Priming for Power: Evaluating Warm-Up Protocols and Sprint Performance in Cycling

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List of Abbreviations

$\dot{V}CO_2$ – Volume of carbon dioxide produced

$\dot{V}O_2$ – Volume of oxygen consumed

$\dot{V}O_2max$ – Maximum rate of oxygen consumption

$\dot{V}O_2$ peak – Peak oxygen consumption

$\dot{V}O_{2,\ rest}$ – Baseline oxygen consumption

$\dot{V}O_2(t)$ – Oxygen uptake at time

°C – Degrees Celsius

~ - Approximately

> - More than

≥ - More than or equal to

≤ - Less than or equal to

± - Standard deviation

Δ - Delta

↑ - Significant increase

1-RM - One maximum repetition test

ANOVA – Analysis of variance

ATP – Adenosine triphosphate

ATP-PC – Adenosine triphosphate – phosphocreatine system

BMX – Bicycle Motocross

CHO – carbohydrate

cm – Centimetre

EMG - Electromyography

FI - Fatigue index

$g \cdot min^{-1}$ - Grams per minute

GET – Gas exchange threshold

H^+ - Hydrogen ion

HR_{max} – Maximum heart rate

Hz – Hertz

$J/rev/kg^{-1}$ – Joules per revolution per kilogram

Kcal – Kilocalorie

$kcal \cdot min^{-1}$ - Kilocalories per minute

kJ – Kilojoule

kJ/min – Kilojoule per minute

$kJ \cdot L^{-1}$ – Kilojoule per litre

L – Litre

LED - Light emitting diode

m – Meters

Max – Maximum

Min - Minute

Ml/kg/min – Millilitres per kilogram per minute

mmol/L – millimoles per litre

n - Number

$N \cdot kg^{-1}$ – Newtons per kilogram

NIRS – Near Infrared Spectroscopy

PAP – Post-Activation Potentiation

PAPE – Post-Activation Performance Enhancement

PCr – Phosphocreatine

RER – Respiratory Exchange Ratio

RMR – Resting metabolic rate

$rev \cdot min^{-1}$ – Revolutions per minute

s – Seconds

TTPC - Time to peak cadence

TTPP - Time to peak power

W – Watts

WBV - Whole body vibration

W_{La} – Energy contribution of anaerobic glycolytic system

W_{PCr} - Energy contribution of anaerobic alactic system

W_{TOT} – Total metabolic energy contribution

$W_{\dot{V}O2}$ – Energy contribution of aerobic system

1. Thesis Overview

1.1 Abstract

Warm-ups are employed to elevate muscular temperature prior to an exercise task, enhancing performance and reducing injury risk. Increases in muscular temperature enhances performance by facilitating an increase in blood flow to the respiring tissues, faster nerve conduction velocity, higher enzymatic activity, and enhanced metabolic responses. Two types of warm-ups exist, increasing muscle temperature differently: Passive warm-ups via external means, and active warm-ups through exercise.

In BMX racing, where scientific literature is sparse, no studies have established warm-up strategies to optimise BMX performance. To begin to address this gap, a systematic review examined the effects of warm-up routines on ≤ 30 s sprint cycling performance, identifying warm-up intensity, duration, and recovery period between the warm-up and exercise task as critical factors influencing sprint performance. However, intensity definition varied, and cadence, a known determinant of BMX performance was a significant omission from the literature included.
To extend these findings, a laboratory-based experimental study explored whether the manipulation of cadence during a sprint-based warm-up could influence subsequent 30 s Wingate performance following a 30-minute recovery, reflecting BMX race conditions. Twelve male recreational cyclists completed warm-ups under

different cadence conditions, with blood lactate, skin temperature, energy system contributions, resting gas exchange, and Wingate performance assessed.

Cadence manipulation successfully elicited intensity variation; however, following a 30-minute recovery, any performance benefits had dissipated, with no significant differences observed between conditions. These findings suggest that maintaining thermal and neuromuscular readiness across prolonged recovery may require a stronger warm-up stimulus, supported by direct markers of readiness and carefully timed before performance.

Keywords: Warm-up, BMX racing, Performance, Cadence, Intensity

1.2 Thesis justification

A warm-up is a practice employed primarily to increase muscular temperature prior to an exercise task and is widely utilised to prepare for sporting competition (1), to reduce injury (2, 3) and contribute towards optimal performance (4, 5).

Substantial evidence has discovered that warm-up strategies can enhance performance (6-8); however, athletes often rely on personal experience and preference to warm-up rather than in alignment with evidence-based recommendations (7, 8). Warm-ups can be divided into two main sub-categories: active and passive. Passive warm-ups involve increasing muscular or core temperature via external means, for example, heating garments (5). Active warm-ups generate increases in temperature through exercise such as cycling or running. Generating greater muscular temperature in a warm-up is one of the main mechanisms that enhances performance (5, 7) as it facilitates an increase in blood flow to the respiring tissues, enhances metabolic responses (9), facilitates faster nerve conduction velocity, and higher enzymatic activity (10). Increases in muscular temperature are driven by metabolic inefficiencies when attempting to supply the muscle with energy (11). It has been seen that for a litre of oxygen consumed, only 4 kilojoules (kJ’s) of the total 20 kJ’s (from the oxidative catabolism of fats and carbohydrates) are utilised to complete the exercise (11). The remaining 16 kJ’s are lost as heat (11). This increase in muscular temperature, even if only by 1 °C, can lead to a 2-5 % increase in short-duration exercise performance (12), resulting from enhanced muscle metabolism, muscle fibre performance, and muscle fibre conduction velocity (7).

In cycling, increased muscle metabolism occurs as a result of greater muscle temperature due to an increased resynthesis of adenosine triphosphate (ATP), via escalation in the rate of phosphocreatine (PCr) utilisation, hydrogen ion (H+) accumulation, increased anaerobic glycolysis and increased muscle glycogenolysis (13-15). Resulting from these metabolic alterations, power production has been seen to be the major beneficiary (14).

Increased muscle fibre performance, from raised muscle temperature, derives from greater PCr and ATP utilisation in type II muscle fibres at high cadences (~ 160-180 revolutions per minute (rev·min^{-1})) (15). The same can be found in type I muscle fibres at lower cadences ≤ 60 rev·min^{-1} (16).

Elevations in muscle temperature also increase muscle fibre conduction velocity due to alterations in the force-velocity and power-velocity relationships (17-19). This facilitates greater power outputs in the exercise task (17), with muscle temperature rises of ~ 3 °C augmenting greater power output and muscle fibre conduction velocity (14). The best warm-up will balance the increase in muscle temperature to the optimal range while limiting the potential fatigue that can develop following exercise (9). If a warm-up is performed at too great an intensity, an impairment in supramaximal activity can occur due to the accumulation of H+ ions inhibiting anaerobic glycolysis (6).

The increase in intramuscular temperature observed following a warm-up activity can be classified under the term post-activation performance enhancement (PAPE). PAPE can be defined as

Another effect that can occur following a warm-up is a post-activation potentiation (PAP) effect on the muscle group utilised during the warm-up, increasing the ability to produce power via increasing the muscle contractile response (6, 7). PAP has been defined as an enhancement of muscular performance stemming from prior near-maximal or maximal neuromuscular activation exercise (20-22). This is measured by maximum twitch force from supramaximal electrical stimulation(23, 24). However, if twitch stimulations are not measured, no confirmation of PAP being evoked exists, thus, other factors including intramuscular temperature increases can be underpinning subsequent performance enhancement(25). Furthermore, the effect of PAP lasts for < 3 minutes(26) when peak voluntary performance enhancement can last 6–10 minutes post warm-up (27), consolidating that other factors are driving performance. As a result, post-activation performance enhancement (PAPE) was developed, defined as when high intensity voluntary contractions from a warm-up enhances subsequent voluntary muscular performance without twitch force assessment (28). Physiological effects from a warm-up include increased oxygen uptake (29), increased muscle fibre activation (30), higher blood and muscle lactate levels (31), and elevation in heart rate (32).

Previous studies have found that active warm-ups lead to greater short-term performance improvements across various sports (5, 9). In addition, incorporating task-specific activities into the warm-up can also produce ergogenic effects (5) by targeting the sport's specific demands. Specifically for the generation of greater power, warm-up guidelines have suggested that including general and specific activities within the warm-up would be beneficial to performance, with the general exercise increasing muscle temperature and the specific exercise increasing neuromuscular activation (33, 34). In high-intensity sports, such as BMX racing, the exercises forming the warm-up aim to enhance supramaximal performance and should be considered within the specific activities of the warm-up.

1.3 Motivation for Thesis

A BMX race event comprises a sequence of races: qualification rounds known as motos, knockout rounds, and the final (35). Each race typically lasts between 30-50 seconds (s), seeing up to eight riders compete to qualify for the final (35). Each BMX track is unique in shape and distance, ranging between 200-400 meters (m) in length, incorporating a plethora of jumps, corners, and flat sections (35). A BMX track encompasses three phases: firstly, the acceleration phase is determined by the gradient of the start ramp and of the rider's ability to generate maximum power. The second is the mixed central phase, during which riders combine impulse actions over obstacles with pedalling where possible to generate or maintain maximum velocity. The third is the stamina phase in which riders attempt to maintain their high cyclic power output, maximum speed via pedalling and coordination; therefore, velocity stamina plays a significant role in the final performance during a BMX race (36). The opportunity to apply power during a BMX race is limited, increasing the importance of the acceleration phase or initial starting sprint in BMX racing (37-40). Previous research states that riders who reach the end of the first jump ahead of their competitors gain an advantage and can finish in a quicker time (41). More specifically, it has been seen that there is a significant correlation between early race performance, the first 8.27 s for males and 9.90 s for females, and finishing in the top 3 positions in a BMX race (42), meaning power output can be seen to be a key performance indicator in BMX racing.

As observed in many cycling events, power-to-weight ratio is a key determinant of lap time in BMX racing (43). This highlights the importance for successful riders to maintain a low body mass, in conjunction with the ability to produce high power output, particularly during the initial acceleration phase (2).

At the start of a race, athletes will attempt to obtain peak power in the shortest time, with time to peak power observed during a BMX race of 2.34 s (44), to accelerate past opponents; however, this power output decreases until the end of the race. During the decrease in power output, velocity continues to rise (45), meaning other factors must be key to performance in BMX racing. Similar to velocity, cadence also increases when power output is decreasing, meaning the increase in velocity and decrease in power could be due to rising cadences (45), making cadence a key performance indicator. Furthermore, this study found that riders could not maintain peak power when reaching a cadence of 125 $rev{\cdot}min^{-1}$, when peak cadences of 212 $rev{\cdot}min^{-1}$ have been discovered in BMX athletes (46), demonstrating that BMX athletes rely on cadence alongside power and impulse actions to create and maintain velocity (45).

The inclusion of specific movements within a warm-up has been seen to increase performance via enhanced neuromuscular activation (33, 47). With peak cadence production being a vital component of BMX race performance, its inclusion within a warm-up may hold benefits to subsequent sprint performance. Furthermore, cycling at high cadences (> 100 $rev{\cdot}min^{-1}$) compared to low cadences (~ 50-95 $rev{\cdot}min^{-1}$) produces different physiological responses. At high cadence, increased cardiorespiratory strain, muscular efficiency, and metabolic costs have been observed, compared to higher heart rate, blood pressure, and blood lactate levels resulting from lower cadences (48, 49). Muscle activation patterns are also influenced by extended high cadence cycling, shifting workload distribution across thigh muscles (50-52). Thus, the manipulation of cadence during a warm-up may result in performance variation.

Energy system contribution during a BMX race has not been studied in the field due to the possibility of equipment interfering with performance; however, research has suggested that the phosphocreatine (PCr) metabolism contributes a large proportion of energy (53). During six-second repeated maximal sprints on a cycle ergometer, it was discovered that, during the first sprint, participants utilised 49.6 % of PCr for energy and the remainder from anaerobic glycolysis. As each sprint was repeated, power output gradually declined, as did the contribution of ATP from anaerobic glycogenolysis, indicating that most ATP production in the latter sprints derived from PCr breakdown and oxidative metabolism (54). Concerning this study, the initial six-second sprint gives a partial indication as to the contributing energy systems during the acceleration phase of a BMX race; however, it is unreliable to infer further information from this study due to the large rest periods (30 s) between sprints. Over an extended 30 s sprint duration, anaerobic glycolysis energy contribution caused 83 % variation of peak power and 81 % variation of mean power (55), highlighting that individuals with a higher tolerance to fatigue can produce higher power over 30 s . Over the course of a BMX race, blood lactate response has been seen to be significantly correlated with mean lap time and mean power over the race (43).

Assessment of respiratory variables during a BMX competition demonstrates the importance of the aerobic system and $\dot{V}O_2max$ in BMX racing, stemming from the need to recover repeatedly throughout a competition, with a typical rest time between races of 30 minutes (43). It has been reported that a high $\dot{V}O_2peak$ could be responsible for 54 % variation in lap performance over repeated efforts (43, 56). This suggests that whilst the sport is predominantly anaerobic in nature, aerobic capacity does indeed play a contributing factor to performance across a competition day. These physiological factors affecting performance are vital to understand when looking to optimise BMX performance with specific warm-ups.

To the best of our knowledge, no research has tested the effects of manipulating a warm-up on BMX performance. This, in part, may be due to the difficulty in replicating the true demands of the sport with laboratory and field testing. Disparities in peak power outputs between participants of 85.21 % have been observed between an eight-second sprint on a straight with a 5 % slope and during a BMX race (36). The disparity can be highlighted again when comparing the peak power of 1145 W discovered in this study during BMX races, to the peak power of 1504 - 1607 W during 30 s Wingate tests in a laboratory environment (57), with both studies utilising nine elite BMX racers.

These studies demonstrate large disparities between lab testing and field testing in BMX racing which, in part, could be due to the differences in equipment and the training status of the athletes. Furthermore, the utilisation of power meters to test the demands of BMX racing in the field is difficult due to a lack of BMX racing-specific power meters (58) that can fully capture the powers and cadences experienced, meaning field testing is limited in what it can measure. Current power meters, such as the SRM crank power meter, have a sampling frequency of 2 Hertz (Hz), meaning two data points are recorded every second (58). BMX athletes have been seen to reach cadences of up to 212 $rev \cdot min^{-1}$ (46), meaning that at this frequency, the power meter would only take a sample every 1.77 revolutions of the crank, potentially missing key data in an intermittent sport.

With the ability to better control the environment, leading to better study reliability, laboratory studies in BMX racing are more common. However, due to the lack of a BMX-specific laboratory test, the careful selection of a performance test is vital. To assess sprint capacity, peak power is often measured over durations of ≤ 30 s (59), with tests such as the Wingate test facilitating the observation of power, cadence, force, and fatigue during the 30 s duration, all of which have been linked with BMX race performance (38, 45). Because of this, and the similar durations of the Wingate test and a BMX race (57), it has been utilised in multiple studies to test BMX performance (56, 59-62).

1.4 Thesis Aims

This thesis aims to explore and manipulate the components of a warm-up to develop an understanding of warming-up for short-duration sprints. To achieve this, two studies were conducted:

1.4.1 Study 1

Warm-up strategies for short-duration sprints. A systematic review.

Study aims

To identify and evaluate various warm-up strategies for cycling sprints lasting ≤ 30 seconds, to determine which approaches can effectively enhance performance during a BMX race.

1.4.2 Study 2

Cadence variation during sprint warm-up does not influence Wingate performance

Study aims

1) To create warm-ups that manipulated cadence over repeated sprints and resulted in significantly different intensities.

2) Assess the effects of the warm-up strategies on Wingate performance following a 30-minute recovery.

Chapter 1

2. Warm-up strategies for short-duration sprints. A systematic review.

2.1 Abstract

Warm-ups, whether active (exercise-based) or passive (external means), aim to elevate muscular temperature, enhancing performance and reducing injury risk. Effective warm-ups encompass the specific demands of the subsequent task, yet no research has directly examined their impact on BMX race performance. BMX racing relies on determinants including power production, high cyclic cadences, impulse actions which are challenging to replicate in field or laboratory settings. Consequently, many studies typically employ shorter sprints, ranging from 10-30 s, to assess performance indicators relevant to BMX racing.

The systematic review identified and evaluated warm-up strategies for cycling sprints lasting ≤ 30 s, determining which approaches can effectively enhance BMX race performance. Across studies, intensity, duration and recovery period before exercise task emerged as key factors influencing warm-up effectiveness. Incorporating task-specific exercises during a warm-up was also found to enhance subsequent performance. However, warm-up intensity was often inconsistently defined, infrequently tailored using participant-specific physiological measures, and cadence was notably underrepresented in the literature.

Future research should prioritise designing task-specific warm-ups, altering either intensity, duration, or the recovery period, to clarify the mechanisms driving performance variation.

Keywords: Warm-up strategies, BMX racing, Sprint performance, Intensity, Cadence

2.2 Introduction

A warm-up is a preparatory activity that elevates skeletal muscle temperature, either through active exercise or passively via external modalities, intending to optimise subsequent exercise performance. Numerous studies provide evidence that warm-up routines significantly enhance performance outcomes across a range of sporting disciplines, including sprint-based running, cycling, and swimming, as well as field-based sports involving repeated sprints (5-7). Warm-up routines are highly adaptable and can be modified to accommodate various factors, including the demands of the sport, environmental conditions (e.g. ambient temperature), logistical constraints of the event, and the athlete's fitness and performance level (5, 63). The extent to which a warm-up enhances performance is primarily determined by its design (1), with the key variables affecting its effectiveness including the intensity and duration of the warm-up, the specific activities incorporated, and the recovery interval between the warm-up and the start of competition (5). An optimal warm-up effectively manipulates the intensity, duration, and recovery period, subsequently increasing performance by generating favourable physiological conditions, particularly elevating skeletal muscle temperature to an optimum level. Increased temperature drives higher enzymatic activity (10) and enhances the metabolic responses (9), furthermore, increased skeletal muscle temperature enables greater blood flow to the respiring tissues and causes faster nerve conduction velocity (10).

In addition to these thermal effects generated by a warm-up, enhanced neuromuscular mechanisms can also come to fruition, including post-activation potentiation (PAP).

PAP refers to a phenomenon whereby skeletal muscle exhibits an enhanced contractile response following previous high-intensity stimuli (25, 64). PAP enhances force production in the skeletal muscle by increasing myosin light-chain phosphorylation occurring in type 2 muscle fibres (25). The magnitude of PAP is influenced by the intensity and duration of the preceding stimuli, as well as the recovery period, with optimisation varying within individuals (25).

Determining the optimal warm-up for a sport requires an understanding of the physiological demands to select exercises that maximise performance outcomes. In high-intensity sports, such as BMX racing, the exercises forming the warm-up aim to enhance supramaximal performance and should be considered within the ‘specific activities’ of the warm-up. The determinants of BMX racing performance are characterised by three distinct phases of a race track: the acceleration phase, determined by the gradient of the start ramp and maximum power production (36, 65) over a large range of cadences (66); mixed central phase, utilisation of rapid impulse actions over obstacles requiring isometric strength with coordination (36), and pedalling to increase and/or maintain velocity; the stamina phase, riders aim to maintain their velocity via high pedalling cadences and coordination (36).
Resulting from these phases, the opportunity to apply power during a BMX race is limited, increasing the importance of the acceleration phase or initial starting sprint in BMX racing (37-42). As a result of this, athletes will attempt to obtain peak power in the shortest time to accelerate past opponents. Subsequently, this power output decreases until the end of the race; however, during the decrease in power output, velocity continues to rise (45), meaning other factors are key to performance in BMX racing. Similarly to velocity, cadence also increases when power output is decreasing, meaning the increase in velocity and decrease in power could be due to cadence (45), making cadence a key performance determinant. Furthermore, this

study found that riders could not maintain peak power when reaching peak cadences of over 125 rev.min^{-1}, demonstrating that BMX athletes rely on cadence alongside power to create and maintain velocity (45).

