gonzalez- Badillo, Rodriguez- Rosell, Sanchez- Medina, Gorostiaga, & Pareja-Blanco, 2014; Perez- Castilla et al., 2018). In this context, it is crucial to understand the smallest worthwhile change that can be used to quantify meaningful differences in physical capacity(Hopkins, Schabort, & Hawley, 2001). These meaningful differences should be specific to the duration of an intervention and the population of interest. Here, we report important typical error data to inform practitioners working with female athletes regarding the magnitude of changes in performance measures, as well as calculated components of both vertical and horizontal force-velocity profiles.

Summary

The inter-session reliability of the force-velocity profile indices taken during the loaded squat jumps using an OptoJump demonstrated that the data illustrated fair to good relative reliability and acceptable absolute reliability. The inter-session reliability of the force-velocity profile indices taken during the 20-m sprint using a StalkerATS Radar Gun demonstrated poor to fair relative reliability and unacceptable absolute reliability. Overall, the Pmax values were deemed as the most reliable absolute and relative measurement for the jump and sprint tests. For the majority of measures there was no statistically significant difference between sessions, and there was no evidence to support a familiarisation effect. The typical error values reported here, provide important information for coaches and athletes, as they can be used to establish the meaningfulness of change scores in female athletes.

Chapter Three: Blood flow restriction was not effective to induce post activation potentiation in power and explosive performance in well trained female athletes

Abstract

Introduction: Post activation potentiation (PAP) is defined as the acute improvements in performance following a conditioning stimulus. Blood flow restriction (BFR) is a novel method that restricts blood flow to specific muscle groups in an attempt to promote hormonal responses resulting in improved performance. Research has shown some success using BFR as a potentiation tool in males BFR; however, there is very limited research done using females. Therefore, the aim of this study was to examine the PAP effects of body weighted squats with BFR on jump and 20-m sprint performance in trained females.

Methods: During the first session the participants were familiarised with the squat exercise with BFR and the jump and sprint protocols. This study was a randomised crossover study, so participants were assigned to either a control or BFR condition in the second session and then completed the other condition in session 3. Participants completed four sets of body weighted squats (30, 15, 15, 15 reps) with occlusion cuffs at a pressure of 180 mmHg when completing BFR condition to induce PAP. Loaded squat jump performance and sprint performance was assessed at baseline, 4 minutes, and 8 minutes post squat protocol, and theoretical maximal power (Pmax), force (F0), and velocity (V0), were calculated in vertical and horizontal directions.

Results: The results used to analyse jump performance showed a negative effect of time in bodyweight (p= 1.01×10^{-7}) and 24 kg jump (p= 2.97×10^{-6}) conditions. There was an interaction effect observed in the bodyweight jump (p = 0.0436), results showing that the decrease in jump height was more extensive in the CON condition. The results used to analyse sprint potentiation were considered unclear (Post 4: *d* = 0.22 ±0.42) or trivial (Post 8: *d*= -0.16 ±0.24). Therefore, reporting no evidence of potentiation in sprint performance at any time point after the conditioning stimulus. Correlational analyses indicated that $Pmax_{VERT}$ was very strongly

correlated with jump performance (r = 0.97), but $F0_{VERT}$ was weak (r = 0.22). In contrast, both $Pmax_{HORIZ}$ (r = 0.71) and $F0_{HORIZ}$ (r = 0.65), were strongly related to sprint speed. Interestingly, $Pmax_{VERT}$ was also very strongly related to sprint speed (r =0.83). Additionally, there was a strong relationship between $Pmax_{VERT}$ and $Pmax_{HORIZ}$ (r = 0.63), but the relationships between the corresponding horizontal and vertical F0 and V0 were weak. There was no indication that high levels of theoretical maximal force ($F0_{HORIZ}$ or $F0_{VERT}$) were related to a greater potentiation response. Across the two intervention sessions, 83% of the participants reported being in the same phase.

Conclusion: The results of this study showed that BFR failed to acutely improve jump and sprint performance therefore failed to elicit potentiation in trained females.

Introduction

The goal of strength and conditioning for athletes is to improve aspects of athletic performance to ensure that athletes have the ability to keep up with the demands of their sport and excel at the highest level (Bishop & Girard, 2013). Having the ability to produce large amounts of force and velocity are essential in an athlete's ability to produce power and execute movements more explosively (Cormie et al., 2008; Harrison et al., 2004). Therefore, this demands training methods and tools that can enhance strength and power both chronically and acutely to ensure performance is maximised.

PAP (Post-activation potentiation) is a phenomenon that has been shown to acutely enhance strength and power and can co-exist with fatigue (Blazevich & Babault, 2019; Hodgson et al., 2005). Post-activation potentiation involves the implementation of a conditioning exercise or stimulus to promote an increase in force exerted by a muscle, in turn increasing muscular power and athletic performance (Robbins, 2005; Tillin & Bishop, 2009). One proposed mechanism of PAP is an increase in calcium sensitivity of the acto-mysoin complex during contraction, but increased muscle temperature, muscle pH, muscle stiffness, and increased neural drive have also been suggested to play a role in the observed performance enhancement (Blazevich & Babault, 2019; Manning & Stull, 1979).

Common methods used to induce PAP include high intensity-low volume resistance exercise, whole body vibration (WBV), and isometric testing. A novel method that has recently been investigated to evoke PAP is the use of blood flow restriction (BFR). While BFR is well established as a method to enhance strength and hypertrophy (Loenneke, 2015), recent work has shown that BFR may hold promise as a conditioning stimulus to elicit PAP (Doma et al., 2020; Wilk, Krzysztofik, Filip, Lockie, & Zajac, 2020). It is known that the mechanisms of action for BFR include elevated metabolic stress, with decreases in oxygen availability (Takarada et al., 2000), heightened lactate, growth hormone, IGF-1, and testosterone responses (Abe, Yasuda, et al., 2005; Takarada et al., 2000), and likely enhanced recruitment of large motor units (Moritani, Sherman, Shibata, Matsumoto, & Shinohara, 1992; Takarada et al., 2000). Given that lactate is known to offset peripheral fatigue (Thomas et al., 2004), and that testosterone has been linked to priming of subsequent efforts (C. Bosco et al., 1996; C. Bosco & Viru, 1998; C. J. Cook, Kilduff, Crewther, Beaven, & West, 2013), and that the effectiveness of conditioning stimuli appears to be mediated by large motor unit recruitment, it appears that a BFR stimulus may promote a physiological environment suitable to elicit PAP (Loenneke et al., 2010).

In fact, early work from Beaven et al. (2012) suggested that repeated cycles of ischemia could enhance subsequent jumping performance. The participants in the study performed a variety of different tests including vertical jumps such as squat jumps, CMJ and sprints. Occlusion at a pressure of 220 mmHg was applied unilaterally to each leg (2 x 3 min per leg). This protocol resulted in an immediate positive effect on jump height; a delayed positive effect on eccentric power in squat jumps, and small beneficial effects in sprint times. More recently, Doma et al. (2020) demonstrated that BFR was effective to elicit PAP in upper and lower-body explosive exercises in males. There is, however, currently no information on the use of BFR as a potentiating stimulus to improve muscular power, force, and velocity in females. Therefore, it is the aim of the study to investigate the effects of BFR on PAP in power and explosive performance in trained female athletes.

Methods

Participants

Fifteen resistance trained team sport females (age = 20.0 ± 5.0 y, height = 167.2 ± 7.3 cm, body mass = 75.1 ± 13.3 kg; mean ± standard deviation [SD]) participated in this study. All participants were competing at regional level in sports such as rugby, rugby league, and netball that required lower body power. Participants were recruited via word-of-mouth and social media platforms and provided written consent form before participating in the study. Ethics was approved by the University of Waikato Human Research Ethics Review Board [HREC(Health)] and in accordance with the Declaration of Helsinki.

