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REVIEW ARTICLE **Open Access**

Performance Characteristics in BMX Racing: A Scoping Review

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Abstract
Performance characteristics across a number of cycle sports have been investigated for decades. However, evidence suggests little is known about the performance characteristics in BMX cycling. As a result, a scoping review was undertaken to explore the quantity and themes of research in this area.
After adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRIMSA) guidelines 104 studies were identified in the initial search and post screening 17 studies were identified as relevant. These studies were categorised into two sub categories; physical and technical characteristics. The first category, physical performance characteristics included ten studies that analysed torque, cadence, and peak power in relation to velocity and time to peak power. The remaining 7 studies related to technical attributes and focused on the development of an effective gate start technique or analysed techniques deemed important during a BMX race. In addition to the categories, 9 of the 17 studies identified in this review reported reliability issues in collecting performance characteristic data, as well as issues surrounding transference of data from the laboratory to the BMX track.
Future research should consider intervention studies examining how time to peak power could be developed and the effect this would have on the start of a BMX race. Future studies may also consider using equipment with higher levels of reliability and testing riders in the track environment. Moreover, this scoping review could serve as a starting point for a systematic review**.**

Keywords: scoping review; performance characteristics, Bicycle motocross

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Introduction
To succeed as an elite athlete requires superior multifaceted abilities combining physiological, technical, cognitive, and emotional performance traits (Janelle & Hillman, 2003). Within cycle sports, several variables have been investigated to define elite performance, including physiological (Coyle et al., 1991; Fintelman et al., 2015; Lee et al., 2002; Martin et al., 2001), anthropometric (Fornasiero et al., 2018; Menaspà et al., 2012), training type (Mujika et al., 2016; Vikmoen et al., 2016), talent development and maturation (Novak & Dascombe, 2014), and physical performance (Vitor-Costa et al., 2015; Pasiakos et al., 2014). The integration of these performance characteristics are considered to be important elements of training adaptation and identifying talent across various cycling disciplines (Adrian & Anjos, 1986; Novak & Dascombe, 2014). However, the delineation of which performance characteristics are the most predictive measure for cycling success remains problematic in certain cycling disciplines (Lorenz et al., 2013). According to Novak & Dascombe (2014) the majority of performance characteristics studies have been conducted on road cycling athletes. Despite the increase in researcher pertaining to other cycling disciplines such as bicycle motocross (BMX) (Bertucci & Hourde, 2011, Di Rienzo et al., 2018), evidence suggests little is known about the performance characteristics in BMX cycling. Therefore, this scoping review aims to (1) provide a more comprehensive understanding of what is known about performance characteristics in BMX by reviewing research conducted between 2000 and 2017, and (2) provide evidence of gaps in research that could be used to help improve BMX performance in the future.

Methods
This scoping review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRIMSA) guidelines to examine the literature on performance characteristics in BMX (Moher et al., 2009). A scoping review is defined as a type of research synthesis that can be used to “map the literature on a particular topic or research area and provides an opportunity to identify key concepts; gaps in the research; and types and sources of evidence to inform practice, policymaking, and research” (Daudt et al., 2013). In this review a customised search was used to identify the relevant studies. This method consisted of four key phases; phase 1, a search of electronic databases; phase 2, relevance

Table 1. Initial Database research results *this figure includes duplication of studies between data base searches.

Cycling Discipline	SPORTDiscus	PubMed	MEDLINE	Total number of studies found
Road Cycling	232	230	206	*668
Mountain Biking	225	130	122	*477
Track Cycling	80	83	65	*228
Bicycle Motocross	72	17	15	*104

screening; phase 3, eligibility criteria; and phase 4, a collaboration with a panel of experts for final inclusion

Data sources and preliminary search strategy

Phase 1 included a comprehensive electronic search of three academic journal databases (i.e. SPORTDiscus, PubMed, and MEDLINE) from the time period January 2000 – August 2017. The initial database search compared the number of peer-reviewed studies in each specific cycle discipline. Four cycling disciplines were compared: road cycling, off-road mountain biking, track cycling, and bicycle motocross. Once the studies were identified, a further search of their reference lists was conducted.

The preliminary search terms used in the initial computerised literature search included: ‘road cycling’, ‘mountain biking, ‘cross-country mountain biking’, ‘downhill mountain biking’ ‘mountain cycling’, ‘MTB’, ‘track cycling’, ‘velodrome cycling’, ‘bicycle motocross’, ‘bicross’ and ‘BMX’.

The review considered peer-reviewed articles containing these terms in the title and text. The number of studies found can be seen in Table 1.