BMX performance has also been linked to concentric capacity and explosive elastic reflex of the muscle, with countermovement, squat, and drop jump performance all being associated with BMX lap time (67). The recruitment of the upper body has a significant correlation with velocity during a BMX race to complete the pumping technique, an autonomous motor function (68-70). The dynamic, isometric technique that is created by a combination of the upper body and single hip and knee extension of the lower body, which leads to greater impact forces to the muscles (71). These physiological factors affecting performance are vital to understand when looking to optimise BMX performance with specific warm-ups.

In addition to understanding the key performance variables, knowledge of the energy systems to fuel the exercise is important. Studies have suggested that BMX racing elicits a high contribution of energy from aerobic and anaerobic systems (43, 56). Specifically, the adenosine triphosphate–phosphocreatine (ATP-PC) system is utilised to a great extent alongside anaerobic glycolysis due to the high-intensity intermittent sprints (43). The ATP-PC system works by utilising phosphocreatine molecules stored within the skeletal muscle. When ATP stores are low, phosphocreatine is hydrolysed into creatine, phosphate, and energy. The energy is great enough for adenosine diphosphate to bond with the now free phosphate to regenerate ATP. The ATP-PC system is able to produce peak ATP resynthesis within one second of the onset of exercise (72), demonstrating the rapid response this system has. Anaerobic glycolysis generates ATP by breaking glucose into pyruvate, which releases energy. However, as oxygen is not available, pyruvate converts into lactate, facilitating the process of glycolysis to continue (73). The production of lactate has been linked to decreases in performance. In a study on simulated BMX race performance, increased blood lactate concentrations correlated to increased total lap time (43). Although lactate is an indirect marker for the metabolic conditions which cause metabolic acidosis (74), there is no biochemical support that lactate induces acidosis, which would decrease exercise performance (74). The role of lactate in anaerobic glycolysis is to facilitate the regeneration of NAD from NADH by accepting hydrogen ions; thus, the process of oxidation, glycolysis, and the production of energy in the form of ATP can continue. Decreased performance deriving from anaerobic glycolysis is caused by hydrogen ions produced during the oxidation of triose phosphate. The hydrogen ions are positively charged (protons) and build up in the tissue, causing cellular acidosis rather than lactate. Without lactate production, muscular acidosis and fatigue would occur at an increased rate, meaning exercise performance would decrease (74). In addition, the Cori cycle and gluconeogenesis utilise the substrates lactate and pyruvate to regenerate glucose (75) for subsequent use in the skeletal muscle in glycolysis to produce energy. Consequently, this demonstrates the vital role lactate has in metabolic processes to support the energy requirements of the body, contrasting the belief that lactate causes detrimental effects to performance.

The relative contribution of each energy system to sprint performance varies considerably across studies, largely due to underlying differences in the underlying estimation models and the physiological assumptions they employ (76). For instance, while some models assume that the ATP-PC system reaches maximal contribution between 6-8 s (77), others estimate that peak contribution occurs within the first second of exercise (76). Further assumptions concern the capacity and power output of each system; in sedentary men the immediate energy stores are often estimated to have a total capacity of ~ 45 kilojoules (kJ), and maximal power output of ~ 300 kJ/min^{-1} (77). By contrast, anaerobic glycolysis, is typically modelled with a capacity of ~200 kJ and maximal power output of ~ 150 kJ/min^{-1} (77). However, direct experimental evidence offers a more nuanced picture. For example, during a 6 s maximal sprint on an ergometer, approximately half (49.6 %) of energy provision has been attributed to PCr breakdown, with the remainder derived from anaerobic glycolysis (54). These estimates, based on changes in muscle metabolites such as lactate and pyruvate, highlight that even brief, high intensity efforts draw on multiple energy pathways, including a measurable aerobic contribution (54).

An assessment of respiratory variables during a BMX competition demonstrated the importance of the aerobic system and $\dot{V}O_2max$ in BMX racing. This importance stems from the need to recover repeatedly throughout a competition, with a typical rest time between races of ~ 30 minutes (43). It has been reported that a high $\dot{V}O_2$ peak could be responsible for 54 % variation in lap performance over repeated efforts (43, 56).

Knowledge of the energy systems that contribute to the performance of a sport is important when designing a warm-up. In short-duration exercise, such as anaerobic sprinting sports, the ability to break down PCr into energy is related to performance (78), meaning if a warm-up utilises PCr stores without adequate restoration time, subsequent short-duration performance can be impaired (5). However, if the intensity and duration of the warm-up are correct, the subsequent increase in muscle temperature can increase PCr degradation as well as glycolysis and glycogenolysis, thus increasing the speed at which energy can be created (11, 79).

Despite this understanding of BMX performance determinants, research on warming-up for optimal performance in BMX racing is currently limited, largely due to several key challenges. Field studies are scarce, partly because of the technological limitations in accurately capturing the power profile of BMX athletes, particularly at the extreme cadences observed during races. The available power meters often lack the sampling frequency necessary to fully capture these dynamics (58). Furthermore, replicating the specific demands of BMX racing in a laboratory setting is challenging. BMX racing involves a series of intermittent sprints at high cadences (45), combined with rapid impulse actions over obstacles to sustain and increase velocity. These unique characteristics are difficult to simulate using standard cycle ergometers, and no validated test exists that accurately replicates these demands. Consequently, laboratory studies have typically employed shorter sprints, ranging from 10 to 30 s, to assess performance indicators relevant to BMX racing (57, 59, 60, 80).

This systematic review aims to identify and evaluate various warm-ups for cycling sprints lasting ≤ 30 s, intending to determine which approaches can effectively enhance performance during a BMX race.

2.3 Methods

2.3.1 Search strategy and selection criteria

This systematic review was conducted in accordance with the guidance set out by the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) Statement (81). Four electronic databases were searched (Web of Science, Google

Scholar, Crossref, and PubMed) up to October 2023 using Publish or Perish by a group of three reviewers. The searches were performed using the Boolean search strategy, restricting search results to relevant studies. This was completed using keywords alongside the operators ‘AND’ and ‘OR’, which are presented in Table 1.

Studies were included or excluded using the PICO (Population, Intervention, Comparison, Outcome) criteria (82). An overview of this can be viewed in Table 1. Furthermore, literature was excluded for the following: not written in English, the full text was unavailable, review literature, conference proceedings and/or abstract only available.

Titles were firstly independently reviewed for relevance and coded with a ‘0’, ‘1’, or ‘2’ in a Microsoft Excel spreadsheet. A code of “0” meant that studies were included, “1” meant that studies were not included, and “2” meant that the studies were reviewed before being included or excluded. The remaining studies then underwent the same process with abstracts. Studies were screened and excluded if they were not assessing cycling performance, not assessing sprint cycling performance, or if the sprint cycling test was >30 s in duration. Rationales for exclusion and inclusion were given at every step and highlighted in Figure 1. Abstracts were then screened for relevance before full-text reading began if a decision was unclear.
Following the final selection of included studies, relevant data were extracted into a Microsoft Excel spreadsheet. Extracted information included 1) participant characteristics, 2) physiological tests conducted, 3) priming strategy/warm-up methods, 4) recovery period between the warm-up, 5) performance test results, 6) effect sizes and 7) a summary of the key findings (see Table 4).

Table 1: Search strategy and inclusion/exclusion criteria based on PICO (Population, Intervention, Comparison, Outcome).

Databases	Boolean search strategy	PICO	Inclusion criteria	Exclusion criteria
Web of Science Google scholar PubMed Crossref	Cycling BMX Bicycle Motocross Explosive Warm-up Warmup Warm up Warming-up Warming up Priming Pre-exercise Pre exercise Pre-ischemic Blood flow Restriction Stretch Re-warm Sprint Repeated sprint Maximal Performance	Population	> 14 years old No previous cycling experience required Free of injury No illness Not pregnant	< 14 years old
		Intervention	Stretching Foam rolling Blood flow restriction Warm-up or pre-exercise Heating and cooling Vibration	
		Comparison	Warm-up strategies Warm-up strategy against control group	No comparison between strategies or control group
		Outcome	Sprint cycling performance ≤ 30 seconds	No outcome data or outcome variables

2.3.2 Methodological Quality Assessment

The methodological quality of all experimental studies was assessed using a modified version of the 11-item Physiotherapy Evidence Database (PEDro) scale (83), previously reported to be a valid and reliable assessment for determining study quality (84, 85). Each study was scored a "1" if it met the criteria or "0" if it did not. Total scores were then calculated for each study, with 0-3 considered poor, 4-6 fair, 7-8 good, and 9-10 excellent. Studies were not excluded if they failed to meet a certain score.

2.3.3 Risk of Bias Assessment

The risk of bias for each study was independently assessed by two reviewers using the Cochrane risk of bias tool, specifically designed for crossover trials (86). Following the guidelines, the key criteria evaluated included random sequence generation, allocation concealment, blinding of participants, personnel, and outcomes, incomplete outcome data, selective outcome reporting, and other potential sources of bias. The studies were categorised as having low risk of bias, high risk of bias, or some concerns, with the latter indicating either insufficient information or uncertainty regarding the potential for bias. Disagreements between the reviewers were resolved by consensus, and a third reviewer was consulted when necessary to achieve a final resolution.

2.4 Results

The initial search identified 4615 studies, which were reduced to 4297 after removing 318 duplicates. A further 3938 studies were excluded based on the title and abstract filtering. The remaining 359 studies were then filtered to include only cycling studies, followed by restrictions to studies that examined sprints > 30 s in duration, resulting in 16 studies included in the present review. An overview of the search and screening process can be viewed in Figure 1.

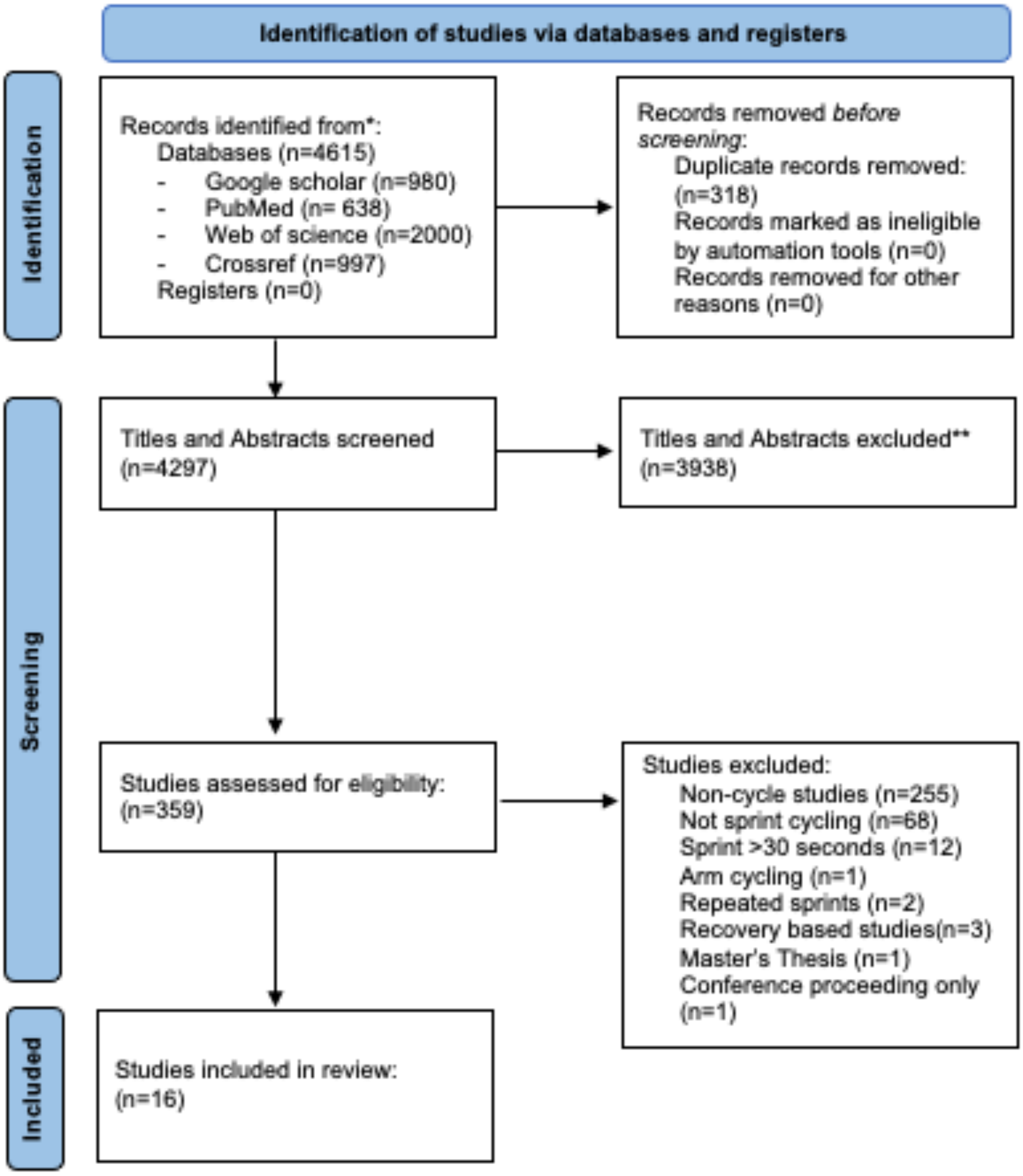


Figure 1: PRISMA flowchart outlining the literature search

Of the 16 studies included in this review, eleven (68.75 %) studied a warm-up intervention involving cycling. Of these studies, seven (63.64 %) manipulated the intensity of the cycling in the warm-up, four (36.36 %) manipulated the duration of the warm-up, and four (36.36 %) manipulated the recovery duration post warm-up. A further four (25 %) studies assessed the use of whole-body vibration (WBV), one (6.25 %) assessed the use of electrical muscle stimulation (EMS), and one (6.25 %) assessed the use of light-emitting diode irradiation (LED).

2.4.1 Study Quality

Sixteen studies assessed the effects of warming-up on performance. A summary of the PEDro scale scoring is listed in Table 2. Overall, one study was of poor quality, seven of fair quality, and eight of good quality. For this systematic review, the PEDro scale was modified to include the item ‘Exercise load controlled and reported’ and remove the ‘Blinding of subjects’ and ‘Blinding of therapists’ from the quality assessment (83).

The removal was due to the impracticality of blinding subjects and therapists, with participants requiring instructions on the intensity or duration of the warm-up or the length of the recovery duration. Furthermore, it has been noted in previous research that blinding is the most frequently not adhered to item on the PEDro scale (85). Another item that many studies in this review failed to complete was receiving the protocol or control as specified. This was due to the studies not mentioning whether this was completed, even if they likely did receive the protocol or control as specified. Hawley et al. (87) was the lowest-scoring study, ranking as ‘poor quality’. This study is notably lower than the other studies included in the review; however, it has not been removed due to the limited literature available, and this review aims to provide a comprehensive evaluation of the warm-up strategies utilised within a warm-up for cycling sprints lasting ≤ 30 s.

2.4.2 Risk of Bias

The results of this assessment can be seen in Table 3. The assessment found that all studies were highlighted to have some concerns surrounding the risk of bias. The concerns originated from possible deviations from intended interventions, more specifically, the studies included in this review reported no information regarding this section of the assessment; thus, they could not be deemed to be of low risk. The risk of bias assessment requires all domains to have a low risk of bias for the study to be classified as low risk (86); however, due to the possible deviations from the intended interventions domain, no study in this review could be classified as having a low risk of bias.

Table 2: Overview of study quality using PEDro scale

Study	Eligibility criteria specified	Random group allocation	Concealed allocation	Similar baseline levels	Exercise load controlled and reported	Assessors blinded	> 85 % of subjects recorded 1 key outcome	Received treatment or control as specified	Between-group statistical comparisons reported	Point measures and measures of variability	Rank
Bajolek et al. (88)	1	1	1	1	1	?	1	?	1	1	8
Chaâri et al. (89)	1	1	1	1	1	?	1	?	1	0	7
Doma et al. (90)	1	1	1	1	1	?	0	?	1	1	7
Duc et al. (91)	1	1	1	1	1	?	1	?	1	1	8
Fujii et al. (92)	1	1	0	0	1	?	1	?	1	0	5
Hawley et al. (87)	0	0	0	0	1	?	0	?	1	0	2
Hill (93)	1	1	1	1	1	?	0	?	1	0	6
Ktenidis et al. (94)	1	1	1	1	1	?	1	?	1	0	7
Racinais (95)	1	1	1	1	1	?	0	?	1	0	6
Rønnestad et al. (96)	1	1	1	0	1	?	0	?	1	1	6
Smith et al. (97)	1	1	1	0	1	?	0	?	1	0	5
Souissi et al. (98)	1	1	1	1	1	?	1	?	1	0	7
Teles et al. (99)	1	1	1	1	1	?	1	?	1	0	7
Tomaras et al. (100)	1	1	1	1	1	?	1	1	1	0	8
Wittekind et al. (101)	1	1	1	0	1	?	0	?	1	0	5
Yaicharoen et al. (102)	0	1	1	1	0	?	1	?	1	1	6

Table 3: Risk of bias assessment

Study	Risk of bias from randomisation process	Risk of bias arising from period and carryover effects	Risk of bias due to deviations from the intended interventions	Risk of bias due to missing outcome data	Risk of bias in measurement of outcome	Risk of bias in selection of the reported result	Overall risk
Bajolek et al. (88)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Chaâri et al. (89)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Doma et al. (90)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Duc et al. (91)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Fujii et al. (92)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Hawley et al. (87)	Some concerns	Low	Some concerns	Low	Low	Low	Some concerns
Hill (93)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Ktenidis et al. (94)	Some concerns	Low	Some concerns	Low	Low	Low	Some concerns
Racinais (95)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Rønnestad et al. (96)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Smith et al. (97)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Souissi et al. (98)	Low	Low	Some concerns	Low	Low	Low	Some concerns

Teles et al. (99)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Tomaras et al. (100)	Some concerns	Low	Some concerns	Low	Low	Low	Some concerns
Wittekind et al. (101)	Low	Low	Some concerns	Low	Low	Low	Some concerns
Yaicharoen et al. (102)	Low	Low	Some concerns	Low	Low	Low	Some concerns