Study Design

This study was conducted as a cross-over randomised study design completed over three sessions. The first session was a familiarisation session, where the participants completed a standardised warm up, the PAP protocol using BFR combined with bodyweight squats, and then followed by the initial portion of the experimental testing protocol: loaded squat jumps and a 20 m sprint test on an indoor track. Each session consisted of a standardised warm-up (see Table 9) followed by six loaded squat jumps (two repetitions each at body weight, 24, and 48 kg) and a maximal effort 20-m sprint. During the second and third sessions participants were randomly assigned to either a BFR or no-BFR (CON) condition. The experimental sessions were separated by no more than 3 day, and at least 48 hours. All sessions began with participants completing a menstrual cycle questionnaire, followed by warm up, 4 min rest; baseline testing; intervention (the conditioning stimulus, see below for details); and then jump and sprint testing completed 4 min and 8 minutes after the conditioning stimulus.

Table 9: Warm-up protocol

Exercise	Sets/Laps	Time	Rest (s)
Jog	4	__	__
High Knees	2	__	__
Butt Kicks	2	__	__
Pogo Jumps	2	30s	20
Squat Jumps	2	30s	20
20m Sprint (70%)	1	__	10
20m Sprint (80%)	1	__	10
20m Sprint (90%)	1	__	10

Conditioning protocol

The conditioning stimulus to elicit PAP for both the BFR and control involved performing four sets of bodyweight squats (30, 15, 15, 15 repetitions) at a speed of 60 bpm following a metronome (Soundbrenner, Mobile App) with 30 second rest between each set. This protocol has previously been demonstrated to promote robust changes in growth hormones, lactate, and cortisol (Kim et al., 2014) and lead to significant strength/hypertrophy gains over time (D. J. Scott et al., 2017). Occlusion cuffs (Sports Rehab Tourniquet, SportsRehab, Australia) were placed on both lower limbs at the most proximal region of the quadricep at a standardised pressure of 180 mmHg. The control condition performed an identical PAP protocol, except that it was completed without occlusion cuffs.

Testing protocol

For the testing protocol, participants completed a series of six squat jumps (2 repetitions at body weight, 2 at 24 kg, and 2 at 48 kg). Two minutes after the loaded jumps, each participant also completed one maximal 20-m sprint. This protocol was performed three times in each session (Baseline, and 4-minutes and 8-minutes post the conditioning stimulus).

Loaded squat jumps

Participants were given appropriate cueing and verbal encouragement (Robin Healy, Kenny, & Harrison, 2016; Pedley, Lloyd, Read, Moore, & Oliver, 2017) and instructed to squat in a 90-degree angle, hold at the bottom for approximately two seconds before jumping up as high as they could without using the momentum of their arms. Two jumps were performed with bodyweight, and then with 12 kg and 24 kg dumbbells in each hand, in that order. Each jump was separated by 30 seconds recovery. Jump height data was recorded using OptoJump (Microgate, Bolzano, Italy) and initial analysis was done utilising Microsoft Excel.

20-m Sprint

Individuals completed one maximal 20 m sprint on an indoor track in athletic clothing. Participants were given appropriate cueing and verbal encouragement (Robin Healy et al., 2016; Pedley et al., 2017) and instructed to sprint from a standing start as fast as they could without decelerating until after a cone positioned at the 20 m mark. Instantaneous sprint velocity was recorded at 46.8 Hz using a radar gun (Stalker ATS II, Texas, USA) securely placed 1 m behind the participant at a height of 1 m above the ground. Speed data was collected in Stalker ATS II software and exported to Microsoft Excel.

Statistical Analysis

All performance data approximated a normal distribution when assessed via the Shapiro-Wilk test and descriptive data are represented as mean ± standard deviation (SD). Data were analysed in SPSS via a 2-way ANOVA with repeated measures to determine whether differences existed between time points (Baseline vs. post 4 vs. post 9; within-subject) and training groups (BFR vs CON) (between-subject) and Greenhouse-Geiser correction were applied. Cohen's effect size (*d*) was also calculated as the difference in group means divided by the standard deviation of the pooled data to quantify the magnitude of difference in measures between conditions. Cohen's *d* were interpreted using thresholds of <0.2, 0.2, 0.5, and 0.8 for trivial, small, moderate and large, respectively. Effects were deemed clear if the 95% confidence intervals did not overlap the thresholds for both small positive and negative effects (*d* ± 0.2). The level of statistical significance was set at $p < 0.05$. Correlation coefficients (Pearson's r- values) were determined for the whole group (n = 15) to describe associations between components of the F-v profile and performance, and interpreted using thresholds of 0.00 to 0.19 very weak, 0.20 to 0.39 weak, 0.40 to 0.59 moderate, 0.60 to 0.79 strong, and 0.80 to 1.0 very strong (Evans, 1996).

Results

Jump Potentiation

There was no evidence of potentiation of jumping performance at any time point in either the BFR or CON condition as jump height was consistently lower than baseline in all efforts (Figure 2). In fact, the repeated-measures ANOVA detected a negative effect of time in the bodyweight ($p= 1.01 \times 10^{-7}$) and 24 kg jump ($p= 2.97 \times 10^{-6}$) conditions. *Post hoc* analyses showed multiple significant decreases from baseline in both the BFR and CON conditions for the bodyweight and 24 kg jumps (Figure 2). There was no significant main effect of group (p ranged from 0.6892 to 0.8379) and the difference between the jump heights at all time points after the conditioning stimulus were trivial (*d* ranged from -0.18 to -0.08). A significant interaction effect was observed in the bodyweight jump (p = 0.0436), and *post hoc* analyses demonstrated that the decrease in jump height from baseline was clearly greater in the CON condition at the 4-min (*d*= 1.01 ±0.79, p = 0.0409) and 8-min (*d*= 0.90 ±0.94, p = 0.1113).