Table 4: Overview of studies included in the systematic review

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Bajolek et al. 2023 (88)	Male n=12 Age: 31±10 years	30 s sprint	Intensity: CON = 100 W with 3 x 10 s sprint EMS = 100 W with 3 x 10 s sprint + Bilateral EMS stimulation on knee extensor Duration: 10min	2min	**PEAK POWER** (W) CON= 876.25 ± 238.41 EMS= 758.5 ± 221.7 **MEAN POWER** (W) CON= 580.58 ± 139.75 EMS= 545.92 ± 129.33	PEAK POWER= (η2 = 0.143) MEAN POWER= (η2 = 0.013)	No ↑ in peak or mean power following control or electrical muscle stimulation ($p > 0.05$)
Chaâri et al. 2015 (89)	Male n= 11 Age: 22.6 ± 2.5 years	30 s sprint	Intensity: 50 % max aerobic power Duration: 5min OR 15min Intervention: Duration and recovery period	5min or 0	n/a	n/a	Rest interval did not influence peak or mean power, or fatigue index ($p > 0.05$).
Doma et al. 2018 (90)	Male n= 20 Age: 22.9 ± 5 years	30 s sprint	Intensity: CON = 60 W cycle with 10 s sprint Intervention = 60 W cycle with 10 s sprint + 8.5 % BM 10 s sprint Duration = 5 min	2min (CON), 5min (T5) or 10min (T10)	**PEAK POWER** (W) CON= 1768 ± 348 T5= 1790 ± 387 T10= 1779 ± 390 **MEAN POWER** (W) CON= 715±123 T5= 710±135 T10= 731±115 **TOTAL WORK** (W) CON= 21.314±3.677 T5= 21.157±4.023 T10= 21.775±3.436	MEAN POWER= large effect (eS=1.57) TOTAL WORK= large effect (eS=1.57)	8.5 % BM cycle ↑ subsequent peak and mean power after T10 rest vs CON ($p < 0.05$). Overloaded cycling - subsequent total work in T5 and T10 vs CON ($p < 0.05$)

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Duc et al. 2020 (91)	Male n= 14 Age: 24 ± 5 years	10 s sprint	Intensity: CON= self-selected cycle WBV = self-selected cycle + WBV during half squat exercise (15 reps at 40 Hz) (WBV Duration: 15min	60 s	**PEAK POWER** (W) WBV**=** 1693±356 CON= 1637±349 **MEAN POWER** (W) WBV=1121±174 CON= 1085±175	moderate and large effects of WBV on peak and mean power output (ES = 0.73 and ES = 0.89, respectively)	WBV ↑ peak and mean power compared to CON ($p \le 0.05$).
Fujii et al. 2023 (92)	Male n= 10 Age: 24 ± 3 years	30 s sprint	Intensity: 43 % $\dot{V}O_2$max cycle with 1, 4, or 7 sprints at 110 % $\dot{V}O_2$max followed by 60 % $\dot{V}O_2$ max at 70 rev·min^{-1} Duration: 5min OR 15min	10min	n/a	n/a	No ↑ in power following all WU conditions ($p > 0.05$).
Hawley et al. 1989 (87)	Male n= 24 Age: 21 ± 2.5 years	30 s sprint	Intensity: WU = Incremental cycle at 90 rev·min^{-1}. No WU Duration: 8min	5min	**PEAK POWER** (W) NO WU= 855.4 ± 81.2 WU= 867.1 ±112.2 **MEAN POWER** (W) NO WU= 655.5 ± 66.4 WU= 654.5 ± 90.8 **RELATIVE PEAK POWER** (W/kg) NO WU= 11.5 ± 1.2 WU= 11.6 ± 1.4 **MEAN RELATIVE POWER** (W/kg) NO WU= 8.8 ± 0.9 WU= 8.7 ± 1.2 **FATIGUE INDEX** (%) NO WU= 41.9 ± 6.8 WU= 44.1 ± 7.8	n/a	No ↑ in peak or mean power ($p > 0.05$). Fatigue index - following WU ($p < 0.05$). Un-trained participants could be a cause of fatigue

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Hill 2013 (93)	Male n= 10 Age: 30 ± 10 years	10 s sprint (torque of 0.834 $N \cdot kg^{-1}$)	Intensity: WBV = 80 $rev \cdot min^{-1}$ against a torque of 0.12 $N \cdot kg^{-1}$ with 5 s sprint + 2min WBV NO WBV = 80 $rev \cdot min^{-1}$ against a torque of 0.12 $N \cdot kg^{-1}$ with 5 s sprint Duration: 10min	30 s	**PEAK POWER** (W) WBV= 1458 ± 283.7 NO WBV= 1506.3 ± 232.5 **TTPP** (s) WBV= 2.07 ± 0.36 NO WBV= 2.19 ± 0.46 **PEAK CADENCE** ($rev \cdot min^{-1}$) WBV= 140.8 ± 10.5 NO WBV= 139.8 ± 10 **TTPC** (s) WBV= 6.21 ± 0.93 NO WBV= 6.41 ± 1.08	n/a	2min of WBV was not effective at increasing any measure ($p > 0.05$)
Ktenidis et al. 2021 (94)	Male n= 12 Age: 25 ± 5 years	30 s sprint	Intensity: cycle at gas exchange threshold (GET) plus 70 % Δ Duration: 6min	15min (T15) or 30min (T30) or 0min (CON)	**PEAK POWER** (W) T30= 595 ± 84 CON= 567 ± 85 T15= 569 ± 95 **RELATIVE PEAK POWER** (W/kg) T30= 7.91 ± 0.74 CON= 7.54 ± 0.79 T15= 7.47 ± 0.78	n/a	↑ Peak and relative peak power following T30 compared to T15 and CON (no WU) ($p < 0.01$).
Racinais 2005 (95)	Male n= 8 Age: 27 ± 8 years	3 x 7 s sprint	Intensity: CON = 50 % $\dot{V}O_2max$ AWU = 50 % $\dot{V}O_2max$, 3 x 5 s sprints Duration: 3min vs 12min	5min	n/a	n/a	Maximal power and velocity ↑ after AWU vs CON ($p < 0.05$). No ↑ in power, force, or velocity between sprints at 5, 10, 15min post WU.

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Rønnestad et al. 2017 (96)	n= 11 Age: 18 ± 1 years	15 s sprint	Intensity: CON= submaximal with 2 x 25 s submaximal sprints WBV = submaximal with 2 x 25 s submaximal sprints 30 s of half squats with WBV Duration: 20min	1min	**PEAK POWER** (W) WBV= 1413 ± 257 CON= 1353 ± 213 **MEAN POWER** (W) WBV= 850 ± 119 CON= 828 ± 101	**ES with ratios of 0.2, 0.5, and 0.8 (Small, Medium, large)** WBV had a moderate effect on Peak Power and Mean Power (ES = 0.71 and ES= 0.58, respectively)	WBV ↑ peak power vs CON ($p < 0.05$). Mean power had no significant increases ($p = 0.08$).
Smith et al. 2001 (97)	Male n= 9 Age: 25.11 ± 1.16 years	10 s sprint (resistance=5.8 $J \cdot rev \cdot kg^{-1}$)	Intensity: CON= cycle at 10 % of test workload with 4 x 2 s sprints Intervention: cycle at 10 % of test workload with 4 x 2 s sprints +10 90 % 1RM squats Duration: 4min	3-5min (CON)or 5min (T5) or 20min (T20)	**PEAK POWER (W)** CON= 1152.78 ± 59.05 T5= 1197.44 ± 62.43 T20= 1173.11 ± 59.17 **AVERAGE POWER (W)** CON= 982.9 ± 48.42 T5= 1029.9 ± 55.6 T20= 965.4 ± 46.79 **RELATIVE AV. POWER (W/Kg)** CON= 10.8 ± 0.55 T5= 11.4 ± 0.66 T20= 10.6 ± 0.57	n/a	No ↑ in peak power ($p > 0.05$). Addition of squats with T5 - average power vs CON and relative average power vs CON and T20($p < 0.05$, $p < 0.01$).
Souissi et al. 2010 (98)	Male n= 12 Age: 23.5 ± 3 years	30 s sprint	Intensity: cycle at 50 % max aerobic power Duration: 5min (T5) OR 15min (T15)	not reported	No values	n/a	T15 WU ↑ peak and mean power vs T5 but only in the morning

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Teles et al. 2015 (99)	Male n= 10 Age: 27.7 ± 9.3 years	30 s sprint	Intensity: WU = incremental cycle (60-70 % HR_{max}) + 6 s sprint LED = WU + LED irradiation on the lower limbs WBV = WU + 37 squats with WBV WBV + LED CON = rest Duration: 10min	5-8 min	**MEAN POWER** (W) WU= 647.6 ± 64.9 CON= 616.6 ± 63.9 LED= 610.9 ± 65.9 WBV= 606.3 ± 107.5 LED+WBV= 637.3 ± 72.4 **RELATIVE POWER** (W/kg) WU= 12.1 ± 1.0 CON= 11.5 ± 0.9 LED= 11.6 ± 1.0 LED+WBV= 11.9 ± 0.9 **RELATIVE WORK** (J/kg^{-1}) WU= 277 ± 23 CON= 26 ± 24 LED= 260 ± 23 LED+WBV= 272 ± 22	n/a	WU and WBV+LED ↑ mean and relative power vs CON ($p \leq 0.02$). WU ↑ relative work vs CON ($p \leq 0.02$)
Tomaras et al. 2011 (100)	Male n= 10 Age: 33.5 ± 9.1 years	30 s sprint	Intensity: EWU = incremental cycle at 60-70 % HR_{max} with 1 sprint TWU = incremental cycle at 60-95 % HR_{max} with 4 sprints Duration: 15min or 20min	12.5mins	**PEAK POWER** (W) EWU= 1390 ± 80 TWU= 1303 ± 89 **TOTAL WORK** (kJ) EWU= 29.1 ± 1.2 TWU= 27.7 ± 1.2 **FATIGUE INDEX** (%) EWU= 48 ± 2 TWU= 49 ± 3	n/a	↑ peak power and total work following EWU ($p < 0.01$). No ↑ in fatigue index ($p > 0.05$). Fatigue could be created through longer duration or higher intensity

Study	Participants	Test	Warm-up method	Recovery period *	Results	Effect size	Key findings
Wittekind et al. 2012 (101)	Male n= 8 Age: 33 ± 9 years	30 s sprint	Intensity: Moderate = cycle at 40 % peak aerobic power (PAP) Heavy = cycle at 40 % PAP + 80 % PAP Severe = cycle at 40 % PAP + 110 % PAP Duration: 6min; heavy and severe 5 min at first intensity then 1 min at increased intensity	10min	**PEAK POWER** (W) Moderate = 873 ± 110 Heavy = 882 ± 91 Severe = 834 ± 96 **MEAN POWER** (W) Moderate = 672 ± 54 Heavy = 666 ± 56 Severe = 655 ± 59 **FATIGUE INDEX** (%) Moderate = 50 ± 11 Heavy= 53 ± 18 Severe= 50 ± 9	n/a	No ↑ in peak power ($p > 0.05$). MOD WU ↑ mean power vs SEVERE ($p < 0.05$).
Yaicharoen et al. 2012 (102)	Male n= 12 Age: 24.5 ± 6.7	4 s sprint single sprint (SS) or first sprint of repeated sprints (FS).	Intensity: WU = cycle midway between lactate and anaerobic thresholds NO WU Duration: 10min	2min	**PEAK POWER** (W.kg-1) WU+SS= 15.6±2.3 WU+FS= 14.6±2.2 NO WU+SS= 14.4±2.2 NO WU+FS= 13.2±2.0 **WORK** (J.kg-1) WU+SS= 44.2±6.4 WU+FS= 41.6±6.5 NO WU+SS= 42.5±7.0, NO WU+FS= 37.1±6.2	**PEAK POWER** = WU+SS sig. higher than all other conditions, ES= 0.53 (no WU+SS), ES=0.98 (no WU+FS), Effect size too small for WU+FS so not reported. WU+FS sig higher than no WU+FS, ES= 0.59. **WORK DONE**= All conditions sig. higher than no WU+FS, ES= 0.59, 0.91, 0.75 (WU+FS, WU+SS, no WU+SS respectively).	All conditions ↑ relative peak power vs WU+FS ($p < 0.05$). WU+SS ↑ work than all other conditions ($p < 0.05$).

Abbreviations: ↑ = significant increase, ± = standard deviation, FI = Fatigue index, HR_{max} = maximum heart rate, Hz = hertz, LED = light emitting diode, max = maximum, min = minute, n = number, $N{\cdot}kg^{-1}$ = Newtons per kilogram, $rev{\cdot}min^{-1}$ = revolutions per minute, s = seconds, TTPC= Time to peak cadence, TTPP = Time to peak power, W = Watts, WBV = whole body vibration.
* Recovery period between warm-up and sprint performance

2.5 Discussion

This review aimed to identify warm-ups utilised to enhance sprint cycling of ≤ 30 s in duration, evaluate their effectiveness at improving sprint performance, and assess which approaches can effectively enhance performance during a BMX race.

2.5.1 Cycling Specific Warm-up

In the studies that incorporated cycling into the warm-up, variations in the intensity, duration, and recovery period between the warm-up and the exercise task were observed. Modification to these three factors elicited acute physiological changes attempting to have an ergogenic effect on ≤ 30 s sprint performance.

2.5.1.1 Intensity

The literature search identified intensity as one of the most manipulated warm-up variables, although the findings amongst these studies were inconsistent.
Of the seven studies that altered the intensity of the warm-up, three reported that higher intensity warm-ups produced the greatest improvements in performance (90, 95, 102).

One study compared a moderate intensity warm-up corresponding to 50 % $\dot{V}O_2max$ for 12 minutes with a higher intensity warm-up including an identical warm-up with the addition of three 5 s sprints (95). Oxygen consumption was constantly monitored throughout the warm-up with the ergometers resistance altered to maintain relative intensity of 50 % $\dot{V}O_2max$ (95). The higher intensity warm-up significantly increased maximal power and velocity during a 7 s sprint (95), which may be partly due to the specificity of the warm-up to the subsequent exercise task. The specificity of the warm-up by including short-duration sprints may have increased performance by increasing the transmission rate of nerve impulses or neuromuscular activation (5, 103). The greater intensity of the warm-up created by the sprints may have elicited an increase in muscle temperature, which has been seen to have ergogenic effects on short-term sprint performance by increasing maximal power and velocity (5). Increased muscle temperature will increase metabolic reactions through increased enzymatic function (9, 10). Furthermore, greater blood flow will be promoted to the muscle tissue, facilitating increased oxygen delivery and the removal of waste products such as carbon dioxide through the buffering of hydrogen ions (5).

A warm-up at a higher intensity has also been seen to increase sprint performance by utilising a high-intensity overloaded cycle, created by an increased workload to produce a PAP effect (90). All conditions in this study conducted an identical standardised warm-up involving leg swings, a 5-minute aerobic cycle, and a 10 s sprint (90). The control condition only completed the standardised warm-up, with the remaining two conditions completing an overloaded 10 s sprint at a resistance of 8.5 % body mass (BM), followed by either 5 or 10 minutes rest (90). The 20 anaerobically trained participants recruited in this study then completed a Wingate test, resulting in mean power and total work significantly increasing following the PAP warm-up when the recovery duration was 10 minutes compared to the generalised warm-up (90). This indicates that PAP had a positive effect on sprint performance, which may be due to the specificity of the 10 s PAP protocol at 8.5 % BM that replicates the demands of the 30 s Wingate test, which has a resistance of

7.5 % BM. The PAP protocol intensity may have increased the muscle temperature closer to the optimum level for peak performance compared to performing the generalised warm-up alone; however, as no muscle temperature measures were recorded, this can only be hypothesised. It was further hypothesised that sprint performance was enhanced as a result of the PAP warm-up due to an increase in type two muscle fibre recruitment (104), but the PAP effect can only be suggested to be eliciting the enhanced Wingate performance as no direct PAP measures were recorded (90, 100). Due to the recruitment of 20 anaerobically trained participants, the reliability of the results observed in this study is increased due to the sample size and training status of participants.

As no twitch force assessment was conducted in this study and the PAP effects mentioned occurred beyond the < 3-minute PAP threshold (26), this indicates that a PAP effect via increased myosin light-chain phosphorylation (25) is not influencing the results of the study. Instead, the study is likely referring to PAPE where factors including intramuscular temperature drive increased voluntary muscular performance (28), appearing after 8–10 minutes and lasting a further > 15 minutes (27, 105, 106).

Lastly, one study compared the intensity midway between the lactate and anaerobic thresholds of the participants on 4 s sprint performance compared to no warm-up (102). The warm-up, 10 minutes in duration, significantly increased relative peak power following a 2-minute recovery period; however, the total work done was comparable between the conditions (102). The warm-up significantly increased blood lactate, heart rate, and ratings of perceived exertion (RPE) post warm-up compared to the no warm-up condition, highlighting the difference in intensity (102). It was suggested that the increase in relative peak power following the warm-up was due to an increase in muscular temperature; however, this can only be speculated as no measures of muscle temperature were taken in this study (102). The study also compared the 4 s sprint performance to an initial 4 s sprint from an intermittent sprint protocol following identical warm-ups (102), identifying significantly greater peak power from the individual sprint, thus potentially indicating that pacing is a factor on intermittent sprint protocols (102). The four-second sprint utilised has a comparable duration to the acceleration phase during a BMX race, meaning the warm-up protocol in this study could positively impact power output at the start of a BMX race. However, a key difference between this study and the acceleration phase of a BMX race is the recovery period between the warm-up and sprint, in BMX racing, athletes can experience recovery periods of up to 30 minutes prior to a race (43), compared to the 2-minute recovery period preceding the 4 s sprints (102).

The studies that improved short-term sprint performance following a more intense warm-up propose that intense warm-ups successfully raise muscle temperature without depleting PCr stores (5). However, with no study measuring muscle temperature, it can only be speculated that this is responsible for any performance enhancement. Interestingly, the first study found significant increases in sprint performance with a high-intensity warm-up following a 5-minute recovery period, compared to the second, which found no significant increase in performance following a 5-minute recovery, only after the 10-minute recovery. However, this is likely due to variation in intensity of the warm-up, with the PAP warm-up being higher in intensity compared to cycling at 50 % $\dot{V}O_2max$ for 12 minutes with three 5 s sprints.

Alternatively, within the reviewed literature, two studies reported that lower intensity warm-ups were more beneficial to sprint performance than warm-ups when compared to those performed at a higher intensity (100, 101).

A study of 10 highly trained track cyclists discovered that an experimental warm-up compared to a more intense, standard track cycling warm-up was ergogenic to subsequent 30 s Wingate performance, significantly increasing peak power and total work (100). The experimental warm-up consisted of 20 minutes of cycling, starting at 60 % maximum heart rate (HR_{max}), working up to 95 % HR max, followed by four sprints at 8-minute intervals (100). In comparison, the experimental or lower intensity warm-up included a 15-minute cycle, starting at 60 % HR_{max} and ending at 70 % HR_{max} with one sprint (100). The recovery period following both warm-ups was 12.5 minutes, as this replicated the recovery period at a track cycling competition (100). The test completed was a Wingate test at optimal cadence, determined during a prior laboratory visit by conducting an 8 s peak cadence test against only the inertial load, with the participant's optimal cadence extrapolated from the results (100). One minute before the Wingate test, a significant difference in blood lactate was observed between the traditional, more intense warm-up and the experimental warm-up, ~ 6 mmol/L compared to ~ 4 mmol/L, respectively (100). This indicates that the decreased performance following the traditional warm-up may be due to increased fatigue caused by acidosis in the skeletal muscle. Additionally, the blood lactate concentrations in the traditional warm-up condition post Wingate were also significantly greater (100), indicating the warm-up was too great an intensity to elicit increased performance. Furthermore, muscle temperature was indicated to have played no role in the increased performance following the experimental warm-up due to no significant differences in skin temperatures discovered (100). With a recovery time greater than 12.5 minutes, the traditional warm-up may become more ergogenic due to the facilitation of ATP and PCr store restoration to provide the muscle tissue during the test with the fastest sources of ATP.