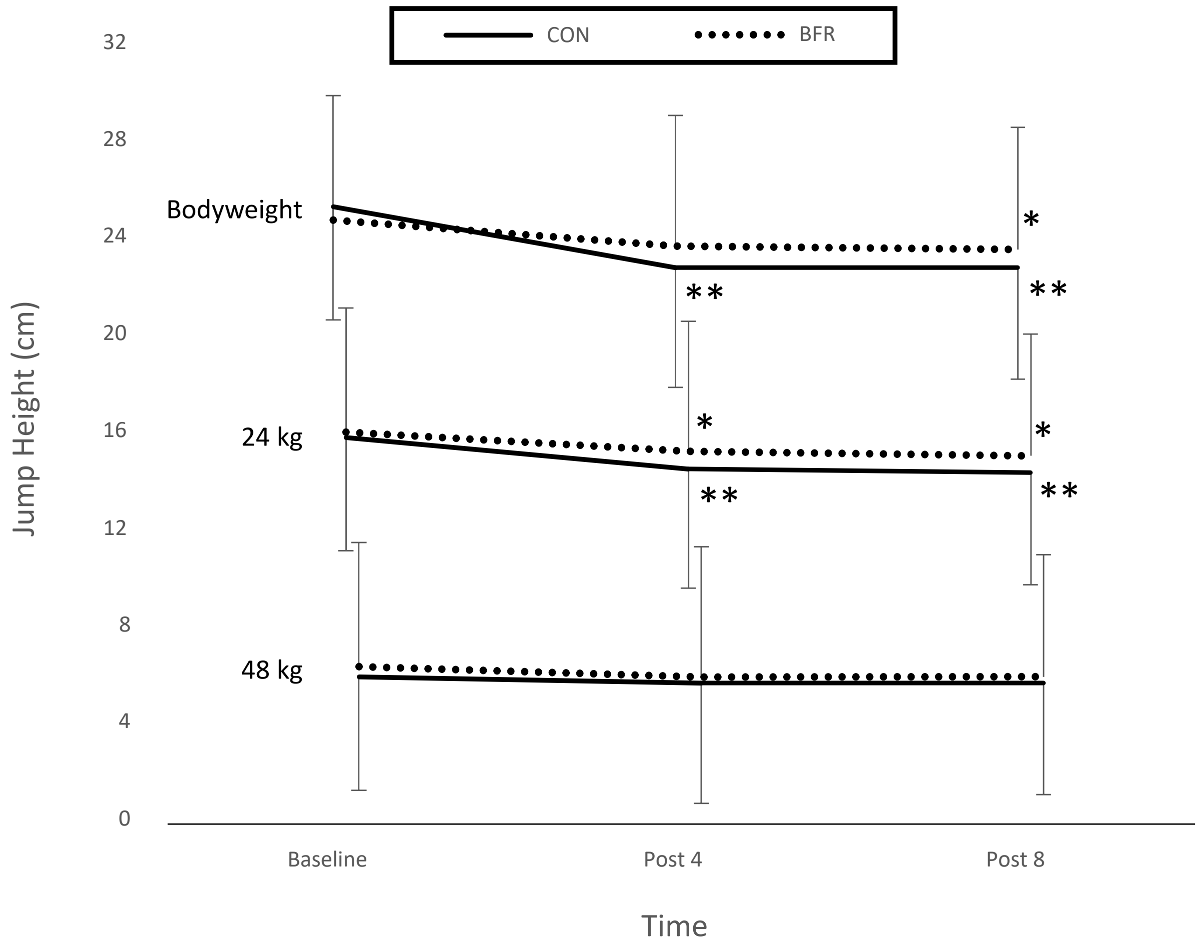


Figure 2: Jump height (cm) after different loads of squat jumps (BW, 24, 48 kg) and at time points (baseline, post 4 and post 8 min) after CON and BFR conditions.

Sprint Potentiation

Again, there was no evidence of potentiation of sprint performance at any time point in the BFR condition as sprint speed was lower than baseline in all efforts. The slight increase in sprint speed observed in the CON condition (0.3 km/h) was not statistically significant (p=

0.5057, Figure 3), and well below the cohort-specific typical error identified for this test (1.12 km/h, see previous Chapter). The repeated-measure ANOVA identified no effect of time (p= 0.5996), group (p= 0.9350), or any interaction effect (p= 0.3380). The difference between the sprint speeds at the time points after the conditioning stimulus were considered unclear (Post 4: *d* = 0.22 ±0.42) or trivial (Post 8: *d*= -0.16 ±0.24).

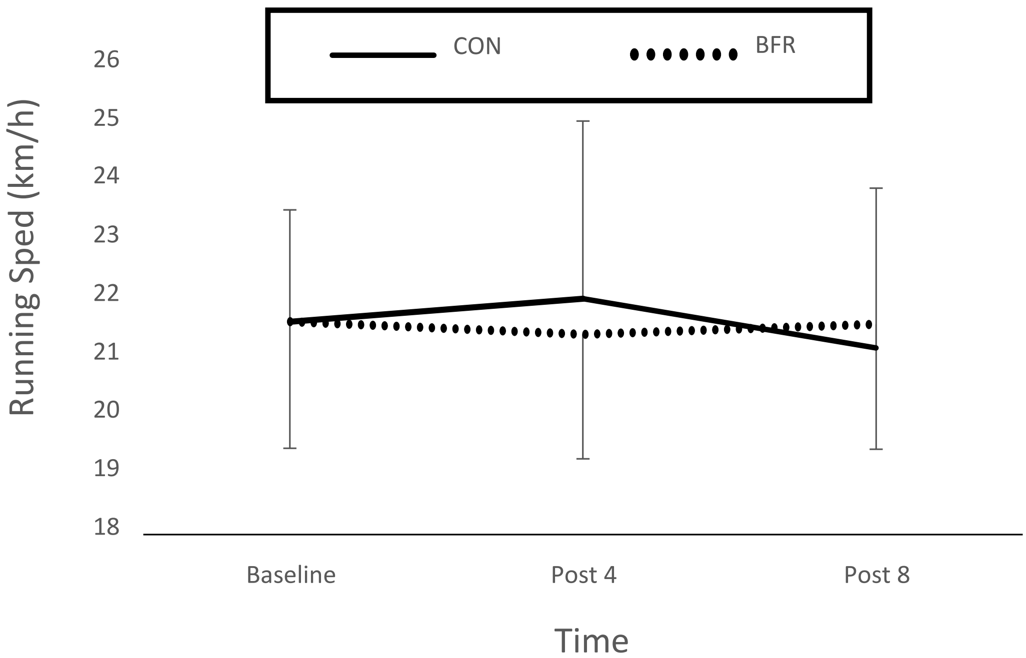


Figure 3: Running speed (km/h) at different time points (baseline, post 4 and post 8 min) after CON and BFR conditions.

Correlational analyses

There was a very strong correlation between jump performance and both $Pmax_{VERT}$ (r= 0.97, p= 2.31x10^{-9}) and $V0_{VERT}$ (r= 0.80, p= 0.0003); however, the relationship between $F0_{VERT}$ and jump performance was weak (r= 0.22, p= 0.4308, Figure 4). There were strong relationships between both $Pmax_{HORIZ}$ (r= 0.71, p= 0.0030) and $F0_{HORIZ}$ (r= 0.65, p= 0.0087) and sprint speed, but the relationship with $V0_{HORIZ}$ was weak and non-significant (r= 0.38, p= 0.1624, Figure 5).