A second study of eight trained male cyclists found decreased mean power in 30 s sprint performance following a higher intensity warm-up compared to a warm-up of a lower intensity, suggesting that it was caused by a decrease in energy production (101). Effects of three warm-up intensities were tested: The moderate intensity warm-up consisted of 6 minutes cycling at 40 % peak aerobic power, the heavy intensity warm-up was 5 minutes cycling at 40 % peak aerobic power with 1-minute at 80 % peak aerobic power, and the severe intensity was 5 minutes cycling at 40 % peak aerobic power with 1-minute at 110 % peak aerobic power (101). The severe and heavy intensity warm-ups caused significantly elevated blood lactate levels compared to baseline, indicating that the two highest intensity warm-ups may have increased fatigue. Furthermore, the severe warm-up was seen to decrease the starting power of the sprint, thus decreasing the mean power significantly compared to the moderate warm-up (101). This was suggested to be because of a significant decrease in the contribution of energy from anaerobic glycolysis following the severe warm-up compared to the moderate warm-up, with the difference in anaerobic contribution being 9 % (101). Conversely, the moderate warm-up did not produce significantly higher peak power compared to the severe warm-up but was not significantly different to the heavy intensity warm-up (101). Furthermore, muscle oxygenation prior to the Wingate was equally raised between the heavy and severe conditions, indicating little differentiation in intensity (101).

Both studies indicate that high-intensity warm-ups can cause greater levels of fatigue, and for sprint performance to be optimal, the generation and maintenance of peak power is vital; this performance is decreased by fatigue. Higher intensity warm-ups have the possibility of causing too much fatigue and consequently being a detriment to performance. This means that lower intensity warm-ups may be more ergogenic in comparison to high intensity ones if the regeneration of energy stores is not facilitated.

Two studies found no significant differences in results when the warm-up intensity changed (87, 92).

One study suggested that the participants were experiencing excessive fatigue during an intense warm-up, an 8-minute incremental cycle, compared to the control group, which completed no warm-up (87). The warm-up was based upon perceived intensity, starting at 'very, very light', then 'moderate' and finishing with 'moderately heavy' (87). Participants had 5 minutes of recovery following this warm-up, which may indicate that the intensity of the warm-up created heightened fatigue, potentially depleting energy stores and decreasing 30 s Wingate performance to a comparable level as receiving no warm-up. This is especially relevant due to the recruitment of untrained participants in this study, who will require a longer duration of recovery compared to trained individuals at the same intensity due to reduced $\dot{V}O_2$ Kinetics (107), slower PCr regeneration (108), and greater induced fatigue (20). Fatigue was also suggested to have occurred due to the inability of participants to maintain the self-paced intensities of 'very, very light', 'moderate', and 'moderately heavy' (87).

This led to participants cycling at a greater intensity than desired and a significant correlation between mean warm-up intensity and fatigue index of the Wingate (87). This is reflected by the study being of low quality using a modified version of the 11-item PEDro scale (Table 2). More reliable results may have been generated by manipulating warm-up intensity in a way that is individualised to each participant such as a percentage of power at $\dot{V}O_2max$.

The second study utilised a combination of untrained participants and competitive athletes, using $\dot{V}O_2max$ to determine the intensity of the warm-up, finding no significant differences in results. Participants completed one, four, or seven sprints at 110 % $\dot{V}O_2max$ separated by 30 s cycling at 43 % $\dot{V}O_2max$ preceding cycling at 60 % $\dot{V}O_2max$, totalling 10 minutes (92). Reasoning for the insignificant results could be the low watts reached during the sprints, 324 ± 35 W (92), which could suggest that intensity was not great enough to increase muscle temperature significantly. Furthermore, the difference in intensity between the three warm-up protocols, being three sprints, may not have elicited a great enough difference in physiological response (for example, a significant difference in muscle temperature) to consequently cause a significant improvement in sprint performance. The similarity between the warm-ups is supported by the lack of significance comparing blood lactate and heart rate results post warm-up (92). In addition, the mixture of untrained and highly trained participants may have caused large variations in sprint performance, impacting the reliability of the results.

Both of these studies used untrained participants, finding no significant differences between low and high-intensity warm-ups (87, 92). In both studies, the use of untrained participants may have led to variations in performance, especially when the training status of participants varied greatly (92), and no familiarisation trial was included, with studies showing that one to two familiarisation trials are required to produce repeatable results (109, 110).

The studies that tested the effect of differing intensities on sprint performance utilised different methods of measuring intensity. Intensity was seen to be measured by power output (90), percentage BM (90), percentage $\dot{V}O_2max$ (92, 95), percentage HR_{max} (100), percentage of peak aerobic power (101), and descriptive feeling (87). The range of methods used to measure intensity are all valid; however, the comparison of intensity across studies is difficult. The advantage of using measures such as HR_{max} and $\dot{V}O_2max$ is due to the creation of an intensity specific to the fitness of the participant, although it requires greater participant visits due to the pre-tests that are required, making them potentially unfavourable to some. Other measures, such as power output or the use of descriptives to control intensity, may lead to greater variation in performance as descriptives are open to interpretation, and the perceived intensity can vary between participants at the same power output.

2.5.1.2 Duration

Three of four studies that increased the duration of a warm-up reported improvements in subsequent sprint performance (89, 95, 98).

Two studies comparing warm-up durations demonstrated that a 15-minute warm-up at 50 % of maximal aerobic power (MAP) enhanced subsequent 30 s sprint performance relative to a shorter 5-minute warm-up at the same intensity, significantly increasing both peak and mean power outputs in the morning (89, 98). When the protocols were repeated in the afternoon, findings diverged: one study observed no significant difference (98) whereas the other reported mixed results depending on the recovery period between warm-up and sprint (89). Specifically, when the 5-minute recovery was included, the 15-minute warm-up again produced superior compared with the shorter condition, both in the morning and afternoon (89). It is often proposed that that longer duration warm-ups provide enhanced performance due to increased muscular temperature, thereby optimising the conditions for muscle contraction and ATP resynthesis, an effect particularly important in the morning when baseline muscle temperatures are lower (111). However, these studies found no significant difference in oral temperature between the warm-up conditions. This may reflect that exercising at 50 % MAP elevates muscle temperature within the first 5 minutes (112), and that oral temperature is a poor surrogate for deep muscle temperature due to limited reliability and validity compared to rectal temperatures (113-115). Consequently, thermal factors alone may not explain the performance gains. Instead, the improved Wingate performance following the 15-minute warm-up has been attributed to an elevated baseline $\dot{V}O_2$, which may enhance oxygen availability and energy turnover at the onset of sprint exercise.

Furthermore, muscle temperature has been seen to be greatest following 10-20 minutes of exercise (5), demonstrating why the 15-minute, longer duration warm-up was more effective at increasing power during sprint performance in comparison to the shorter 5-minute warm-up (89). In the afternoon, when muscle temperature has increased, the ergogenic nature of the longer duration warm-up diminishes, and the recovery period following the warm-up becomes more influential to performance, which can be observed in the power values in this study (89).

Another study testing the effect of warm-up duration on sprint performance found that a longer duration warm-up provided significant increases in maximal power and velocity over a 7 s sprint (95). A 3-minute cycle at 50 % $\dot{V}O_2max$ was compared against 12 minutes at 50 % $\dot{V}O_2max$ with three 5 s sprints (95). The load applied to the ergometer was altered to maintain the 50 % $\dot{V}O_2max$ intensity. These results cannot be attributed to the duration alone due to the addition of three 5 s sprints in the 12-minute warm-up increasing the intensity and specificity. The combination of the added sprints and increased duration significantly increased the generation of muscle temperature compared to the short-duration warm-up (95), facilitating an increase in muscular power (5). On top of this, the specificity of the 5 s sprints would prime the participants for the 7 s sprint in the test by increasing the neuromuscular activation (33). The 12-minute duration of the warm-up may have increased sprint performance as it did not deplete PCr stores, meaning energy stores were restored prior to the sprint test.

A weakness of all three studies that discovered greater performance following longer duration sprints was the use of untrained participants, with one having only eight participants (95), which could affect the reliability of the studies. Reliability was also affected by one study not reporting the rest interval given following the warm-up, thus making it difficult to reproduce results (98).

Conversely, one study did find an ergogenic effect following a shorter duration warm-up (100).

This study determined if a traditional track cycling warm-up, which is long in duration and intense, increased 30 s sprint performance compared to an experimental warm-up, shorter in duration and less intense (100). Trained track cyclists were utilised in this study, improving the reliability. The traditional warm-up started cycling at 60 % HR_{max} and increased to 95 % HR_{max} over 20 minutes, followed by four 6 s sprints. This compares to the experimental warm-up, which was 15 minutes in duration, cycling at 60% HR_{max} up to 70 % HR_{max} with one sprint. The results revealed significantly higher peak power and total work following the shorter-duration experimental warm-up. Furthermore, there were no differences in skin temperature post warm-up, 1-minute before the 30 s sprint, and post sprint (100). These results indicate that the shorter duration, experimental warm-up was more effective at increasing muscle temperature than the longer duration traditional warm-up, which can increase short duration performance (5). Due to the experimental group exercising at a decreased duration, the participants were likely less fatigued and able to recover, resynthesizing ATP and PCr stores, facilitating an increase in sprint performance. Lengthening the duration of a warm-up can augment sprint performance if fatigue is not created; if the duration of the warm-up is too great, energy stores in the muscle will be depleted, leading to a decrease in sprint performance. This is especially important if the intensity is high and/or the recovery period is short.

A difficulty with studies that altered the duration of the warm-up to affect sprint performance was that the intensity and/or the recovery period were often varied alongside duration (95, 100). This means that determining which factor was beneficial to sprint performance becomes difficult.

2.5.1.3 Recovery

Recovery duration is another key factor to determine sprint performance following a warm-up. Of the four studies that altered the recovery period, only one study found that increasing the recovery period increased performance (94).

This study utilised a 30-minute recovery period compared to a 15-minute recovery period, preceded by a 6-minute warm-up at an intensity that corresponded with the participants' gas exchange threshold (GET) plus 70 % of the difference between the GET and $\dot{V}O_2max$ (Δ) (94). Following the warm-up and recovery period, the 12 recreationally active male participants completed a 30 s Wingate test (94). The results found significantly higher peak and relative peak power following the 30-minute recovery in comparison to the 15-minute recovery (94), indicating the necessity of a longer recovery period following a high-intensity warm-up to replenish energy stores required for a 30 s sprint. Furthermore, as the 30-minute recovery did not diminish performance, it can be assumed that the recovery period was not long enough to cause decreased muscle temperature, which in turn would decrease performance. However, as no temperature recordings were taken in this study, this can only be an assumption. Furthermore, the participants in this study were only recreationally active, which can lead to greater variation in results (109, 110), reducing the reliability of the results. Conversely, the utilisation of a warm-up intensity specific to the participants' aerobic fitness is beneficial for the repeatability of the results, especially when the training status of participants is varied.

Blood lactate was significantly higher pre-test following the 15-minute recovery (~ 7 mmol/L) compared to the 30-minute recovery (~ 5 mmol/L), indicating that participants may not be fully recovered, causing decreased performance (94). The recovery period duration is important because it facilitates the regeneration of ATP and PCr stores in the muscle; a large proportion of PCr regeneration occurs in 5 minutes, with full resynthesis requiring 20 minutes (116) compared to ATP stores, which take 2 minutes. For the recovery period to be beneficial to sprint performance, the duration must be long enough to provide resynthesis of energy stores without causing decreased muscle temperature (5). More specifically, after 15-20 minutes of passive rest post warm-up, muscle temperature can be seen to return to baseline levels (9). This is important as performance generally declines following decreases in muscle and body temperature (12).

Conversely, one study found that decreasing the rest interval increased performance (97).

In this study, a 5-minute recovery period has been seen to be most effective at improving relative mean and mean power during sprint performance compared to a 20-minute recovery period (97). Participants completed a 4-minute warm-up at an intensity of 10 % of that used in the test (5.8 J/rev/kg^{-1}) with four, 2 s sprints in the final minute. This was followed by 10 repetitions of squats at 90 % 1RM, which were completed with 2 minutes rest given between repetitions. The squats were followed by 5 or 20 minutes of recovery before a 10 s sprint (97). The control group only completed the ergometer-based section of the warm-up with 3-5 minutes recovery.

The results show that the intervention warm-up with a 5-minute recovery period significantly increased relative average power compared to the control and the intervention warm-up with 20 minutes recovery (97). Average power was also significantly higher compared to control following the 5-minute recovery; however, no other values, including peak power, varied significantly across the warm-ups (97). The inclusion of squats to the warm-up did increase sprint performance, potentially due to an increase in muscle temperature or a PAP effect but, due to the design of the warm-up, excess fatigue caused by a limited recovery time within the warm-up exercises not facilitating full resynthesis of ATP or nervous system recovery, is likely due to the lack significance in the remaining results (97). Moreover, the study inclusion criteria of systematic weight training for over a year (97), facilitating potential large variations in training status, in addition to fatigue being seen to greatly vary between individuals (117), may have caused variations in the results.

The increase in average power was only observed following a 5-minute recovery, which indicates that the 20-minute recovery period was too great, facilitating a decline in muscle temperature, thus not increasing 10 s sprint performance. The control group had a recovery period of 3-5 minutes in this study, which leaves a large variation in recovery period between participants, vital considering that ATP stores are replenished after 2 minutes recovery and a large proportion of PCr stores are regenerated in 5 minutes (97). This could lead to a great variation in performance between participants during the control protocol, as participants with a 5-minute recovery would have a greater proportion of PCr stores regenerated in comparison to participants who only received a 3-minute recovery period. This variation in recovery period in a study that observes the effect of different recovery periods on performance reduces the reliability and validity of the study. Furthermore, the study only used nine participants, reducing the reliability of the results.

A further two studies discovered no significant differences in sprint performance following various recovery durations (89, 90).

One study tested a 5-minute recovery against a 10-minute recovery with comparison to a control group (2-minute recovery), following a cycling warm-up on 30 s sprint performance (90). Twenty anaerobically trained male participants completed a warm-up cycling at 60 W for 5 minutes with leg swings before a 10 s sprint after (control), an additional 10 s overloaded cycle at 8.5 % body mass (BM) was followed by either the 5-minute or 10-minute recovery (90). Mean power, relative mean power, blood lactate concentration, and total work were significantly increased following the 10-minute recovery condition compared to control; the only significant difference between the five and 10-minute recovery conditions was relative mean power (90), demonstrating the benefits of a specific warm-up. However, the small variation in performance between the different recovery periods displays that potentially neither recovery period was optimal for the intensity and duration of the warm-up, with a longer recovery period of up to 20 minutes potentially being beneficial to sprint performance as a result of full PCr resynthesis (116). Conversely, a greater recovery period may result in decreased muscle temperatures and a reduced PAP effect, as a period of 8 minutes to 12 minutes has been seen to induce a PAP effect following dynamic exercises (27, 90), diminishing performance benefits.

Another study tested warming-up on a cycle ergometer for five or 15 minutes at 50 % MAP, followed by 5 minutes rest or no rest in the morning and afternoon (89). Results showed that there was no significant effect of recovery period on peak and mean power, proposed to be due to decreased core temperature (89), which can cause a decrease in muscular power of the leg by 3 % (118). Oral temperature and fatigue index were also not influenced by the recovery period utilised, demonstrating that the inclusion of a 5-minute recovery period does not facilitate a drop in core temperature (89). Furthermore, if a recovery period is available, then longer duration warm-ups appear more ergogenic due to the benefits of increased muscle temperature, whilst facilitating regeneration of ATP and PCr stores. However, this duration may become too fatiguing with a short-duration or no recovery period is available.

Alteration in the recovery period of a warm-up can have positive and negative effects on sprint performance, depending on whether the recovery period duration is considered part of the design of the warm-up. If a recovery period is too great, then PAPE (for example, muscular temperature) and PAP effects can diminish, negatively affecting subsequent performance. Furthermore, if the recovery period is too short, then ATP and PCr stores fail to fully resynthesise, and fatigue can cause negative effects on performance. In BMX racing, athletes can experience a 20–30-minute pre-race holding period where it is not feasible to complete a cycling-based warm-up. Generally, PAPE effects are optimal following a 5.5-minute recovery (119); If a recovery period is too great, then PAPE (for example, muscular temperature) and PAP effects can diminish, negatively affecting subsequent performance. Furthermore, if the recovery period is too short, then ATP and PCr stores fail to fully resynthesise, and fatigue can cause negative effects on performance. In BMX racing, athletes can experience a 20–30-minute pre-race holding period where it is not feasible to complete a cycling-based warm-up. Generally, PAPE effects are optimal following a 5.5-minute recovery (27, 120-123), the optimal recovery period may change. Furthermore, in this systematic review, one study increased 30 s Wingate performance following a 30-minute recovery, indicating the extent to which PAPE effects may last. Relating to BMX racing, the importance of implementing the appropriate recovery period between a warm-up and the race is vital. A recovery period too great or too short would not facilitate the optimum physiological conditions for peak performance.

2.5.2 Other interventions

Outside of altering the intensity, duration, and recovery period, studies have tested the ergogenic nature of specific interventions on sprint performance. Within the literature search conducted in the present study, two techniques were utilised in warm-ups to increase sprint performance: four whole body vibration (WBV) studies and one electrical muscle stimulation (EMS) study.

2.5.2.1 Whole body vibration (WBV)

WBV was frequently utilised alongside an exercise to induce a PAP effect, such as squatting (124). PAP has been linked to increasing phosphorylation of myosin in skeletal muscle, meaning it is more sensitive to a calcium influx, which triggers muscle contractions (125), and makes the motor unit more excitable (126).

When PAP exercises are combined with WBV, previous research has seen power increases (124, 127); however, the time spent on the vibration plate and the frequency of the vibrations both influence results. When 30 s of half squats (15 repetitions) were completed with or without WBV at 40 Hz after a 20-minute cycle, the WBV protocol significantly improved peak power in a 15 s sprint, compared to half squats without WBV (96). This significant increase was not observed in mean power, peak heart rate, blood lactate or rating of perceived exertion (96). The results show a tendency for WBV to increase 15 s sprint performance with a 1-minute recovery period after the half squat exercise (96). Reasoning behind increased sprint performance has been attributed to potentiation of the neuromuscular system (128), specifically, muscle spindles are stimulated, resulting in reflex activation of motor neurons and increased spatial recruitment (129, 130). Furthermore, the study had trained anaerobic cyclists for participants, which increases the reliability of the study. An interesting addition to the study may have been a control group consisting of the 20-minute cycle warm-up (12-minute submaximal cycling with two 25 s sprints separated by 4 minutes), as this would facilitate the understanding of whether the cycling, the squats, or the WBV is creating increases in sprint performance.