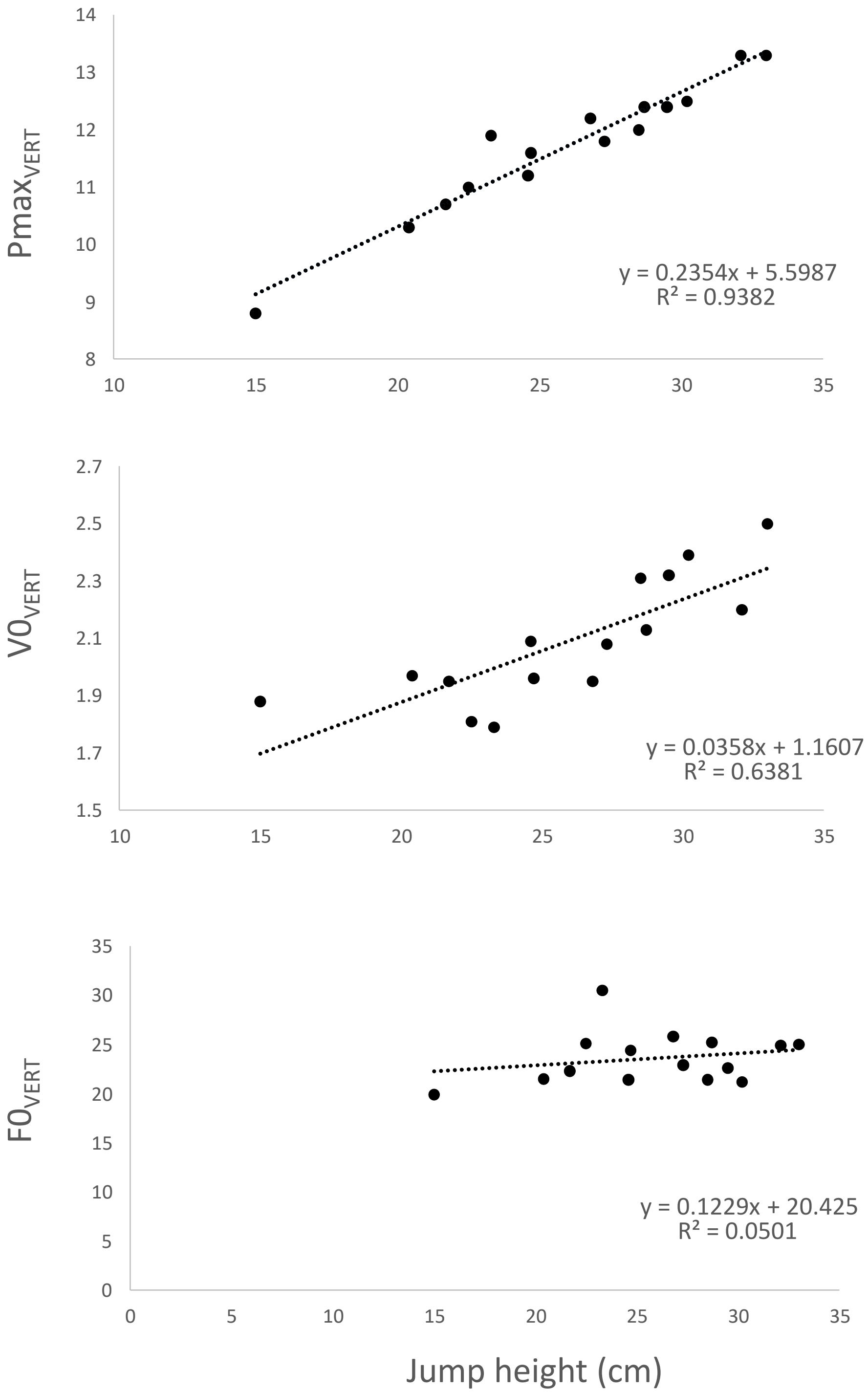


Figure 4: The vertical force (F0), velocity (V0) and power (Pmax) responses to jump height (cm).

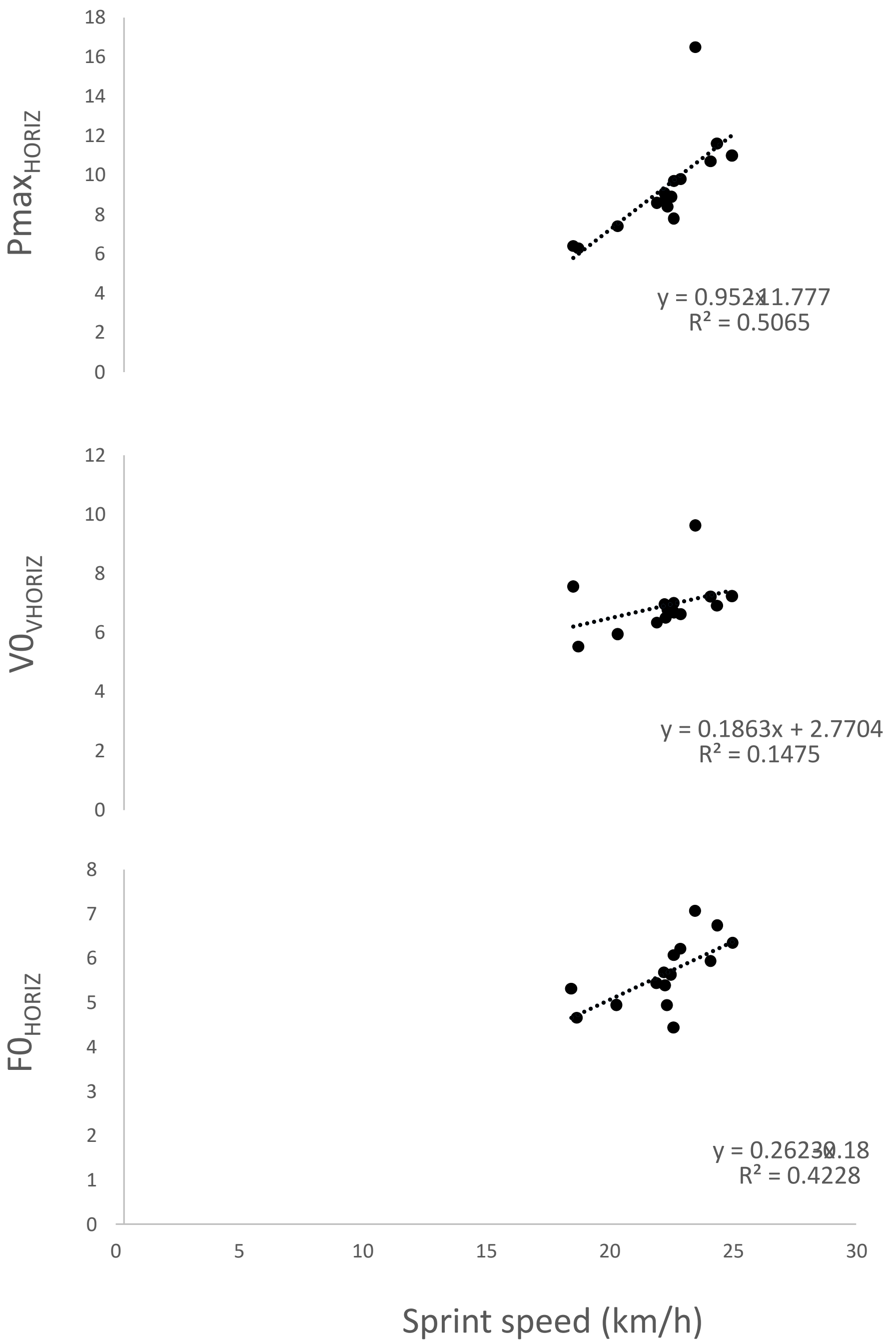


Figure 5: The horizontal force (F0), velocity (V0) and power (Pmax) responses to sprint speed (km/h).

When looking at the relationships between vertical F-v components and sprint speed, $Pmax_{VERT}$ (r= 0.83, p= 0.0001) showed a very strong significant correlation, whereas the relationship was weak and non-significant for $F0_{VERT}$ (r= 0.35, p= 0.2009) and moderate for $V0_{VERT}$ (r= 0.45, p= 0.0924, Figure 6). Alternatively, the relationships between horizontal F-v components and jump height were strong for $Pmax_{HORIZ}$ (r= 0.66, p= 0.0074) and $F0_{HORIZ}$ (r= 0.65, p= 0.0087), but weak and non-significant for $V0_{HORIZ}$ (r= 0.23, p= 0.4096, Figure 7).