A study that included a control group, consisting of a cycling warm-up, found that WBV with squats significantly improved peak and mean power during a 10 s sprint compared to squats without WBV (91). However, no significant differences in performance were observed when compared to the cycling warm-up alone (91). The study used the same WBV protocol as the previous study (15 squats at 40 Hz over 30 s) with a prior cycling warm-up and the same 1-minute recovery time before a 10 s sprint. There were differences within the cycling warm-up, including the duration increasing to 15 minutes and the intensity being self-selected. Participants could choose the power output and cadence throughout the warm-up and were encouraged to complete several 6 s sprints (91). This could influence the reliability of the results of the study, as altering the intensity of a warm-up can affect the muscle temperature, which affects sprint performance. The study also measured muscle activation across the quadriceps muscle using surface electromyography (EMG) and found no significant difference during the sprint with or without WBV. Unfortunately, EMG was not recorded during the sprint following the cycling warm-up only. The results of this study indicate that the cycling portion of the warm-ups may be the vital factor in improving sprint performance, as the WBV combined with the squats and a prior 15-minute cycle did not significantly increase sprint performance in comparison to the cycling warm-up alone. Thus, the cycling warm-up may generate greater increases in muscle temperature compared to the squats and/or WBV.

When WBV has been tested with no exercise during the application, the results have shown no significant improvement in sprint performance (93). This was found following a 10-minute cycling warm-up at 80 $rev \cdot min^{-1}$ against a torque of 0.12 $N \cdot kg^{-1}$ (93). Participants also completed a 5 s sprint at the seventh minute (93). Following the warm-up, participants would stand on a WBV platform for 2 minutes with vibration or without. The vibration was set at a frequency of 26 Hz, which is considered low frequency (131). One minute after the intervention, a 10 s sprint was conducted at 0.834 $N \cdot kg^{-1}$ (93). There was no significant difference in peak power, time to peak power, peak cadence, or time to peak cadence (93). This result may be due to the low frequency used during the WBV not being a great enough stimulus to have an ergogenic effect on sprint performance, or the use of WBV without a PAP exercise, like squats, is not effective at increasing sprint performance. Nevertheless, the use of WBV with squats as a warm-up for sprint cycling has shown no significant difference in sprint performance compared to a control group with no warm-up (99). Light-emitting diode (LED) irradiation on the lower limbs also provided no significant differences to sprint performance compared to the control group (99). When WBV was combined with LED irradiation on the lower limbs, a significant increase in peak power and relative power was observed compared to the control group, which also occurred following a 15-minute incremental cycle from 60 % HR_{max} to 70 % HR_{max} and ending with a 6 s sprint (99). During the WBV intervention, participants would undergo 37 squats over a 5-minute duration (99); however, the study fails to mention the frequency of the vibrations used for the WBV, making comparisons to other WBV studies difficult. The WBV and LED protocols involved no cycling warm-up, meaning the cycling warm-up likely increased muscle temperature, leading to an increase in 30 s sprint performance. However, this does not explain how the combination of WBV and LED irradiation increased 30 s Wingate; furthermore, the study found no significant differences in muscle temperature (99). This was attributed to a PAP effect caused by the high-intensity sprint within the cycle warm-up and the squats in the WBV protocol, but this again does not explain why the WBV intervention alone did not improve sprint performance (99).

2.5.2.2 Electrical muscle stimulation

Similarly, electrical muscle stimulation (EMS) of the knee extensor muscle has been seen to provide no significant improvements to 30 s sprint performance (88). The EMS was conducted following a 10-minute cycle at 100 W with three 10 s sprints, with the control group only participating in the cycle warm-up (88). There were no significant differences in peak and mean power between the two protocols. This could, in part, be because of the EMS amplitude varying from participant due to the setting being on the maximum the participants could tolerate, which may not have been great enough to induce a potentiating effect. However, the non-significant differences in results indicate that the performance is generated from the cycle warm-up, via the generation of muscular temperature, facilitating greater sprint performance.

2.5.3 Cadence

Cadence is a key performance variable in BMX racing, as athletes will reach high cadences attempting to maintain velocity. As warm-ups have been suggested to contain specific elements of the sport/exercise being conducted (5), high cadences should be targeted during a warm-up before a BMX race. In this review, six studies monitored cadence during the warm-up before sprint performance, ranging from 60 rev·min^{-1} (101), 70 rev·min^{-1} (92, 95), 80 rev·min^{-1} (93, 101), 90 rev·min^{-1} (87), and one controlling cadence but not reporting the value (102). This range of cadences (60-90 rev·min^{-1}) can be described as a moderate cadence (132). There was no trend between higher cadences used and increased sprint performance, although no study included in this review varied cadence during the warm-up to influence sprint performance, meaning comparison is difficult.

Over a sustained constant cycle, cadence selection has been seen to elicit physiological changes which could affect subsequent sprint performance. A constant cycle at 65 % maximum power for one hour found significantly higher neuromuscular activation when cycling at 110 rev·min^{-1} compared to 50 rev·min^{-1} (52). This may be due to the increased positive work required from the front of the leg at higher cadences (133). Conversely, a study measuring muscle activity at the vastus lateralis discovered decreased neuromuscular activity following 15 minutes of cycling at high cadence (90 $rev \cdot min^{-1}$) compared to low cadence (50, 51). This may be due to the study only monitoring the muscle activity of one muscle, when it has been seen that differences in muscle activity at high and low cadences vary depending on the role the muscle has during the pedal cycle (52). In comparison, the previous study monitored muscle activity at the vastus lateralis, rectus femoris, gastrocnemius lateralis, and biceps femoris (52). Cardiorespiratory demands of work have also been seen to be increased following cycling at 120 $rev \cdot min^{-1}$ compared to 70 $rev \cdot min^{-1}$ and 90 $rev \cdot min^{-1}$ (49). The same study also identified that high cadences decreased muscular efficiency (49), which could influence the effectiveness of a high cadence warm-up to improve subsequent sprint performance. High cadences compared to low cadences have been shown to increase heart rate, systolic blood pressure at the same intensity (48) compared to low cadences, which reduces pressure response, increases blood flow, increases oxygen extraction by the skeletal muscle, facilitating increased oxidative phosphorylation and decreased myocardial response (52, 134, 135). Selecting an appropriate range of cadences is important to observe physiological differences in high and low cadences. A study found no significant differences in heart rate, cardiac output, $\dot{V}O_2$, and tissue oxygen extraction following a 6-10-minute warm-up at 50 or 65 % $\dot{V}O_2max$ (136). The cadences utilised in this study were 80 $rev \cdot min^{-1}$ and 100 $rev \cdot min^{-1}$; the difference of 20 $rev \cdot min^{-1}$ was subsequently suggested not to be great enough to elicit any significant difference in physiological measures (136).

Literature suggests that cycling at high compared to low cadences causes different physiological responses. The effectiveness of a warm-up may then be influenced by the cadence selection throughout its duration. In a sport such as BMX racing, where cadence plays a pivotal role in performance and, with warm-ups suggested to include specific elements of the sport (5), the manipulation of cadence in a warm-up could evoke improved performance and should be explored.

2.6 Future research

Future research should aim to test specific warm-ups to the performance test utilised, embracing the key demands of the test. Research should either alter the intensity, duration, or recovery period as the independent variable to clearly highlight what is causing variation in performance. Future research should also test the effect of cycling at different cadences during the warm-up on sprint performance, as cadence is a key performance variable in sprint cycling events such as BMX racing.

2.7 Conclusion

There are several outcomes from this systematic review. 1) Intensity, duration and recovery period are all important factors when developing a warm-up, and the manipulation of these depends on the physiological demands of the subsequent exercise. 2) The inclusion of task-specific exercises during a warm-up has ergogenic effects on sprint performance. 3) There is a lack of consistency in measuring intensity. Intensity should be specific to the participant by using physiological measures such as HR_{max} to determine intensity. 4) There is sparse reporting of cadence, and the manipulation of this during the warm-up could be important to increasing sprint performance. 5) Interventions that were not cycling orientated, such as EMS, did not consistently increase sprint performance and are often impractical when translating to performance in the field.

3. Justification for Experimental study

From Chapter 1, it was concluded that effective warm-ups should reflect the specific demands of the subsequent performance task, in order to optimally prepare the athlete. Intensity of the warm-up should be prescribed relative to the athlete's individual training status, ideally determined through physiological measures. However, the role of cadence has largely been overlooked in warm-up research for ≤ 30 s sprint performance, potentially playing a role in intensity modification.

In acknowledgement of this research gap and considering the established importance of cadence in BMX racingand the inclusion of task-specific exercises in a warm-up , the next logical step was to design an experimental study manipulating cadence within a sprint-based warm-up. The 30 s Wingate test facilitates the assessment of key determinants of BMX race performance, providing a controlled means to evaluate outcomes when no validated BMX racing laboratory test exists. Furthermore, recognising that BMX athletes often face a 20-30-minute pre-race holding period with limited opportunity for further warm-up, means developing a warm-up with a great enough intensity and duration to maintain PAPE effects over the recovery period duration. Thus, understanding of the physiological responses and subsequent sprint performance following a 30-minute recovery period should be explored.

Chapter 2

4. Cadence variation during sprint warm-up does not influence Wingate performance

4.1 Abstract

There is extensive literature on warm-up strategies for 30 s Wingate tests, yet the specific role of cadence manipulation within sprint-based warm-ups, particularly when performance occurs after a prolonged recovery period (30 minutes), is unclear. This randomised, within-participant, crossover study tested whether altering cadence during warm-up sprints influences subsequent Wingate performance after a 30-minute recovery.

Twelve male recreational cyclists (age 25.5 ± 9.1) completed four laboratory visits: a $\dot{V}O_2$max and peak cadence test, and three subsequent intervention trials in a randomised order. The trials consisted of a control, sprints at 70 % peak cadence, and sprints at peak cadence. Each warm-up began with a 10-minute submaximal cycle at 40 % of the peak power obtained during the $\dot{V}O_2$max test, with sprints 3 minutes post. Following a 30-minute passive recovery period, participants began the Wingate test. Respiratory gas exchange was measured during the warm-up, Wingate test, and for 30 minutes post Wingate test to assess energy system contribution. Skin temperature and capillary blood lactate were measured throughout. Cadence manipulation altered warm-up intensity (average peak cadence = 140.6 ± 9.9 rev·min^{-1} and 193.5 ± 9.8 rev·min^{-1} ($p < 0.001$) in the 70 PC and 100 PC conditions, respectively) across conditions. While skin temperature observed no significant differences ($p > 0.05$), blood lactate was significantly different between warm-up conditions post warm-up and prior to the Wingate test ($p < 0.001$). However, no significant differences were observed in peak power, mean power, peak cadence, mean cadence, time to peak power, lowest power, total work, fatigue index and fatigue slope ($p > 0.05$) resulting from Wingate performance following the 30-minute recovery period. Respiratory gas-exchange and energy system contributions did not differ meaningfully between conditions during the Wingate or recovery ($p > 0.05$). Adjusting cadence during repeated-sprint-based warm-ups modified the immediate physiological load but did not improve 30-minute delayed Wingate performance under the present protocol. To maintain thermal and neuromuscular readiness across prolonged recovery, future protocols may need a larger stimulus, supported by direct markers of readiness and carefully timed before performance.

Keywords: Warm-up, Wingate test, Intensity, Cadence, Performance, Recovery period

4.2 Introduction

Warm-up routines aim to enhance performance and reduce injury risk by increasing muscle temperature, improving tissue elasticity, and facilitating neuromuscular coordination (63, 137). The design of an effective warm-up depends on modality (active or passive) (5), specificity to the performance task, and key variables such as duration, intensity, and the recovery period before competition (5).

Warm-up intensity is a critical determinant of performance, primarily due to its influence on muscle temperature. Heat generated during exercise arises from metabolic inefficiency, and greater exercise intensity increases this thermal effect (11). A greater intensity or duration of exercise would demand a greater metabolic cost, thus generating high muscular temperatures. Moderate intensities, typically 40-60 % $\dot{V}O_2$max, are associated with favourable increases in muscle temperature (5). However, when intensity approaches or exceeds ~60 % $\dot{V}O_2$max, the associated metabolic cost may accelerate depletion of high-energy phosphate stores, impairing short-duration performance (5, 138). Conversely, very low intensities (~40 % $\dot{V}O_2$max) may be insufficient to raise muscle temperature (5). It is important to note that these effects were observed in protocols where no recovery period was provided between the warm-up and the subsequent exercise task, which may have influenced the outcomes (5).

Warm-up duration is another important factor. Muscle temperature rises quickly during the first 3–5 minutes of exercise and typically plateaus after 10–20 minutes (112). When intensity remains high and recovery is short, however, long warm-ups can impair short-duration performance through rapid phosphocreatine (PCr) depletion (138, 139). PCr availability typically plateaus after 3–6 minutes of high-intensity exercise (140), aligning with the observed decline in performance during extended high-intensity warm-ups.

The recovery period required after a warm-up also interacts with intensity and duration.
PCr stores can resynthesise to near-full capacity within ~ 5 minutes, although full recovery may require up to 20 minutes (116). Studies extending recovery from 3 to 6 minutes following high-intensity warm-up reported improved peak power (138). However, excessive recovery periods (~ 15-20 minutes) risk muscle temperature decline, offsetting the benefits of the warm-up (5). Thus, the recovery must balance energy store replenishment against thermal decay.

Specificity is another consideration with warm-ups incorporating movements that mimic the performance task, shown to enhance neuromuscular activation (33, 47). Research on short-duration tasks, however, is limited and inconsistent (5). For example, a Wingate-specific warm-up yielded no performance improvement compared to no warm-up, but did increase fatigue index in untrained participants (87). By contrast, a protocol incorporating repeated short sprints within the warm-up enhanced power and force during 7 s cycling efforts compared to a general warm-up (95). Interpretation is complicated because these studies often varied both specificity and duration simultaneously.

In the context of BMX racing, performance is shaped by three phases: an initial acceleration phase off the start ramp, a mixed central phase of impulse efforts over obstacles interspersed with pedalling, and a stamina phase, in which riders attempt to maintain high cyclic power and velocity (36). Early race performance, particularly the first sprint from the start gate, is a critical determinant of outcome (37-41). Riders with the highest power-to-weight ratios tend to accelerate fastest, influencing lap time and race success (43) (141). Although BMX is highly anaerobic, recovery between heats (~ 30 minutes) highlights the role of aerobic capacity ($\dot{V}O_2$ peak), which can explain over 50 % of lap performance variation across repeated efforts (43, 56).

Cadence is also a key performance determinant. While power output peaks early in a race and declines thereafter, cadence and velocity continue to rise (45). This suggests that sustaining velocity relies not only on power but also on cadence efficiency, particularly as peak cadence often exceeds 125 rev·min^{-1} (45).

The metabolic profile of BMX sprints and Wingate tests further justifies their comparison with blood lactate responses from a BMX race (14.5 ± 4.5 mmol/L) (56), comparable to those recorded following a Wingate test (14.1 ± 0.5 mmol/L) (142). Furthermore, in 6 s short-duration sprints, similarly seen in BMX racing, the ATP-PCr system and anaerobic glycolysis contribute almost equally (~ 50 % each) to energy supply (54). In 30 s efforts, such as the Wingate test, anaerobic glycolysis contributes ~ 50 %, PCr ~ 30 %, and aerobic metabolism ~ 20 % (55). Thus, the Wingate test provides a valid laboratory model to examine the energy system contributions, power output, and fatigue relevant to BMX performance, despite the lack of a validated BMX-specific test (38, 45, 58).

Although numerous studies have investigated warm-up effects on sprints ≤ 30 s in duration, most have focused on manipulating the duration (98), intensity (87, 92, 100, 101), recovery period (94), or combinations thereof (89, 90). Cadence as a manipulation of warm-up intensity remains relatively unexplored. High cadences (> 100 rev·min^{-1}) have increased cardiorespiratory strain, muscular efficiency, and metabolic costs relative to lower cadences (~ 50-95 rev·min^{-1}), eliciting higher heart rate, blood pressure, and blood lactate levels (48, 49). Extended high cadence cycling also alters muscle activation patterns, shifting workload distribution across thigh muscles (50-52). These changes could provide an ergogenic stimulus if harnessed appropriately during a warm-up. Finally, research examining extended recovery periods is sparse. Severe-intensity warm-ups have been shown to enhance Wingate performance after 30 minutes of recovery compared to shorter (15-minute) intervals (94), suggesting that benefits can persist if the warm-up stimulus is sufficiently potent.

Therefore, the aim of this study was two-fold. (1) To manipulate cadence within sprint-based warm-ups to elicit distinct exercise intensities, and (2) to examine whether these manipulations influence Wingate test performance following a 30-minute recovery period.

4.3 Methods

4.3.1 Participants

A priori power analysis was conducted using G*Power (latest ver. 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) for a repeated measures

ANOVA with three conditions. Based on prior data showing a peak power difference of 48 W and a pooled SD of 102.5 W (Cohen's *d* = 0.47), the effect size was converted to *f* = 0.38, assuming a within-subject correlation of *r* = 0.7. With a Bonferroni-adjusted alpha level of 0.0167 and power set at 0.80, the required sample size was 12 participants

Twelve recreationally active men (age 25.5 ± 9.1 years; 179.2 ± 4.7 cm; 75.9 ± 5.2 kg; $\dot{V}O_2max$ 43.9 mL/kg/min) volunteered via advertisements. Inclusion criteria were age 18-50, recreational cycling experience, good health, and no current injuries. All participants completed a physical activity readiness questionnaire (PAR-Q) and provided written informed consent. Ethical approval was granted by the University of Essex Ethical Committee (ethics application ETH2425-0223).

4.3.2 Design

Participants attended the laboratory on four occasions at the same time of day (± 1 hour), with at least 48 hr between visits (laboratory temperature 19 °C). Visit 1 was a preliminary testing and familiarisation session, including anthropometric assessment, $\dot{V}O_2max$, peak cadence and a Wingate test. The following three visits were conducted in a random order, in a crossover design: (1) Control warm-up (CON), (2) a high cadence warm-up at 70 % peak cadence (70 PC), and (3) a severe cadence warm-up at peak cadence (100 PC).

4.3.3 Experimental procedures

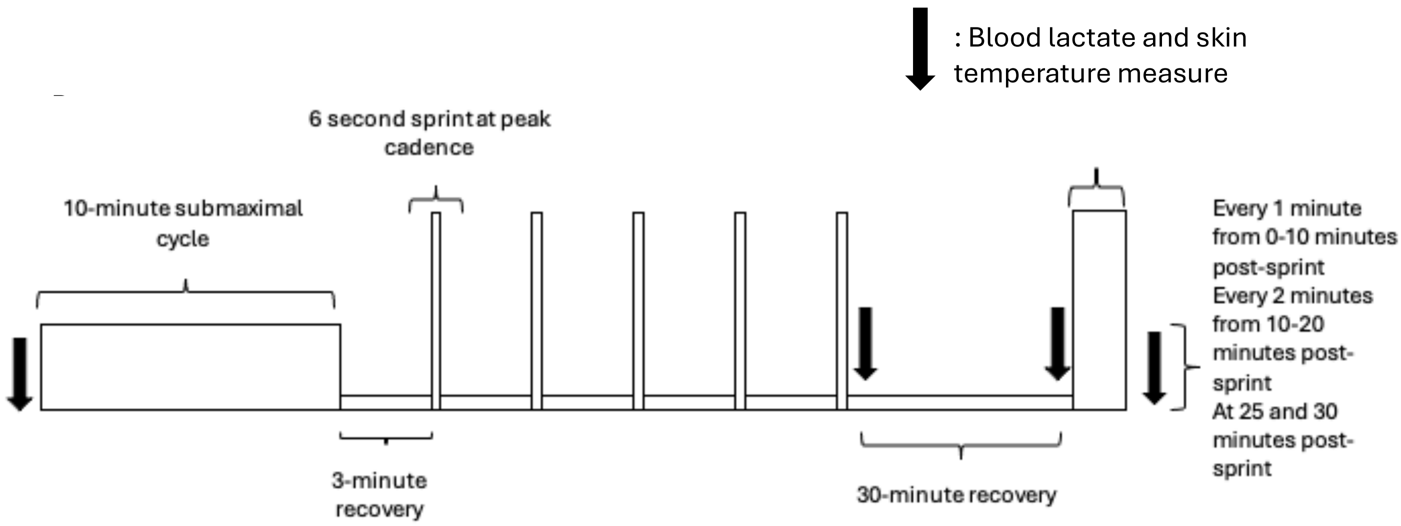
Participants were instructed to avoid strenuous exercise and alcohol for 24 h and caffeine for 12 h before each visit. All exercise testing was conducted on an electronically braked cycle ergometer (Excalibur Sport, Lode, Netherlands). Power and cadence were recorded using PowerLab hardware and Chart software (ADInstruments, Australia).