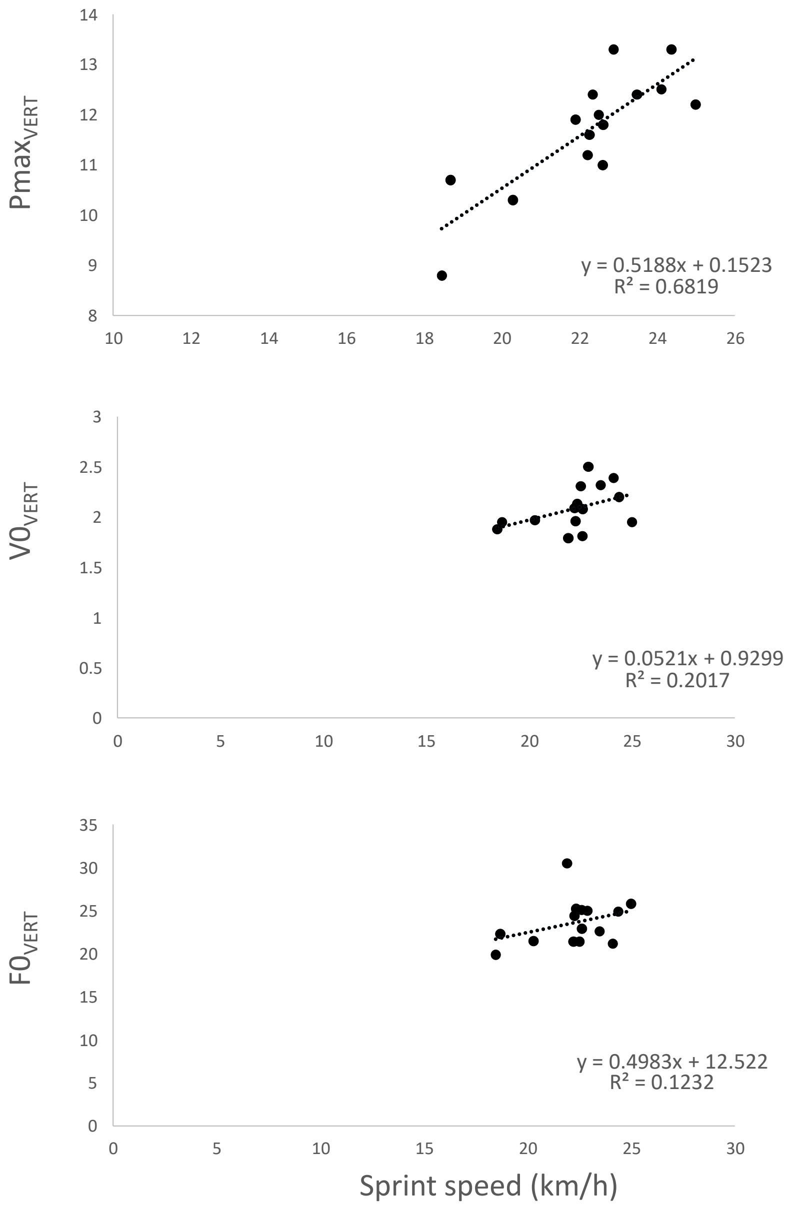


Figure 6: The relationship between vertical force (F0), velocity (V0) and power (Pmax) on sprint speed (km/h).

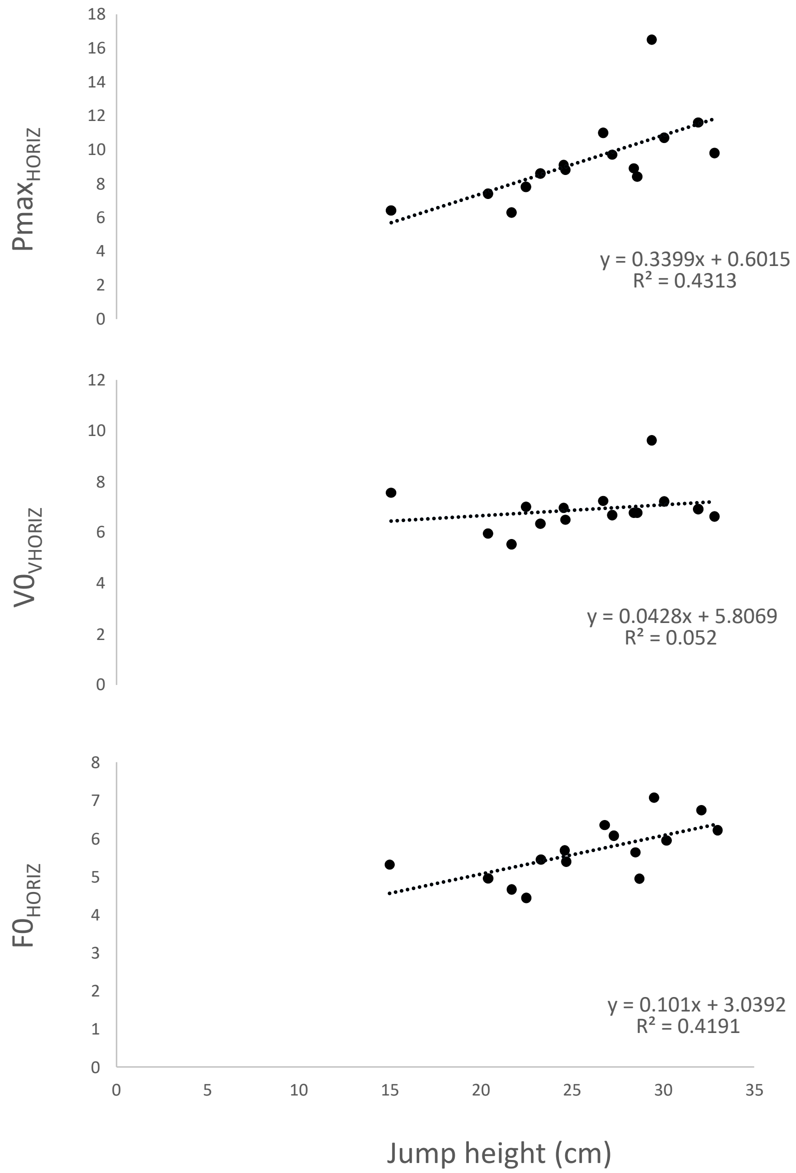


Figure 7: The relationship between horizontal force (F0), velocity (V0) and power (Pmax) on jump height (cm).

When looking at the relationships between the corresponding horizontal and vertical components of the F-v profiles, there was a strong relationship between $Pmax_{VERT}$ and $Pmax_{HORIZ}$ (r= 0.63, p= 0.0118), a weak non-significant relationship between $V0_{VERT}$ and $V0_{HORIZ}$ (r= 0.33, p= 0.2297), and a very weak non-significant relationship between $F0_{VERT}$ and $F0_{HORIZ}$ (r= 0.03, p= 0.9155, Figure 8).

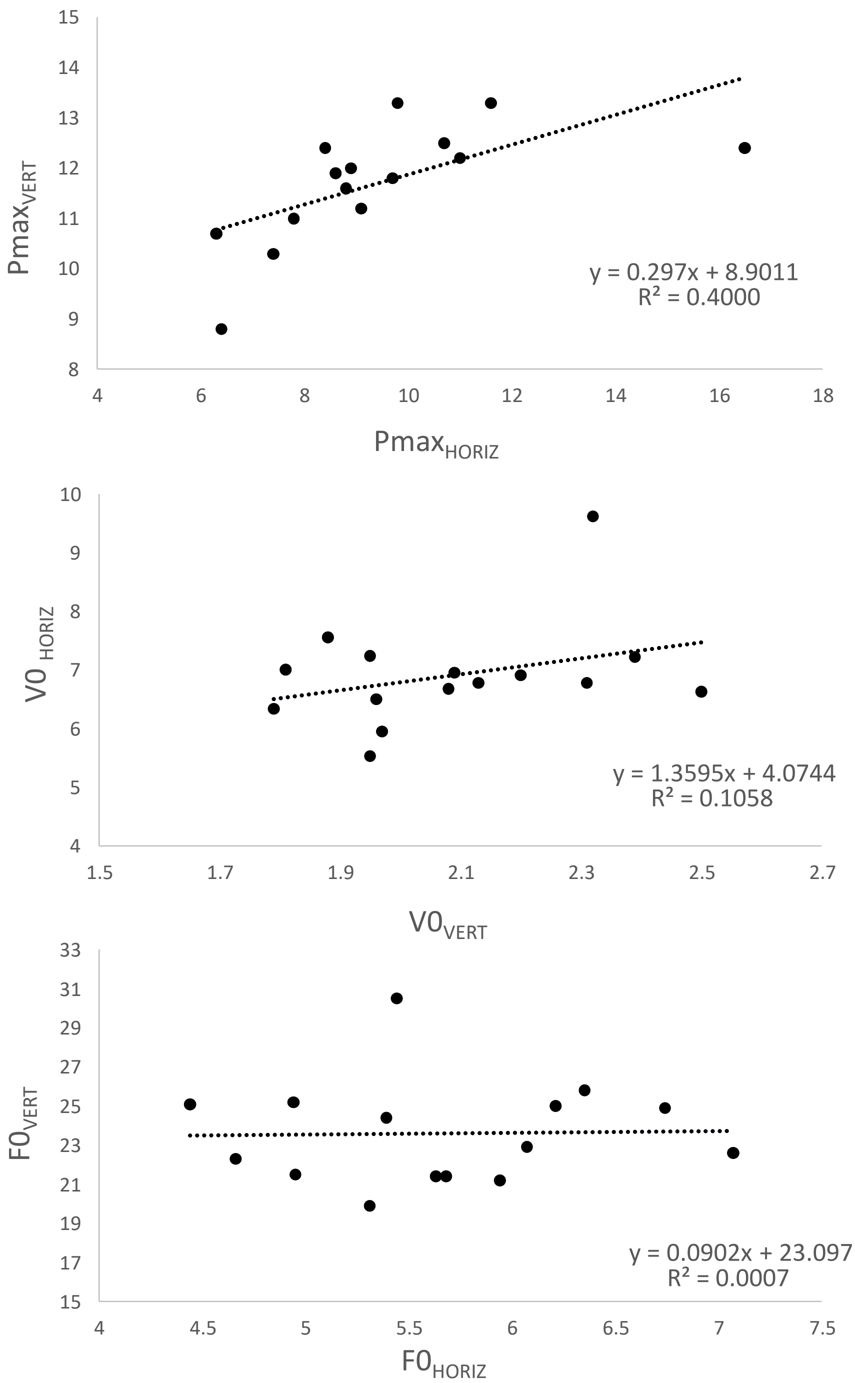


Figure 8: The relationship between vertical force (F0), velocity (V0) and power (Pmax) on horizontal force.

One other noteworthy correlation was that the relationship between $V0_{VERT}$ and $F0_{VERT}$, although not statistically significant, was negative (r= -0.29, p= 0.2944). There were no significant correlations found between the magnitude of potentiation observed in the jump or sprint and any individual component of the horizontal or vertical F-v profile. Specifically, the r-values ranged from -0.24 to 0.41 when investigating relationships between the magnitude of potentiation in the jump performance and the individual components of the horizontal and vertical F-v profiles and ranged from -0.46 to 0.13 when looking at the corresponding magnitude of potentiation in the sprint speed. Thus, these results showed no indication that if you were fast or strong you had a bigger potentiation response.

Results of menstrual cycle questionnaire

Menstrual cycle

Five participants (33.3%) reported being on their menstrual period and ten participants (66.7%) reported not being on their menstrual period at the time of the familiarisation session. Two (13.3%) reported being on their menstrual period, and thirteen participants (86.7%) reported not being on their menstrual period during testing session one (T1). At session two, four participants (26.7%) reported being on their menstrual period and eleven (73.3%) reported not being on their menstrual period in testing session two (T2). Two of the four that reported being on their menstrual cycle in this session were not on it in the first session and they stated having irregular periods due to contraception.

Age

Eight (53.3%) of the participants reported getting their menstrual cycle at 12 years old. Three participants (20%) at 13 years old, and one participant each (6.7%) at ages 10, 11, 14, and 15.

Contraception

Six participants (40%) reported no being on any contraception; three participants (20%) reported being on depo provera; two (13.3%) reported being on the rod; two (13.3%) have the IUD, and two (13.3%) are on the pill although two different types. Forty percent of the participants reported having their menstrual period while on their contraception; 13.3% reported not getting their menstrual period on their contraception, and 6.7% reported getting their period occasionally while on contraception. This study has reported on the use of oral contraception's and menstrual cycle status however we did not monitor or have any methodological control (Baker, Siboza, & Fuller, 2020). Studies have shown that on average women who are on oral contraception can have poorer power performance than those not on OC (Elliott-Sale et al., 2020). It has been suggested that it is related to the reduction of concentrations of oestrogen and progesterone which is commonly seen in the early phase of the follicular phase (Elliott-Sale, Cable, & Reilly, 2005; McNulty et al., 2020).

Discomfort

Eight participants reported experiencing discomfort while on their periods; 6 reported no discomfort and one reported that they sometimes experience discomfort.

Discomfort and performance

In the familiarisation session, 11 participants reported experiencing no discomfort and four reported experiencing discomfort that they perceived could affect performance. At T1, 13 participants reported experiencing no discomfort that would affect performance and two reported having cramps. At T2, 12 participants reported experiencing no discomfort that would affect performance and three reported experiencing some discomfort but did not clarify what. Perception is extremely important for performance, and although we did not measure pain perception and the relationship between menstrual phase and performance, it has been suggested that the rise in hormones seen in the luteal phase compared to the follicular phase can influence pain (Fillingim et al., 1997; Hoeger Bement et al., 2009).

Issues

Eleven participants reported no issues with menstrual cycle; four participants reported issues with menstrual cycle. Two mentioned stomach cramps; one participant mentioning getting cramps, sore back, and headaches, and one mentioned having irregular periods. Two participants stated that they use Panadol to help with the pain.

Menstrual phases

At the time of the familiarisation session, ten participants reported not knowing what phase they were in, two reported being in the luteal phase, and three reported being in the follicular phase. In session two (T1), nine participants reported not knowing what phase they were in, three reported being in the luteal phase and three reported being in the follicular phase. In session three (T2), nine participants reported not knowing what phase they were in. Two reported being in the follicular phase and four reported being in the luteal phase.

Overview

The main purpose of completing both T1 and T2 in the same week was in an attempt to make sure that our participants were in the same phase of their menstrual cycle. Of those who knew what phase they were in 83% of the participants reported being in the same phase and 17% reported being in different phases; however, they reported knowing that it was due to their contraception.

Discussion

The current study compared the PAP effects of bodyweight squats with or without BFR on sprint and jump performance in trained female athletes. The findings from this study demonstrated that there was no significant differences or improvements in CMJ jump height, or 20-m sprint times for either the BFR condition or the control condition, suggesting that occlusion protocol implemented does not induce a potentiation effect in trained female athletes. Specifically, jump height and sprint speed were lower at both time points following the BFR intervention; however, the decrease was significantly less than that observed in the CON condition for the bodyweight jumps at the four-minute time point.

For PAP to be successful in improving performance, the balance between PAP and fatigue is essential (L. B. Seitz & Haff, 2016). This PAP- fatigue continuum, means that the recovery needs to match the intensity of the stimulus (L. B. Seitz & Haff, 2016). Research has shown greater volumes of power training is more valuable for women due to their higher resistance to fatigue, which in turn exhibits lower levels of neuromuscular fatigue than men (Ansdell et al., 2019; Häkkinen, 1994; Linnamo, Häkkinen, & Komi, 1998; Rissanen, Walker, Pareja-Blanco, & Häkkinen, 2022). Linnamo and colleagues reported that a protocol of 5 x 10 x 40% 1RM leg press power slowed the reduction of maximal and rapid force production in females compared to men (Linnamo et al., 1998). The current study used a 30, 15, 15, 15 repetition method, based on prior work that had demonstrated robust anabolic hormone responses (Takarada et al., 2004)), increases in muscle activation (Yasuda et al., 2014), and improvements in sprint performance in trained males (B. R. Scott et al., 2017). Fujita and colleagues used a similar method but with bilateral leg extensions, and observed an enhancement in muscle protein synthesis, SK16 and mTOR signalling pathway after low load resistance exercise with BFR (Fujita et al., 2007). Unfortunately, the intervention protocol for the current study indicated signs of being too fatiguing, revealing that the level of fatigue outweighed potentiation likely explains why there was no improvements in jump height and 20-m sprint speed.

Blood flow restriction is still not fully understood, occlusion of the lower limbs restricts blood flow to the muscle in turn increasing metabolic stress (Takarada et al., 2000). It has been shown that low intensity resistance training combined with BFR can influence the promotion of a variety of different hormonal responses and systemic adaptations (C. J. Cook, Kilduff, & Beaven, 2013). Increases in endocrines such as lactate and systemic hormones such as plasma growth hormone, insulin-like growth factor-1, norepinephrine, and testosterone have all been reported after low-intensity exercise training with blood flow restriction (Abe, Yasuda, et al., 2005; C. J. Cook, Kilduff, & Beaven, 2013; Kawada, 2005; Loenneke, Abe, et al., 2012; Loenneke, Fahs, et al., 2012; West et al., 2013). BFR has also been used to activate and induce an earlier onset of type II fast twitch muscle fibres (Tillin & Bishop, 2009) which are all key aspects of improving overall performance and have been directly related to the underpinning mechanisms of PAP (Tillin & Bishop, 2009).