During the familiarisation session, stature (Seca 213 Stadiometer, Birmingham, UK) and body mass (Seca 875, Birmingham, UK) were assessed, and participants completed three exercise tests in sequence. First, a $\dot{V}O_2max$ test was conducted following a 3-minute warm-up at 30 W. The test commenced at 90 W and increased by 30 W each minute until exhaustion, with participants instructed to maintain 80 $rev{\cdot}min^{-1}$ throughout. Tests were terminated when cadence dropped below 60 $rev{\cdot}min^{-1}$ for more than 5 s. Breath-by-breath gas exchange was measured using a Vyntus CPX Metabolic Cart (Vyaire Medical, Germany), facilitating the calculation of the participants' $\dot{V}O_2max$ over a 30 s moving average.

Second, participants completed three 6 s maximal sprints at zero resistance to determine peak cadence. Cadence was sampled at 0.2 s intervals, and the average of the three trials was used to calculate peak cadence (coefficient of variation = 3.85 %). Recovery between sprints was standardised to 3 minutes. Finally, a 30 s Wingate test was performed using body mass-adjusted resistance to familiarise participants with the protocol and with wearing the respiratory mask during maximal effort. Body-mass-adjusted resistance was calculated as 0.7 × body mass (kg) to determine Wingate loading.

During the intervention sessions, participants first completed a 5-minute seated rest period on the ergometer, with skin temperature and fingertip blood lactate sampled in the final minute. Warm-ups then commenced. In the CON condition, participants cycled for 10 minutes at 40 % of peak power output determined from the $\dot{V}O_2max$ test, maintaining 70–80 rev·min^{-1}, without sprints. In the high-cadence condition, the same 10-minute submaximal warm-up was followed by a 3-minute recovery and then five 6 s sprints at 70 % peak cadence, each separated by 3-minute recovery. In the severe-cadence condition, the protocol was identical, except sprints were performed at 100 % peak cadence. All trials were followed by a 30-minute passive recovery period, after which participants performed the Wingate test. Gas exchange was recorded continuously before and during both the Wingate and the subsequent 30-minute recovery. Blood lactate and skin temperature were measured every minute during the first 10 minutes of recovery, every 2 minutes during the following 10 minutes, and at 25 and 30 minutes (see Figure 2).

A.



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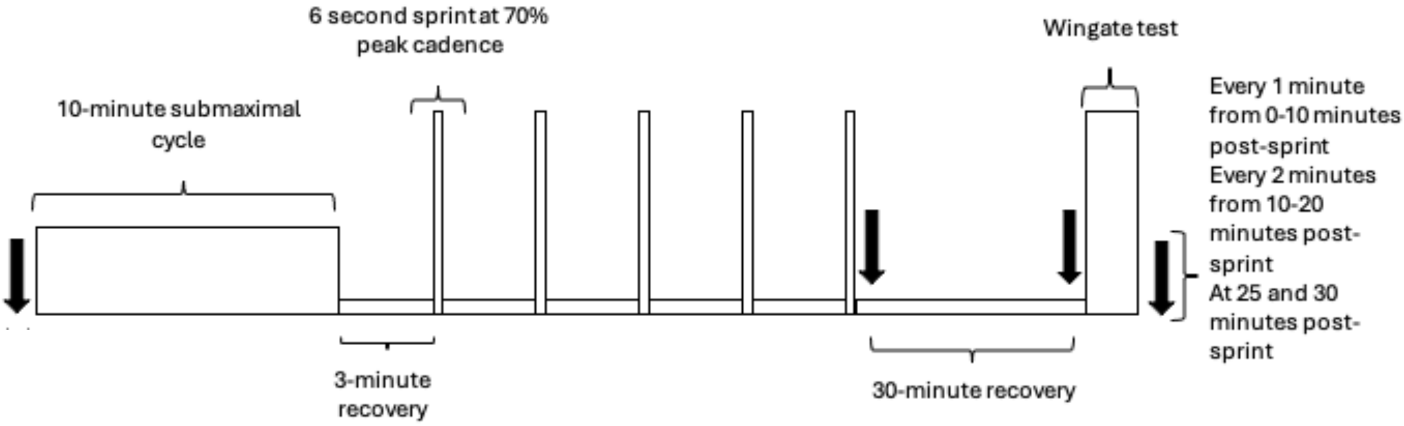

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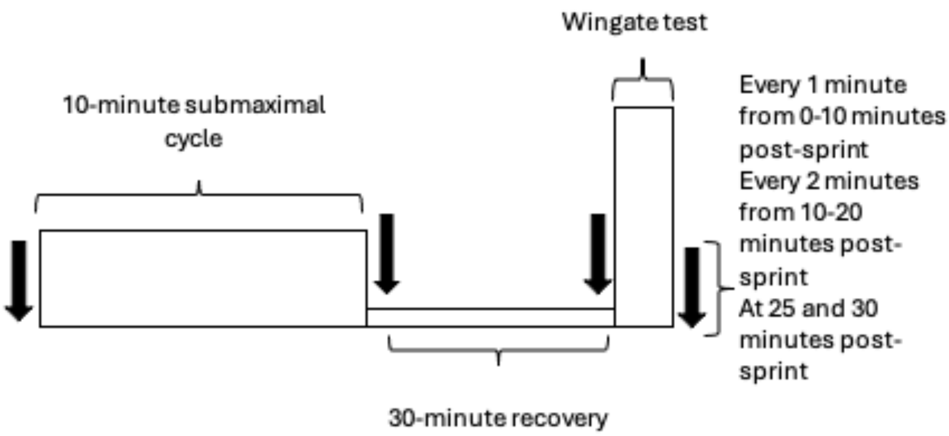

Figure 2: Schematic of experimental procedures, A. 100 PC, B. 70 PC, and C. CON

4.3.4 Measures

4.3.4.1 Power output and cadence

During the repeated sprint warm-up protocol, for each sprint, peak cadence was defined as the single highest sample during the 6 s window, time to peak cadence was determined relative to sprint onset, and mean cadence was calculated across the 0 to 6 s window. The peak and mean cadences achieved during the 6 s sprint were then calculated as a percentage of the peak cadence achieved during the peak cadence test (percentage peak/mean cadence).

During the Wingate test, peak power and peak cadence were defined as the single highest observed sample, with corresponding times to peak. Mean power and mean cadence were computed as the arithmetic mean across the full 30 s, and total mechanical work was calculated by summing the work performed in each 5 s interval during the Wingate test. For each interval, mechanical work (in joules) is calculated by multiplying the power output (in watts) by the duration of the interval (5 s). The total mechanical work is the sum of these values across all intervals. Fatigue index (%) was calculated as;

Faitgue Index (%) = (peak power − lowest power after the peak) ÷ peak power) × 100.

Power output and cadence values were exported from Chart software (ADInstruments, Australia) and determined using a custom-built MATLAB script.

4.3.4.2 Gas Exchange

Gas exchange was measured throughout all trials using the Vyntus CPX system, which was calibrated with a 3 litre (L) syringe and standard gas mixtures before each session. Participants wore a silicone facemask adjusted to minimise leaks. Breath-by-breath data were filtered using a 30 s moving average, with outliers (> 3 SD) removed, and synchronised with ergometer data for subsequent analysis. Resting values were collected during the seated baseline and pre-Wingate phases, with continuous recording during warm-up, Wingate, and recovery. Resting values were used to calculate carbohydrate oxidation, fat oxidation, and energy expenditure rates at rest, utilising the calculations (143, 144):

Carbohydrate ($g \cdot min^{-1}$): $(4.55 \cdot RER - 3.21) \cdot \dot{V}O_2 \; L \cdot min^{-1}$

Fat ($g \cdot min^{-1}$): $1.67 \cdot (1 - RER) \cdot \dot{V}O_2 \; L \cdot min^{-1}$

Energy expenditure ($kcal \cdot min^{-1}$): $3.941 \cdot \dot{V}O_2 + 1.106 \cdot \dot{V}CO_2 \; L \cdot min^{-1}$

4.3.4.3 Blood lactate and Skin temperature

Capillary blood samples were taken at rest, immediately post-warm-up, pre-Wingate, and throughout recovery as described above. Samples were obtained from the fingertip using a single-use lancet (Unistik 3 Extra, Owen Mumford, Oxford, UK). Prior to this, the fingertip was cleaned using an antiseptic wipe. Blood was collected into a capillary tube and then immediately transferred to an Eppendorf tube (EKF diagnostic, Magdeburg, Germany). Samples were analysed immediately using a Biosen blood lactate analyser (EKF Diagnostics, Germany).

Skin temperature was recorded at the anterior thigh midpoint, between the patella and inguinal crease (100, 145). A mark was placed where the probe (Libra Medical Ltd, Model ET402, Ascot Berks, UK) should be placed and secured in position using micropore tape. Skin temperature was recorded immediately prior to lactate sampling. Skin temperature has been tested as a valid proxy for intramuscular temperature within 1.3 cm of the skin surface (145) and is less invasive than core temperature measures. Despite no existing published literature testing the reliability or validity of the probe utilised in this study, it has been used across sport science literature to measure skin temperature (146) and rectal temperature (147-149).

4.3.4.4 Energy System Contributions

Energy system contributions were estimated in MATLAB from gas exchange, blood lactate, and a model of post-exercise oxygen uptake. The 30 s Wingate window was defined from a user-specified start time. Baseline oxygen uptake ($\dot{V}O_{2,\ rest}$) was obtained from the lowest 30 s moving average within the 120 s pre-sprint period.

Aerobic energy ($W_{\dot{V}O2}$)

$\dot{V}O_2$ during the 30 s Wingate was cleaned (moving mean ± 3 SD outlier removal, linear interpolation of gaps), and expressed relative to $\dot{V}O_{2,\ rest}$. Aerobic energy was the time integral of $\dot{V}O_2$ above baseline over the 30 s, converted using a constant caloric equivalent of oxygen (20.9 kJ·L^{-1}):

$$W_{\dot{V}02} = \left(\int_0^{30\ s} \left[\dot{V}O_2(t) - \dot{V}O_{2,rest}\right]\right) \times 20.9\ kJ \cdot L^{-1}$$

Equation 1

Where $\dot{V}O_2(t)$ represents oxygen uptake at time (t), in L·min^{-1} and $\dot{V}O_{2,\ rest}$ signifies baseline oxygen uptake.

Anaerobic glycolytic energy (W_{La})

Glycolytic energy was derived from the net blood lactate accumulation, defined as the peak concentration during recovery minus the pre-sprint value. Following the oxygen-equivalent approach,

$$W_{La} = \Delta\left[La^{-}\right] \times 3\, mL\, O_2\, mmol^{-1}kg^{-1} \times BM\,(kg) \times 20.9\, \times 10^3\, J \cdot L^{-1}$$

Equation 2

Where $\Delta\,[La^{-}]$ reflects the net blood lactate accumulation, $3\, mL\, O_2\, mmol^{-1}kg^{-1}$ is the conventional oxygen equivalent pr mmol lactate per kg of body mass and $20.9\, \times\, 10^3\, J \cdot L^{-1}$ is the conversion from litres of oxygen to joules. This avoids assumptions about blood volume and ATP stoichiometry and is consistent with established practice for translating lactate accumulation into an oxygen equivalent.

Anaerobic alactic energy (W_{PCr})

Post-exercise $\dot{V}O_2$ above baseline was sampled over a user-defined recovery window and fitted with a bi-exponential model,

$$\dot{V}O_2(t) = A_1 e^{-\frac{t}{\tau 1}} + A_2 e^{-\frac{t}{\tau 2}} \rightarrow W_{PCr} = \left(A_1 \frac{\tau_1}{60}\right) \times 20.9\, \times 10^3\, \mathrm{J}$$

Equation 3

Where A_1 represents the fast-phase amplitude of post-exercise $\dot{V}O_2$ above baseline in $L \cdot min^{-1}$ and τ_1 as the fast-phase time constant in seconds. Negative $\dot{V}O_2$ deviations below baseline were clamped to zero before fitting. This captures phosphocreatine resynthesis demands reflected in the fast phase of excess post-exercise oxygen consumption.

Total metabolic energy

Total metabolic energy for the 30 s sprint was calculated as,

$$W_{TOT} = W_{VO2} + W_{La} + W_{PCr}$$

Equation 4

With relative contributions calculated as a percentage (%) of W_{TOT}.

Metabolic power

Metabolic power was determined as the mean metabolic power during the 30 s Wingate test (W).

$$P_{met}\ (W) = \frac{W_{TOT}}{30\ s}$$

Equation 5

Net Efficiency

The mean mechanical power during the Wingate test was compared P_{met} to provide net efficiency,

$$Efficiency\ (\%) = 100\frac{AP}{P_{met}}$$

Equation 6

Whereby AP refers to the mean external mechanical power from the ergometer over the 30 s Wingate duration.

4.3.5 Statistical analysis

Descriptive statistics were reported as mean ± standard deviation. Firstly, the Shapiro-Wilk test was employed to assess whether the data were normally distributed.

The outcome variables of the 70 PC and 100 PC warm-ups (peak cadence, mean cadence, time to peak cadence) were analysed using a paired samples t-test.
The primary outcome variables obtained following the Wingate test (peak power, mean power, peak cadence, mean cadence, time to peak power, lowest power, total work, fatigue index and fatigue slope) were analysed using one-way ANOVAs with warm-up condition (CON, 70 PC, and PC) as the within-subjects factor. Post hoc comparisons were adjusted using Bonferroni correction.

Secondary outcome variables, including oxygen uptake ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), relative oxygen uptake ($\dot{V}O_2$), respiratory exchange ratio (RER), resting metabolic rate (RMR), blood lactate concentrations, skin temperature, carbohydrate (CHO) oxidation, fat oxidation, and energy system contributions (aerobic, anaerobic glycolytic, ATP-PCr), were also analysed. For these variables, one-way ANOVAs were employed when parametric assumptions were met. If the normality assumption was violated and couldn't be corrected through data transformation, the Friedman test was used. Significant results from the non-parametric test were further explored using the Wilcoxon signed-rank tests with

Bonferroni correction for multiple comparisons. Data was checked for homogeneity of variances by utilising Levene's test.

Statistical significance was set at an alpha level of 0.05 for primary analyses, and all statistical analyses were performed using SPSS (Version 29) software.

4.4 Results

4.4.1 Baseline

4.4.1.1 Blood lactate

No differences were observed between the CON (1.04 mmol/L ± 0.7), 70 PC (1.22 mmol/L ± 0.5), and 100 PC (0.91 mmol/L ± 0.4) conditions at baseline ($p = 1.000$).

4.4.1.2 Skin Temperature

Skin temperature data is omitted for two participants due to technical difficulties with the equipment; therefore, the temperature data presented reflects $n = 10$.

There were no significant differences in skin temperature between the CON (30.5 °C ± 1.5), 70 PC (30.9 °C ± 0.8), and 100 PC (30.3 °C ± 1.1) conditions at baseline ($F_{(2, 27)} = 0.54$, $p > 0.05$).

The omission of significance between blood lactate and skin temperature baseline measures indicates that participants were all in a similar physiological state prior to each trial.

4.4.2 Repeated Sprint Warm-up

Significant differences in peak cadence (t (11) = 18.71, $p < 0.001$), mean cadence (t (11) = 10.71, $p < 0.001$), time to peak cadence (t (11) = 3.64, $p < 0.005$), and target mean cadence (t (11) = 6.45, $p < 0.001$) were discovered between the 70 PC and 100 PC warm-ups (see Table 5). Target peak cadence was not significantly different between warm-up conditions ($p > 0.05$) (see Table 5 and Figure 3).

Table 5: Cadence outcomes of the warm-up interventions

	Peak Cadence (rev·min^{-1})	**Mean Cadence (rev·min^{-1})**	**TTPC (s)**	**Target peak cadence (%)**	**Target mean cadence (%)**
70 PC	140.57 ± 9.87	109.86 ± 12	4.99 ± 0.78	110.45 ± 5.05	86.10 ± 5.22
100 PC	193.46 ± 9.75 *	135.84 ± 12.98 *	5.85 ± 0.1 *	107.35 ± 4.15	75.22 ± 4.35 *

± = standard deviation, rev·min^{-1} = revolutions per minute, TTPC = time to peak cadence, s = seconds, % = percentage
* Significant difference compared to 70 PC

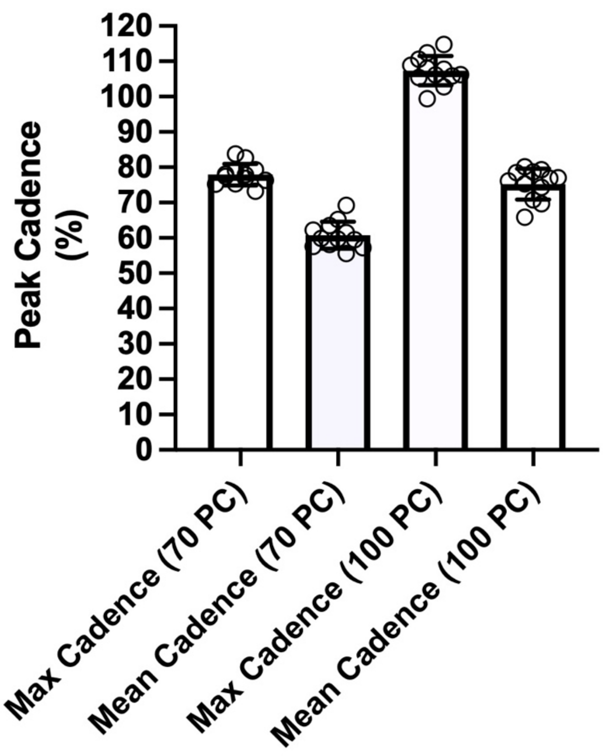

Figure 3: Percentage achievement of cadence target in warm-up interventions

Max cadence – Average maximum cadence achieved over the five warm-up sprints
Mean cadence – Mean cadence achieved over the five warm-up sprints

4.4.3 Post Warm-up comparisons

4.4.3.1 Blood lactate

There were significant differences in blood lactate concentrations immediately post warm-up ($F (2, 32) = 15.59$, $p < 0.001$). Post hoc comparisons indicated that the 100 PC warm-up condition was significantly different to the 70 PC and CON conditions ($p < 0.001$). No difference was observed between the 70 PC and CON conditions ($p = 1.000$) (see Figure 4).