There has been many studies that have shown that PAP and BFR can influence hormonal responses including (Boullosa & Tuimil, 2009; Garcia-Pinillos, Soto-Hermoso, & Latorre-Roman, 2015) who reported greater lactate measures as a result of PAP. Overgaard, Højfeldt and Nielsen (2010) and Hwang and colleagues (2020) reported greater levels of lactate following a BFR training protocol. Cardinale and Stone (2006) reported that increases in testosterone promoted an increase muscle strength, size and type I and II fibres following a BFR training protocol. Abe and colleagues (2005) reported an increase in serum IGF-1 and growth hormone after two weeks of low intensity 'Kaatsu' training. Of note, all of these studies were performed with trained male participants.

The purpose of this study was to investigate the effects on females. A study by Kim and colleagues investigated the hormonal effects in trained female athletes. They investigated the effects of two different exercise regimens, a low intensity blood flow restriction group and a traditional high intensity resistance training group and found increases in growth hormone and cortisol levels post exercise after both conditions (Kim et al., 2014). These studies emphasise that blood flow restriction training can be used as a tool to increase hormonal responses in females, that may in turn influence adaptation and specific performance measures. However, it is also worthwhile noting that not all studies have had success with increasing different hormone responses. For example, Doma and colleagues (2020) reported no statistically significant increases in lactate levels following a twenty four lunge BFR protocol in trained males. These observations may have been due to the PAP protocol, physical characteristics of the participants, the recovery periods and timing of the lactate measures (Doma et al., 2020). Unfortunately, the BFR protocol used for this study was unsuccessful in promoting any performance improvement and we did not measure EMG, hormone responses, or lactate, therefore we are unable to report on any association between these factors and PAP induction following our BFR protocol. However, the research above means that we can be confident that the protocol did induce hormonal responses in females.

After reviewing the literature, the most common and most successful time point for improving sprint was between 4 to 8 minutes and jump between 4-15 minutes, hence why in the present study we assessed jump and sprint measures at 4 and 8 minutes post intervention. In the study by Doma et al. (2020), which has the most similar properties to the current study, the authors took measures at four different time points. Interestingly the results from this Doma study found that the most improvements were seen between 9 to 15 minutes emphasising that a range factor impact potentiation and that responses can be highly individual. The main contrasts between the current study and the study by Doma et al. (2020) is the sex of the participants and the differences in intervention protocols, with a lower volume of single-leg occlusion implemented in male participants.

The orientation and specificity of the movement has potential to influence the success of performance measures. Due to the importance of horizontal force production in the ability to enhance sprint performance and the significance of vertical force production in vertical jumps it can be assumed that the specificity of the movement would induce adaptations and acute effects related to a specific movement (Dello Iacono, Martone, Millic, & Padulo, 2017).

In their study, Dello Iacono and colleagues used a vertical oriented drop-jump stimulus in an attempt to improve both vertical jumps and horizontal sprints. The results demonstrated that the lack of specificity of the exercise resulted in no improvements in sprint performance (Dello Iacono, Martone, & Padulo, 2016). Loturco and colleagues performed a study where they showed that the vertical jump group produced greater adaptations in vertical jump ability and the horizontal jump group produced greater enhances in horizontal jump distances (Loturco et al., 2015). The research provided suggests that the specificity of the movement is crucial and evidently, could be a potential reason as to why the current study did not elicit any performance improvements in sprinting.

The results from this study for jump performance showed that $F0_{VERT}$ was of little importance in participants ability to jump higher; whereas $Pmax_{VERT}$ was essential in increasing jump height. Contrary to research by (P. Samozino, Rejc, Di Prampero, Belli, & Morin, 2012) who suggest that jumping performance relates more to high impulse versus the muscles ability to produce power. There was also small but insignificant correlation between $Pmax_{HORIZ}$ and jump height emphasising that you do not need to have a lot of power horizontally to be powerful vertically. It also emphasises that using a horizontal stimulus is not as efficient as a vertical stimulus when trying to improve vertical performance. The results for sprint performance showed that both $F0_{HORIZ}$ and $Pmax_{HORIZ}$ were important aspects of sprint speed. Interestingly, it can be noted that $Pmax_{HORIZ}$ was the most important aspect when trying to improve sprint performance. Of note, the results also showed that $Pmax_{VERT}$ was also key component in sprint speed performance. Research has shown that PAP is found to have a more positive effect in participants that have higher strength levels (R. Healy & Comyns, 2017). The findings from the current study did not support this notion as there was no relationship between the magnitude of potentiation and either horizontal or vertical F0. It should be noted however, that, the intervention overall was ineffective in eliciting potentiation. The results showed that the participants who produced the most force vertically did not produce the most force horizontally (no relationship between $F0_{VERT}$ and $F0_{HORIZ}$). Thus, the data reinforced that the ability to generate high levels of force vertically and horizontally are separate physical capacities that should be trained distinctly.

As this study was ineffective for demonstrating the benefits of bodyweight squats with blood flow restriction, we can appreciate that there were some potential limitations to this study. First, we recognise that the intervention protocol may have been too fatiguing, therefore, failing to acutely improve jump and sprint performance. Second, the standardisation of the methods; absolute loads that were used, cuff pressure, and cuff width failed to recognise individual characteristics and capabilities. Third, the conditioning stimulus was vertically oriented, which may not be efficient for more sport-specific exercises or for eliciting an improvement in horizontal performance such as sprinting. Fourth, we only took measures at 4- and 8-minutes post intervention; however, research has shown that potentiation can occur at up to 20 minutes. Finally, our small cohort of female-only participants may not be a true indication of the wider female population justifying the need for further research. While we noted self-reported menstrual phase data, we did not exclude the 17% of participants that reported being in a different phase of their cycle during the two testing sessions. Thus, for future research it may be worth adjusting the intervention protocol to try to find a better balance between fatigue and potentiation. If possible, increasing the population size and making the protocol more specific to each individual participant. Undergoing more extensive tracking of menstrual phase data and ensuring that participants are all in the same phases during sessions. It may also be worth including more movement specific exercises as a conditioning stimulus as it may be more beneficial for improving vertical/horizontal based performance.

Conclusion

In conclusion, the current study showed that body-weighted squats with BFR did not improve jump height or 20-m sprint performance 4-minutes or 8-minutes post exercise in trained female athletes. Thus, we suggest that the methodology of this study was inappropriate to elicit PAP and is not beneficial or effective for improving power performance in trained female athletes.

Chapter Four: Discussion, Practical Applications, Strengths, Limitations, Future Direction, and Conclusion

Discussion

Practical implications

From this study, it is evident that further investigation into the effects of BFR on relative power measures of lower-body expressions in female participants is needed. A clear implication of this research is the need for higher understanding of what factors can be used to induce PAP such as volume, intensity, and recovery, more specifically, how these factors differ in female participants compared to male participants. Acknowledging how the menstrual cycle can affect female performance is key to understanding how the different factors can affect the way the participants react to different PAP methods.

Strengths

A strength of this research was that the equipment used such as BFR cuffs; OptoJump; Radar Gun; weights, were all easily transportable and could be used in different indoor settings. The equipment was simple to use and still provided efficient data. The pilot study conducted played a key part in the selection of the equipment and weights used.

A second strength of this research was that the protocol was easy to complete in a timely manner and minimal experience was needed. This meant that the participants were not waiting around and were able to get the testing done swiftly. The familiarisation session allowed participants to learn the protocol and correct technique, making the testing session quick and effective.

A third strength of this research was that there was an opportunity to test up to four participants at one time, and only one person was needed to record all the data. This made the process easier as only one person needed to organise time around the participants availability.

A fourth strength to this research was the effort to ensure that the participants were in the same phases of their menstrual cycle, so their performance did not differ too extensively.

This required having a minimum of one day in between to allow for recovery but also ensure that each participant completed their testing sessions within the same week, generally about 48 hours in between. The results from this research are novel and emphasise the lack of research using BFR and PAP in female participants. Importantly, the BFR cuffs are easy to use in a lab, field or at home setting and can be used to prime muscles, elicit robust hormonal responses, and enable recruitment of large motor units whilst minimising fatigue.

Limitations

As with any research, the limitations must be noted. While we did our best to obtain reliable data, the limitations allow us to acknowledge what can be improved for future research.

- Cuff width: (It is important to understand how variations in the cuff application can affect the physiological responses and subsequent adaptation to BFR training. Wilk and colleagues emphasised that cuff width matters. They compared two different cuff widths and showed that BFR with the wide cuffs were more successful in promoting performance improvements compared to BFR with narrow cuffs and no BFR condition (Wilk, Krzysztofik, Filip, Zajac, et al., 2020).

- The current study only had a limited number of participants, while fifteen was my target number. A larger population size may provide more accuracy and less variability in the results.
- The BFR cuff pressure was standardised at 180 mmHg. Future research could consider making it more specific to the individual's systolic blood pressure.
- The weights used during the loaded jump squats were selected during the pilot study and were standardised. Future research could also consider selecting the weights more specific to the individual's body weight or strength level.

- As there have been few studies investigating BFR as a means of inducing PAP, there was minimal literature to reference when selecting intensity, volume, and recovery, and the time points of assessment.
- As with all female participants, the menstrual cycle plays a key part of overall performance. Whilst there was a menstrual cycle questionnaire, future research could consider ensuring that the participants are all in the same menstrual conditions e.g. no contraception, or all on the same contraception, and take a more intensive approach to tracking.
- We used a protocol that had been used by Fujita et al., (2007) that demonstrated significant physiological responses; however, after analysing the results of this current study, it was clear that the protocol (30, 15, 15, 15 repetitions with 30 second rest between each set) was too fatiguing and the volume of work meant that fatigue outweighed PAP.
- Given that potentiation can occur at a range of time points after the conditioning stimulus, taking measures at more time points may be of benefit as individual participants will differ in recovery.

Future research

The data observed from this BFR study demonstrated that the specific protocol was not as effective for improving performance in female athletes as we had hypothesized. However, this study has provided a foundation for further study into the effects of using BFR to induce PAP for power performance in female athletes. For future research, an investigation into the different training variables including volume, intensity, recovery, and athlete characteristics including age; body weight; strength, training experience is a necessity when trying to determine the most effective way to execute PAP methods. More research on BFR, the physiology of how it affects the body, and the most effective way to incorporate it to acutely enhance performance, will be thoroughly important to the advancement of the method. Additionally, a more in-depth analysis into the effects BFR has on performance measures, specifically power and explosivity related in both male and female participants, would be beneficial and would provide coaches, athletes, and other interested parties with potentially crucial information. Another vital element for future research is the differences in how females respond to different stimulus. A key question for future research is how female physiology may affect performances and how distinct interventions including BFR can influence the ability for potentiation. An investigation into why there is more research done on males, and a critical investigation into what methods can be used to improve female performance, will be significant for the ever-growing body of research regarding female participants.

Conclusion

In summary, the present thesis reports on the reliability of the indices within a force-velocity profile in relation to jump and sprint testing. It also reports on the effects of using BFR to elicit PAP in female athletes. While the data collected showed no significant benefit of using BFR, it is encouraging, and it can be used as a template with some advancements or changes for future research into how BFR can be used to improve athlete performance.

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Appendix

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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

26 March 2021

Jade Wharemate
Te Huataki Waiora - School of Health
DHECS
By email: jadewharemate15@gmail.com

Dear Jade

HREC(Health)2021#05 : Investigation of the effects of using blood flow restriction to stimulate post activation potentiation in well-trained female athletes

Thank you for sending in your amended application.

We are now pleased to provide formal approval for your project.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

RMD Walker

Dr Ruth Walker
Acting Chairperson
University of Waikato Human Research Ethics Committee

Informed Consent Form

Title – Investigation of the effects of using blood flow restriction to stimulate post activation potentiation in trained female athletes.

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

I also understand that:

I am free to withdraw from the study at any time or to decline to answer any particular questions.

I can withdraw any information I have provided up to two weeks after participating in the research activities by contacting the principal investigator.

Any data or answers will remain confidential in regard to my identity through a coding system.

The data might be published, so every effort will be made to ensure confidentiality and anonymity. However, anonymity cannot be guaranteed.

I agree to provide information to the researchers under the conditions of confidentiality set out on the Participant Information Sheet.

Consent to Participate

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

Participant: Proxy (if participant < 16 y): Researcher:

Signature: ______________________ ______________________

Name: ______________________ ______________________

Date: ______________________ ______________________

Additional Consent (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes.

Participant: Proxy (if participant < 16 y): Researcher:

Signature: ______________________ ______________________

Name: ______________________ ______________________

Date: ______________________ ______________________

Menstrual cycle questionnaire

1) Are you currently getting your menstrual period?

   Yes No

2) How old were you when you first got you menstrual period?
   10 11 12 13 14 15 16 17 18 19 20

3) Are you currently on any contraception?
   - If so, what contraception do you use?

4) Do you receive your menstrual period when using this contraception?

   Yes No

5) Do you experience any discomfort when you have your period?

   Yes No

6) Do you experience any discomfort that you believe will affect your performance? (e.g stomach cramps)

7) Do you have any issues with your menstrual period?
   - If so, what issues? How do you manage them?

8) Do you know what phase of your menstrual cycle you are in?
   - If so, are you in the luteal or follicular phase?

9) Is there anything we should know about you and your menstrual cycle?

Physical Activity Readiness Questionnaire (PAR-Q) and You

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly:

YES	NO		
☐	☐	1.	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
☐	☐	2.	Do you feel pain in your chest when you do physical activity?
☐	☐	3.	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4.	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5.	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6.	Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7.	Do you know of any other reason why you should not do physical activity?

If you answered:

YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want – as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active:

- If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- If you are or may be pregnant – talk to your doctor before you start becoming more active.

Please note: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Name BW: Leg length (stand): Leg length (squat):

Questionnaire: Yes/NO

FAMILIARISATION	PRE 1	PRE 2
BW Jump		
24kg Jump		
48kg Jump		

Menstrual cycle questionnaire (Session one)

1) Are you currently getting your menstrual period?

   Yes No

2) Are you currently experiencing any discomfort that you believe will affect your performance? (e.g stomach cramps)

3) Do you know what phase of your menstrual cycle you are in? (Please circle)
   Luteal Follicular Do not know

Con/BFR Questionnaire: Yes/NO Perceived Recovery:

	PRE 1	PRE 2	POST 4 (1)	POST 4 (2)	POST 8 (1)	POST 8 (2)
BW Jump						
24kg Jump						
48kg Jump						

Menstrual cycle questionnaire (Session two)

1) Are you currently getting your menstrual period?

   Yes No

2) Are you currently experiencing any discomfort that you believe will affect your performance? (e.g stomach cramps)

3) Do you know what phase of your menstrual cycle you are in? (Please circle)
   Luteal Follicular Do not know

Con/BFR Questionnaire: Yes/NO Perceived Recovery:

	PRE 1	PRE 2	POST 4 (1)	POST 4 (2)	POST 8 (1)	POST 8 (2)
BW Jump						
24kg Jump						
48kg Jump						