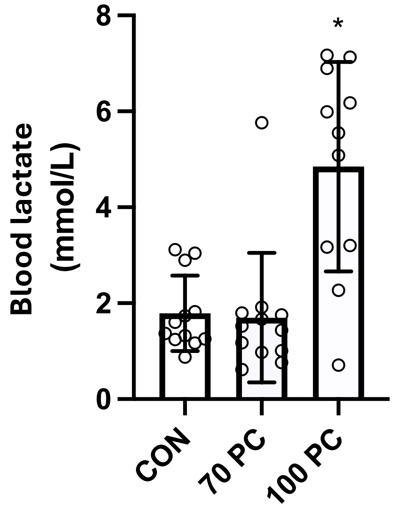

Figure 4: Blood lactate concentrations post warm-up

(*) indicates a significant difference from CON and 70 PC

4.4.3.2 Skin temperature

There were no significant differences in skin temperature between the CON (31.8 °C ± 1.3), 70 PC (32.1 °C ± 1.2), and PC (31.9 °C ± 0.9) conditions post warm-up (F (2, 27) = 0.54, $p > 0.05$).

4.4.4 Pre-Wingate comparisons

4.4.4.1 Resting Gas

Analysis discovered mean $\dot{V}O_2$ (F (2,33) = 0.38, $p > 0.05$), mean $\dot{V}CO_2$ (F (2,33) = 0.28, $p > 0.05$), mean relative $\dot{V}O_2$ (F (2,33) = 0.37, $p > 0.05$), mean RER (F (2,33) = 0.37, $p > 0.05$), RMR (F (2,33) = 0.35, $p > 0.05$), CHO oxidation (F (2,33) = 0.33, $p > 0.05$), and fat oxidation (F (2,33) = 0.78, $p > 0.05$) to all be not significant between all warm-up conditions (see Table 6).

Table 6: Resting gas measures pre-Wingate test

	$\dot{V}O_2$ ($L \cdot min^{-1}$)	$\dot{V}CO_2$ ($L \cdot min^{-1}$)	Relative $\dot{V}O_2$ ($L \cdot min^{-1}$)	RER	RMR (kcal)	CHO oxidation ($g \cdot min^{-1}$)	Fat oxidation ($g \cdot min^{-1}$)
CON	0.54 ± 0.08	0.48 ± 0.10	7.09 ± 1.35	0.90 ± 0.11	2.65 ± 0.40	0.48 ± 0.28	0.10 ± 0.08
70 PC	0.56 ± 0.11	0.51 ± 0.12	7.36 ± 1.48	0.92 ± 0.10	2.76 ± 0.54	0.56 ± 0.31	0.08 ± 0.09
100 PC	0.58 ± 0.17	0.52 ± 0.16	7.71 ± 2.35	0.89 ± 0.08	2.86 ± 0.85	0.48 ± 0.24	0.12 ± 0.06

± = standard deviation, $\dot{V}O_2$ = volume of oxygen, $\dot{V}CO_2$ = volume of carbon dioxide, RER = respiratory exchange ratio, RMR = resting metabolic rate, CHO = carbohydrate, $L \cdot min^{-1}$ = litres per minute, kcal = kilocalories, , $g \cdot min^{-1}$ = grams per minute, kcal = kilocalories

4.4.4.2 Blood lactate

There were significant differences in blood lactate concentrations pre-Wingate test (F (2, 33) = 9.93, p < 0.001). Post hoc comparisons indicated that the 100 PC warm-up condition was significantly different to the 70 PC and CON conditions (p < 0.001). No difference was observed between the 70 PC and CON conditions (p = 1.000) (see Figure 5).

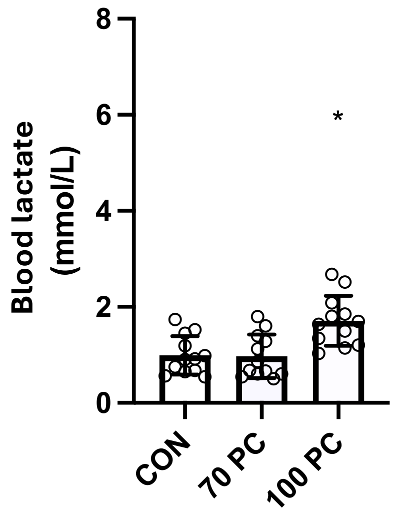

Figure 5: Blood lactate concentrations pre-Wingate test

(*) indicates a significant difference from CON and 70 PC

4.4.4.3 Skin temperature

There were no significant differences in skin temperature between the CON (31.8 °C ± 1.5), 70 PC (31.9 °C ± 1.1), and 100 PC (31.7 °C ± 1.2) conditions pre-Wingate (F (2, 27) = 0.54, p > 0.05).

4.4.5 Wingate Metrics

No significant differences were observed between warm-up conditions for any Wingate variables. This included peak cadence F (2,33) = 0.465, p >0.05, time to peak cadence $F (2, 33) = 0.31$, $p > 0.05$, mean cadence $F (2,33) = 0.13$, $p > 0.05$, peak power $F (2,33) = 0.06$, $p > 0.05$, time to peak power $F (2,33) = 0.07$, $p > 0.05$, mean power $F (2,33) = 0.09$, $p > 0.05$, lowest power $F (2,33) = 1.65$, $p > 0.05$, total work $F (2,33) = 0.10$, $p > 0.05$, fatigue index $F (2,33) = 0.71$, $p > 0.05$, and fatigue slope $F (2,33) = 0.17$, $p > 0.05$ (see Table 7).

Table 7: Key Wingate test performance outcomes

	Peak Cadence (rev·min^{-1})	Time to peak cadence (s)	Mean Cadence (rev·min^{-1})	Peak Power (W)	Time to peak power (s)	Mean Power (W)	Lowest Power (W)	Total Work (kJ)	Fatigue Index	Fatigue slope
CON	148.41 ± 9.28	7.13 ± 1.68	116.60 ± 10.94	900.58 ± 185.41	6.09 ± 2.27	651.86 ± 64.06	406.59 ± 105.44	19.58 ± 1.88	53.34 ± 14.81	20.64 ± 7.46
70 PC	145.01 ± 8.62	7.78 ± 2.42	114.43 ± 10.3	876.58 ± 187.12	6.41 ± 3.08	641.0 ± 69.54	361.73 ± 124.29	19.25 ± 2.04	56.30 ± 18.12	21.51 ± 8.97
100 PC	145.55 ± 9.9	7.71 ± 2.51	115.60 ± 10.84	878.95 ± 182.09	6.47 ± 2.51	647.02 ± 60.28	435.07 ± 57.51	19.45 ± 1.79	49.25 ± 9.08	19.64 ± 7.47

± = standard deviation, rev·min^{-1} = revolutions per minute, s = seconds, W = watts, kJ = kilojoules

4.4.6 Energy Contributions

No significant difference between the three warm-up conditions were found following One-way ANOVA in $\dot{V}O_2$ $F(2,33) = 0.18$, $p > 0.05$, Lactate $F(2,33) = 1.18$, $p > 0.05$, PCr $F(2,33) = 0.27$, $p > 0.05$, total work $F(2,33) = 0.45$, $p > 0.05$, metabolic power $F(2,33) = 0.42$, $p > 0.05$, and net efficiency $F(2,33) = 0.26$, $p > 0.05$ (see Table 7 and Figure 6).

Table 8: Energy contributions during Wingate test

	$\dot{V}O_2$ (kJ)	**Lactate (kJ)**	**PCr (kJ)**	**Total work (kJ)**	**Metabolic power (W)**	**Net efficiency (%)**
CON	14.50 ± 4.01 (3.37 %)	43.55 ±5.44 (7.01 %)	41.28 ± 12.28 (8.09 %)	99.33 ± 15.06	3310.90 ± 501.89	20.02 ± 2.95
70 PC	14.86 ± 2.85 (3.7 %)	38.99 ± 8.74 (6.6 %)	41.97 ± 9.95 (7 %)	95.82 ± 13.11	3194.03 ± 473.08	20.35 ± 2.34
100 PC	15.53 ± 5.69 (6.44 %)	39.59 ± 9.02 (5.1 %)	38.96 ± 9.93 (7.31 %)	93.92 ± 14.62	3136.28 ± 483.71	20.81 ± 2.79

± = standard deviation, $\dot{V}O_2$ = volume of oxygen, PCr = phosphocreatine, kJ = kilojoules, W = watts, % = percentage

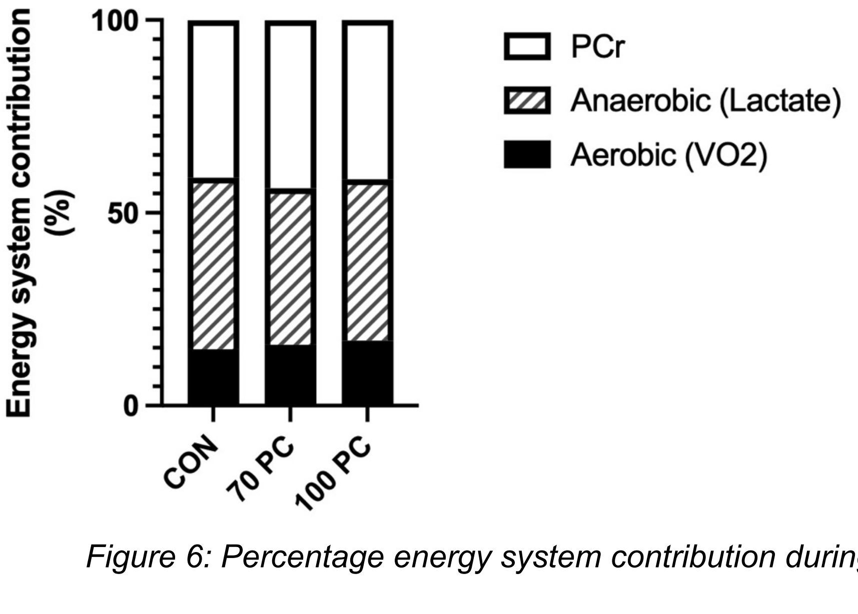

Figure 6: Percentage energy system contribution during the Wingate test

4.5 Discussion

This study examined whether manipulating cadence during the warm-up would influence 30 s Wingate performance when the test was performed after 30 minutes of rest. The warm-ups successfully differentiated cadence profiles, as shown by higher mean and peak cadence and shorter time to peak cadence (see Table 5 and Figure 3), yet there was no clear effect on subsequent Wingate performance. Taken together, the data indicate that although cadence manipulation altered the immediate characteristics of the warm-up, the physiological stimulus achieved here was insufficient to translate into a performance benefit after the recovery period.

A useful way to situate this null finding is to contrast the present protocol with severe intensity warm-up studies that do report benefits after prolonged recovery. For example, cycling for 6 minutes at gas exchange threshold (GET) plus 70 % the difference between the GET and $\dot{V}O_2max$ (Δ) (~ 260 ± 27 W in that cohort) improved Wingate performance after 30 minutes (94, 150). In the current work, the submaximal stage of the warm-up averaged 133 ± 18 W for 10 minutes, and the five 6 s sprints were performed without any external resistance, indicating that the intensity of the warm-up was below the requirement to provide performance benefits. The biomarker profile is consistent with the smaller overall load: post-warm-up blood lactate remained modest, and pre-Wingate concentrations were ~ 1.0 – 1.7 $mmol \cdot L^{-1}$ across conditions, below the ~ 3 $mmol \cdot L^{-1}$ proposed to be associated with ergogenic effects before brief intense tasks (29, 150, 151). Skin temperature rose from baseline to pre-Wingate by ~ 1.1–1.4 °C yet did not differ between conditions. Together, these observations indicate that the warm-ups altered cadence behaviour, but did not generate sufficient metabolic or thermal perturbation to carry a benefit through the subsequent 30 minutes.

The decision to use unloaded sprints was grounded in a clear hypothesis: remove resistance so that participants accelerate rapidly and spend longer at the target cadence. In practice, the delivered exposure fell short of the target, particularly in the 100 PC condition. Relative deviation from target was ~ 8 % at 70 % peak cadence and ~16 % at peak cadence (see Table 5 and Figure 3), driven by lower mean cadence across the five efforts when the target was highest. This likely reflects the simple constraint that reaching very high cadences requires more time to accelerate, so the 6 s window captured less time near the target. The practical implication is direct. If cadence exposure is the mechanism under test, the recording window should begin once the target cadence is reached, with a standardised acceleration allowance, or an external load should be added to increase torque and muscle recruitment while preserving the cadence target.

Across constant work designs, higher cadences provoke higher heart rate, blood pressure, and blood lactate, reduce gross efficiency, and shift thigh muscle activation (vastus lateralis, rectus femoris) compared with lower cadences over prolonged bouts (48, 49, 52, 133, 136, 152). However, most of these studies used cadences in the 70–126.5 rev·min^{-1} range and sustained exposures of 20–60 minutes at fixed power (48, 49, 52, 133, 136). In this study, peak cadence targets were often higher (for example, mean cadences during warm-up sprints of ~110 and ~136 rev·min^{-1} in the 70 PC and 100 PC conditions, respectively), with very short sprint exposures and no external load. The mismatch in both cadence range and loading paradigm limits direct comparison and offers a plausible explanation for the modest physiological separation observed here despite clear differences in cadence metrics.

Two mechanisms that have been proposed to support short-duration performance are worth considering. First, lactate-related modulation of muscle excitability. Elevated lactate can aid the restoration of sodium–potassium pump activity in fatigued muscle, which helps stabilise membrane excitability and can support force generation during brief intense effort (153). In our data, pre-Wingate lactate concentrations were low, about 0.99 $mmol \cdot L^{-1}$ in CON, 0.97 $mmol \cdot L^{-1}$ at 70 PC, and 1.71 $mmol \cdot L^{-1}$ at 100 PC (see Figures 4 and 5), which sits below the ~3 $mmol \cdot L^{-1}$ level sometimes associated with ergogenic effects before short sprints (29, 150, 151). It is therefore plausible that this mechanism was not engaged to a meaningful extent under the present protocol. Notably, lactate per se does not appear to impair skeletal muscle performance directly in this context (154), so the problem is not excessive lactate, but rather an insufficient pre-performance concentration to confer benefit.

Second, elevation of the primary $\dot{V}O_2$ amplitude following priming. Severe intensity priming can increase the amplitude of the primary $\dot{V}O_2$ response in a subsequent task, reduce the oxygen deficit, and spare anaerobic contribution, which together may extend time to exhaustion and reduce fatigue-related acidosis when tasks have a significant aerobic component (151, 155). In our study, the estimated aerobic fraction of the Wingate was about 15–17 % across conditions, which is within the reported range for 30 s sprints but remains a minority share of total energy. Even if

$\dot{V}O_2$ kinetics were slightly primed, the scope for this to raise mean power materially in such a short task is limited unless the initial stimulus also produces a durable thermal and neuromuscular advantage.

Skin temperature at the mid-thigh is a limited proxy for intramuscular temperature, and small changes in skin temperature do not guarantee improvements in sprint output. Using direct intramuscular temperature measures would likely have clarified whether thermal decay across the 30 minutes contributed to the null result. This is highlighted by skin temperature only being able to be accurately utilised as a proxy for intramuscular temperature up to depths of 1.3 centimetres (cm) under the skin (145). The utilisation of muscle temperature would have facilitated comparison to literature that states muscle temperatures in the range of 37-39.3 °C are required to increase short-duration cycle performance due to an enhanced metabolic environment and facilitating greater force-generating capacities of the muscle, including cross-bridge formation (156, 157).

Recovery duration interacts with stimulus size. A 30-minute interval is realistic in sports where athletes wait between efforts, including BMX racing, and severe intensity priming can retain benefits over this timescale (94). The present data suggest that when the warm-up intensity is modest, the advantage decays. Phosphocreatine resynthesis is largely complete by 5–20 minutes, so the 30-minute window should not penalise subsequent sprint capability on that basis (116). What appears limiting is that the initial stimulus was not large enough to maintain thermal and neuromuscular readiness into the performance window. The cadence manipulation changed the pattern of the warm-up, but the combination of moderate submaximal work and unloaded sprints produced only small and transient internal changes that had largely dissipated by the time of testing.

Specificity also matters, and during the Wingate, power peaks early, cadence rises and then diverges from power as fatigue accrues. If the warm-up stimulus does not increase both the rate of force development and time at the cadences that matter for the early phase of the Wingate, its translation may be weak. Adding external resistance to the warm-up sprints would plausibly recruit higher threshold motor units (158), and better mirror the neuromechanical demands of the Wingate start, while still allowing cadence targets to be met if the acceleration period is standardised.

The energy system estimates support this interpretation. Aerobic contribution during the Wingate remained modest, while glycolytic and ATP–PCr shares dominated as expected for 30 s efforts. Post warm-up lactate was lower than values reported in severe priming studies (94), and pre Wingate lactate had returned close to baseline by the time of the test. Where prior work has reported improved performance after long recoveries, a common thread is a short, severe intensity segment that creates a large perturbation in the internal milieu, higher lactate, higher muscle temperature, and a shifted $\dot{V}O_2$ response that persists into the performance window. That signature was not achieved here.

Several limitations warrant acknowledgement. The sprints were unloaded, which likely constrained the magnitude of neuromuscular and metabolic stress. Participants did not consistently achieve the intended time at the target cadence, reducing the delivered dose of the manipulation. Skin temperature rather than intramuscular temperature was measured, resulting in an incomplete picture of thermal degradation (145). Short interruptions to gas exchange sampling occurred when the respiratory mask was removed due to nausea; the impact of this was minimised by removing aberrant data points and interpolation. The sample comprised recreationally active men only, which limits generalisability. This was due to differences in metabolic, contractile, and haemodynamic properties existing between male and female skeletal muscle (159). Furthermore, the impact of the menstrual cycle and contraceptives on exercise performance is largely unknown, hindered by a lack of studies with methodological quality on the subject (160, 161), making the inclusion of both sexes difficult when testing the physiological responses to exercise (159). Estimates of glycolytic energy from blood lactate rely on assumed blood volume (162) and stoichiometry from lactate to ATP, so values should be interpreted as approximations rather than absolutes.

Future work should test whether a warm-up that includes a brief severe intensity segment after a submaximal phase can sustain thermal and metabolic readiness across a 30-minute delay. Protocols ought to compare the present design with variants that raise work rate toward severe intensity for several minutes and that add external resistance to the sprints. The cadence manipulation should ensure exposure at the target cadence by starting the 6 s recording once the cadence threshold is reached, with a standardised acceleration allowance, so that the intended stimulus is actually delivered. Utilisation of passive methods, including heated garments, to maintain intramuscular temperature could be considered in future work, especially during the recovery period. This may act to delay the decline of intramuscular temperature post warm-up and increase the longevity of the ergogenic physiological stimuli. Use of compression garments can increase skin temperature by ~ 1 °C (163), however, this effect is not observed in core temperature (164-168) meaning diminishing PAPE effects over the duration of the recovery period are unlikely to be influenced. Conversely, heated garments can maintain muscle temperature and subsequently improve 30 s sprint performance (169) highlighting the potential benefit of heated garments on sprint performance following long duration recovery periods.

Mechanistic monitoring should include intramuscular temperature, high-resolution cadence exposure, electromyography, and indices of $\dot{V}O_2$ kinetics and phosphocreatine recovery to quantify the balance between resynthesis and thermal decay. It would also be valuable to titrate pre-performance blood lactate towards the putative ergogenic range of about 3 $mmol \cdot L^{-1}$ without inducing undue fatigue, to establish dose–response relations. Studies in trained sprint cyclists and BMX athletes are needed to assess generalisability beyond recreational participants.

4.5 Conclusion

Cadence manipulation during the warm-up altered cadence behaviour but did not change 30 s Wingate performance after a 30-minute interval. The most plausible reason is that the combination of a moderate submaximal stage and unloaded sprints did not deliver enough mechanical and metabolic stress to maintain a benefit through recovery. Future protocols should combine a short, severe intensity segment with loaded sprints, standardise time at target cadence, and verify thermal and physiological readiness with direct measures, to establish whether performance gains can be realised when long recoveries are unavoidable.

5. Thesis Discussion

Warm-up practices before a BMX race are uncommon and largely informed by the athlete's previous experiences rather than scientific research. This is due to a scarcity of scientific research focusing on warm-ups in BMX racing, but also in BMX racing as a sport. Existing studies associated with BMX racing have largely focused on understanding the determinants of the sport, primarily highlighting the importance of peak power (37-40) and the ability to produce and maintain high cyclic cadences (80). However, the absence of a BMX race-specific power meter (58) to measure these determining factors means field and semi-field testing are difficult to conduct reliably. Furthermore, due to a lack of a validated BMX race-specific laboratory test, more generalised anaerobic tests must be utilised to measure the determinants of BMX performance in a laboratory setting. As a result, the overarching aim of this thesis was to explore and manipulate the components of a warm-up to develop the understanding of warming-up for short-duration sprints, potentially providing practical applications to warm-ups in BMX racing.

Chapter 1 systematically examined sprint-based warm-up interventions, $\leq$ 30 s in duration, aiming to evaluate the warm-up strategies employed to determine effectiveness of improving subsequent sprint performance. It was discovered that methodologies fell into three distinct categories: warm-ups that altered the exercise intensity, durations, and recovery period given between the warm-up and performance task. Furthermore, a lack of emphasis on the role of cadence in a warm-up for sprint performance was discovered, alongside emphasising the importance of prescribing intensity specifically to each participant's physiology, making intensity relative and not generalised. The warm-ups that incorporated movements specific to the performance task were also discovered to be beneficial to performance.

For a sport such as BMX racing, the outcomes of Chapter 1 mean a warm-up should integrate brief, high-intensity, cycling-based efforts reaching high power cadence outputs. The intensity of the warm-up should aim to be severe as BMX athletes can wait up to 20-30 minutes in a pre-race holding period with little opportunity to warm-up in this time; thus, the physiological stimuli induced by the warm-up must be great enough to sustain their ergogenic nature for up to 30 minutes post warm-up. The intensity of the warm-up should be predetermined and monitored via physiological measures (i.e. heart rate) to provide live indications as to the intensity being administered. The lack of consistency in results of non-cycle-based warm-ups means that a warm-up prior to a BMX race should be conducted on a bike, further enhancing the specificity.

The inclusion of specificity in warm-ups involves incorporating movements that mimic the performance task and are ergogenic, as they can enhance neuromuscular activation (33, 47). Research on specific warm-ups for short-duration tasks, however, is limited and inconsistent (5), with complexities in interpretation due to the variation of specificity and duration simultaneously occurring in the literature. In BMX racing, the initial acceleration phase is reliant on maximal power production, and as velocity increases, cadence increases, causing power outputs to decrease (45). As a result, a mixture of high-intensity sprinting-based warm-up exercises could be employed, aiming to reach peak power and subsequently, peak cadence to improve BMX performance.

Cadence was underrepresented in the literature captured in Chapter 1; however, it can have profound physiological effects. Studies included in Chapter 1 that monitored cadence, ranging from 60-90 rev·min^{-1} (87, 92, 93, 95, 101, 102) and described as moderate cadences (132), did not directly manipulate cadence to assess its effect on performance. In the wider literature, higher cadences have provoked higher heart rate, blood pressure, lactate, reduced gross efficiency, and shifted thigh muscle activation (vastus lateralis, rectus femoris) compared with lower cadences over prolonged bouts (48, 49, 52, 133, 136, 152). These studies used cadences in the 70–126.5 rev·min^{-1} range and sustained exposures of 20–60 minutes at fixed power (48, 49, 52, 136), greatly different to the demands of BMX racing, limiting the application of these findings. Furthermore, with no studies directly utilising cadence manipulation as a means to alter intensity and enhance subsequent performance, the effect this would have on BMX race performance is unclear.

Chapter 2 investigated the effect of cadence manipulation during sprints within a warm-up for a 30 s Wingate test. Although the intensity of the warm-ups was successfully altered by manipulating cadence, the Wingate results displayed no significant differences between all warm-up conditions across all measures. It was clear that the manipulation of cadence to influence warm-up intensity was not sufficient to improve Wingate performance after a 30-minute recovery. This means that during a BMX race competition, a warm-up conducted at this moderate intensity, at any cadence, would likely not improve BMX race performance following a 30-minute recovery.

BMX race athletes can experience a 20-30-minute holding period, with little opportunity to warm-up in this time, further influencing the warm-up and recovery period duration required. The intensity of the warm-up utilised in Chapter 2 was influenced by previous research, which tested a severe intensity warm-up preceded by a 30-minute recovery period (94). The present study added five sprints at either 70 % or peak cadence to increase the specific nature and intensity of the warm-up. Power and cadence outputs, blood lactate, skin temperature, resting gas exchange, and energy contributions were all measured to assess the effect of the warm-up interventions on performance and physiological mechanisms driving them.

The warm-up interventions were significantly different, completing the initial aim of the study: to manipulate cadence within sprint-based warm-ups to elicit distinct exercise intensities. Intensity variation was monitored by blood lactate; significantly different following the 100 PC warm-up compared to 70 PC and CON warm-ups. However, the Wingate results displayed no significant differences between all warm-up conditions across all measures; it was clear that the manipulation of cadence to influence warm-up intensity was not sufficient to improve Wingate performance after a 30-minute recovery. Limited physiological effects were induced with blood lactate levels generated in this study not reaching ergogenic levels proposed in the literature to increase sprint performance (29, 150, 151), reinforcing that the warm-up intensity was not sufficient to alter performance. Skin temperature also failed to significantly increase following the warm-up, not reaching the proposed temperatures to enhance performance (156, 157). Furthermore, the blood lactate elevations that were observed following the warm-up had returned to near baseline levels after the 30-minute recovery period, suggesting that the recovery period duration was too great for the intensity of warm-up utilised. Thus, for BMX racing performance to be augmented following the 30-minute pre-race holding period, the intensity of the warm-up would have to be increased beyond the intensity utilised in Chapter 2, achieved by potentially increasing sprint resistance or duration while maintaining cadence targets, providing a means of eliciting a more potent stimulus. For exercise tasks involving high cyclic cadences or shorter recovery intervals, cadence-modulated warm-ups may still hold value and require further investigation.

5.1 Limitations

It is important to note that there were limitations within this thesis. The absence of a BMX race-specific laboratory test meant that the selection of a 30 s Wingate test was necessary to test key determinants such as power output, cadence, and fatigue index, all linked to BMX race performance (37-40, 80). However, differences remain between the determinants of a BMX race and a Wingate test, meaning that the findings from Chapter 2 are difficult to turn into practical applications for BMX racing. During a BMX race, only 30-40 % is spent pedalling (170), meaning that if a BMX race is 30-50 s in duration (35), then riders can spend from 9- 20 s sprinting during a race. This shows that additional intermittent metabolic costs are generated throughout a BMX race, which are not captured during the continuous 30 s Wingate format, and the replication of these in a laboratory setting is difficult. The Wingate test is a validated test of anaerobic fitness, with 50.3 ± 5.1 % of the energy required for the 30 s sprint contributed by the anaerobic system (ATP-PC system: 31.1 ± 4.6 %, aerobic system: 18.6 ± 2.5 %) (55). Unfortunately, direct comparison to energy contribution data from a BMX race is not possible due to a lack of research and the equipment required likely influences the athlete’s ability to perform maximally (53). However, the blood lactate response from a BMX race (14.5 ± 4.5 mmol/L) (56) are comparable to those recorded following a Wingate test (14.1 ± 0.5 mmol/L) (142) indicating that both the Wingate test and a BMX race may have similar anaerobic contributions for energy production, partly mitigating the limitations of utilising the Wingate test as a proxy for BMX race performance.

The warm-up design also posed challenges. In Chapter 2, stationary start sprints were conducted, meaning participants required acceleration time to reach 70 % or peak cadence during the 6 s sprint, leading to variations from the targeted cadences. The 70 PC intervention resulted in a mean cadence value of 60.8 % of their target cadence compared to the 100 PC intervention, which only achieved 75.2 %. This means that while the 70 PC intervention was 9.2 % from the targeted cadence, the 100 PC intervention deviated by 24.8 %. This deviation likely reduced the intended stimulus, providing evidence for the lack of intensity in the warm-up interventions. Future designs could consider a flying-start protocol, although this would introduce challenges for standardisation.

Furthermore, the Wingate tests in Chapter 2 were performed from a stationary start and conducted in a standing position to reflect BMX race conditions. Whilst these adaptations improve the standardisation of the test (171) and ecological validity, they reduce the comparability with the traditional Wingate test. The Wingate test is commonly conducted with a flying start, meaning participants will sprint before the onset of the predetermined load to the ergometer and thus, the start of the test (172). This was done to reduce the effect of not considering the flywheel acceleration at the start of the test (173). Consideration must be made before comparing the results of the present study to others utilising Wingate tests that implement a flying start, as peak power has been seen to be higher following flying start Wingate tests (171). On top of this, Wingate test performance fluctuations are seen when comparing seated versus standing Wingate tests, with greater peak power production found in standing Wingate tests (174-177). This is proposed to be due to an increase in muscular recruitment, causing increased energy transfer to the pedals, with the performance increase seen within the initial 5 s (174). Opposing results have been observed when using untrained cyclists, seeing increased Wingate performance following a seated Wingate in untrained cyclists and, conversely, increased Wingate performance following unseated Wingate tests in trained cyclists (178). As a result, the results of this study should be compared with caution to other Wingate-based research.

With increased muscle temperature being a key outcome of a warm-up to improve subsequent short-duration performance (5), a more thorough measurement of this could be utilised compared to the skin temperature measurements used in the present study. However, this has been previously used as a proxy for muscle temperature (100), seen only to correspond with muscle temperatures at depths of 0.8 °C and 1.3 °C (145), meaning the skin temperatures recorded in Chapter 2 may not have provided a comprehensive understanding of the muscle temperatures experienced.

Finally, participant variability was notable; $\dot{V}O_2max$ varied by 6.1 ml/kg/min, with $\dot{V}O_2max$ ranging by 21.5 ml/kg/min across the cohort, suggesting heterogeneous training status. This has been seen to affect blood lactate concentrations in aerobically trained compared to untrained participants following a Wingate test (179), potentially influencing the results of the current study.

5.2 Practical applications

The findings from the Systematic review (Chapter 1) identify that warm-up intensity, duration, and the recovery period duration between warm-up and performance onset are key factors to consider when developing a warm-up. Furthermore, the determinants of the exercise task should impact the manipulation of these factors when designing an effective warm-up. Practitioners and/or coaches should aim to include specific exercises in the task warm-up, seen to improve neuromuscular activation (33, 47). Furthermore, the studies included in Chapter 1 that tested non-cycling-based warm-ups discovered inconsistencies in subsequent sprint performance, meaning translation to sporting events is difficult, especially when the equipment required is often impractical and not readily available.

The repeated use of a high or severe intensity warm-up throughout a sporting event, such as a BMX race (due to the qualification races, semi-final, and final), may not be practical and has not been tested over repeated sprints. This thesis focused primarily on cycling-based warm-ups; nevertheless, prior work has reported associations between non-cycling exercises, such as jump capacity, and BMX performance (67), indicating that alternative active warm-ups may have merit in this context.

Literature suggests that a blood lactate level of ~ 3 mmol/L pre-exercise is sufficient to provide performance benefits to the subsequent exercise task (29, 150, 151) and the importance of increased muscular temperature to subsequent performance (5). Warm-ups should be designed and tested with monitoring of these two variables at regular intervals post-warm-up. This would allow for accurate insights into the physiological effects of the warm-up, facilitating future adjustment of duration and intensity and providing a strong indication as to the duration of the recovery period required before the exercise task.

5.3 Future Research

Future research should look to utilise physiological measures to determine intensity, making it specific to the participant and their fitness level, whilst defining the most reliable ways of determining intensity, for example, using an intensity that corresponds with the participant's GET plus 70 % Δ (94). On top of this, future research should aim to determine which physiological effects are most applicable to monitor when assessing the effectiveness of a warm-up. These suggestions would aid future comparisons between warm-ups and strengthen knowledge on physiological trends derived from different warm-ups.

The utilisation of cadence as a means to alter intensity during a warm-up was achieved in this thesis; however, future research should look to apply this in a warm-up with an intensity which corresponds to the selected recovery period, to determine whether sprinting at different cadences can enhance subsequent sprint performance. Compared to the 0 W resistance employed during the warm-up sprints in chapter 2, future research could utilise a greater sprint intensity generated from increasing the load on the ergometer during the sprints, requiring participants to apply a greater force to the pedals to overcome the inertia. If the resistance was increased, research may be required to increase the duration of the sprint to facilitate the achievement of the cadence targets, further enhancing the warm-up intensity. An additional suggestion is that the sprint intensity is satisfactory, but the sub-maximal cycle intensity before the sprints could increase to an intensity closer to 70 % Δ which has previously increased performance following a 30-minute recovery period (94). Another aim of future research when modifying cadence should be to reduce the variability in cadence output of the warm-up. Fixing the cadence a participant cycles at is possible via an ergometer; however, this is achieved by the addition of load to reduce the participant's cadence and thus, creating potential variation in intensity between participants in the same warm-up intervention.

Plyometric movements may elicit PAP, transiently enhancing a muscle's capacity to generate force and power (180, 181), both of which are central determinants to BMX race performance (37-40). Although substituting cycling with plyometrics reduces task specificity, which is often considered beneficial for subsequent performance through neuromuscular activation (33, 47), PAP-oriented protocols may still offer a pragmatic solution within BMX pre-staging areas where space and equipment are constrained.

Future research should, therefore, evaluate non-specific plyometric PAP protocols delivered independently, and in combination with brief cycling blocks, with designs tailored to the operational constraints of BMX events. Studies should test the feasibility and efficacy of short, repeatable PAP 'top-ups' during the holding period, define optimal exercise selection, loading, and timing relative to gate start, and compare these against cycling-specific warm-ups for outcomes relevant to BMX race performance. In parallel, practical solutions to the typical 30-minute pre-race holding period warrant consideration, including event-management strategies. For example, the governing body, British Cycling, could work with event organisers to ensure access to suitable warm-up areas that enable riders to complete an evidence-based cycling warm-up when space permits.

Passive methods of maintaining PAPE effects generated during a warm-up are mixed. A compression garment worn during a 5-minute warm-up has increase skin temperature by ~ 1 °C compared to loose fitting shorts (163). In theory, increasing the length of recovery period that can be experienced before PAPE effects diminish. However, this effect is not observed in core temperature (164-168) meaning wearing the compression garment is not influencing any PAPE effects that increase performance. Another passive method is the use of heated garments, which have maintained intramuscular temperature during a 30-minute recovery period (169). This heated garment was an insulated pant with a heating element, covering the thigh muscles (169). Additionally, the use of the heated garment produced greater 30 s cycling sprint performance compared to standard clothing (169), potentially increasing the longevity of PAPE created by the warm-up. Future studies should consider passive warming measures, defining optimal temperatures and effective timings of use for a 30-minute recovery period.

In addition to the physiological measures employed in Chapter 2 (i.e. power, cadence, metabolic estimates, blood lactate concentration and skin temperature), future research could utilise further measures to undertake additional mechanistic assessment. Utilising near-infrared spectroscopy (NIRS) to measure muscle tissue oxygenation levels could have provided muscle-specific oxygenation dynamics, developing knowledge on the role of cadence in intensity fluctuation. Heart rate could be another measure that would provide insights into the intensity of the warm-ups and the recovery status of the participant during the 30-minute recovery period prior to the Wingate test, for comparison to baseline and post-warm-up heart rate. Furthermore, rating of perceived exertion measures could be valuable when assessing physiological exertion on participants for anaerobic performance tests (182, 183), potentially indicating if intensity is too great or if intensity deviation between interventions is not great enough. If muscle temperature is recorded in future research, potentially more accurate, yet invasive, measurements such as a needle thermistor at ~ 3 cm or core temperature using a rectal probe could be utilised. This is due to both techniques providing more accurate indication of muscular temperature, 0.1 °C and 0.01 °C respectively (184). Additionally, core temperature could be monitored throughout the recovery period, providing more definitive recommendations regarding the recovery period duration.

A multitude of the limitations of this thesis are related to the shortfalls of the Wingate test when applying results to BMX racing. As a result, future research should create and validate a specific laboratory test for BMX racing which encompasses a majority of the demands of the sport, facilitating direct application of the test results to the sport. Furthermore, research into warm-ups that could be completed in the confines of a BMX pre-staging area should also be conducted, as this would eradicate the need to warm-up 30 minutes before a race. The utilisation of anaerobically trained participants, including BMX race athletes, when conducting this type of sprint testing should be targeted, potentially leading to more consistent results with little variation in physiological effects, such as blood lactate concentration and strengthening the practical application to sprint-based sports.

5.4 Conclusion

This thesis investigated and manipulated warm-up strategies for short-duration sprints and determined their effectiveness and suitability for BMX race performance enhancement. A systematic review of warm-up strategies in sprints ≤ 30 s in duration highlighted the importance of intensity, duration, and recovery period whilst revealing a lack of exploration into the role of cadence in warm-ups. Building on these insights, the experimental study demonstrated that cadence could effectively be used to manipulate warm-up intensity, yet the interventions employed did not significantly enhance subsequent 30 s Wingate performance.

The findings suggest that the warm-ups utilised in the experimental study lacked intensity to generate and sustain ergogenic effects across the recovery period, with blood lactate levels returning to near baseline values before performance testing. Moreover, the methodological constraints of using a Wingate test as a proxy to replicate the demands of a BMX race limited practical applicability. Nevertheless, the thesis underscores the potential value of designing warm-ups to replicate the demands of BMX racing, including the integration of BMX-specific cadences and consideration of practical constraints such as a prolonged pre-race holding period.

Future research in this area will require the development of a validated BMX-specific laboratory test, alongside investigations into warm-up protocols that are feasible within the constraints of competition environments. Research employing trained participants and incorporating additional physiological measures may further develop understandings of the underpinning mechanisms that create an effective warm-up. Overall, this thesis highlights the need for a more nuanced and sport-specific approach to warm-up design in BMX racing, providing the basis for future evidence-based practice.

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