Phase 2 involved a secondary search of BMX peer-reviewed studies by consulting the reference lists of articles captured in phase 1. In order to identify BMX performance characteristics studies, a relevance screening process was undertaken. This process was undertaken to remove BMX studies that did not relate to performance characteristics of BMX cycling. For example, all the studies relating to injuries in BMX cycling, BMX free style and studies not related to BMX racing were removed at this stage. The initial relevance screening process combined studies from all three databases and duplicate studies were also deleted. The following search strings were used to conduct searches across all three databases undertaken (i.e. SPORTDiscus, PubMed, and MEDLINE):

i) ‘determinants of performance’ OR ‘performance indicators AND performance characteristics’ OR ‘performance’.
ii) ‘BMX OR bicycle motocross’ OR ‘bi-cross’.

In phase 3 a full text assessment was undertaken to ascertain the eligibility of the remaining studies. The final screening process focused on studies that included findings related to performance characteristics of BMX cycling. The following eligibility criteria were applied to the studies

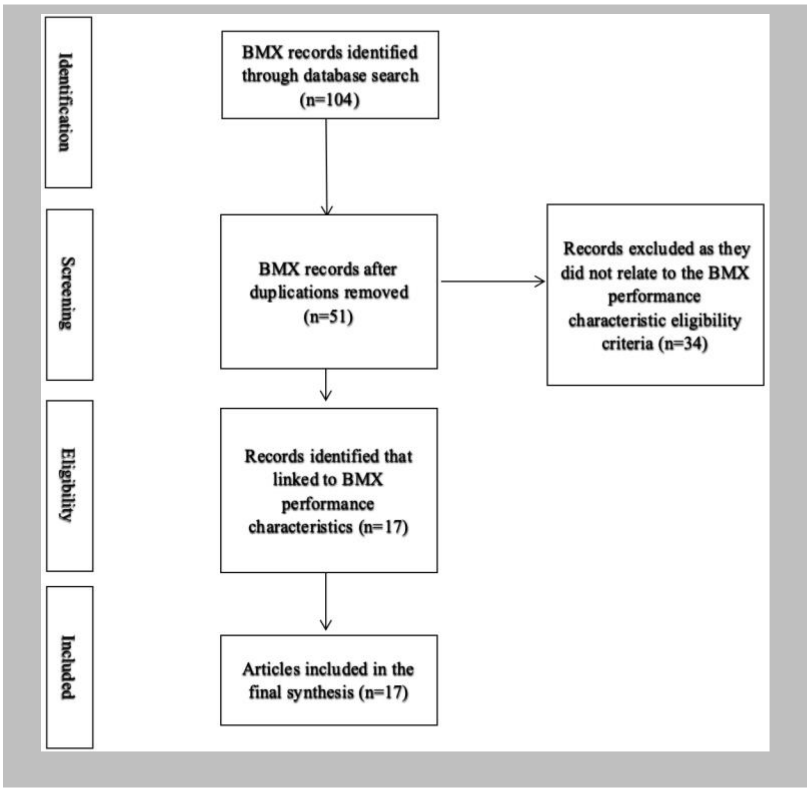
Eligibililty criteria

Eligibility criteria were applied to the title and abstract screening process to assess relevance to the research question. The eligibility criteria applied were:

(1) Must be written in English in a published peer-reviewed journal; PhD theses; or peer-reviewed reports.
(2) Must be published between 1st January 2000 and 31st August 2017.
(3) Studies must relate to performance characteristics in BMX cycling.
(4) Studies must be empirical in nature.
(5) Cannot be a review of literature, a scoping review, systematic review; or validation of a protocol or instrument.
(6) Cannot include studies where other cycling disciplines are included in the analysis.

Studies that matched the eligibility criteria were downloaded and categorised using the bibliographic manager Mendeley™ (Elsevier, Netherlands). All articles were then subjected to both title and abstract screening within the software.

Phase 4 involved the review of the title and abstract of every article by two independent cycling researchers not involved in the study using a framework developed by the first author (i.e. title, study aims, sample, design etc.). There were no disagreements between the two



independent researchers and the first author regarding the framework. All the articles considered relevant following title and abstract screening were obtained for full-text review. The first author was responsible for independently reviewing all the studies. Studies which did not meet the eligibility criteria were excluded at this stage. Following this independent review, the first and second author performed one final review of the articles in order to maintain internal consistency.

Results

Phase 1 search conducted in September 2017, yielded 104 potentially relevant studies. Removal of duplicate articles resulted in a total of 51 articles. Following a full text assessment, a further 34 studies were eliminated as they did not meet the performance characteristics eligibility criteria. After data characterisation 17 articles were included in the final selection (refer to Fig. 1 for an illustration of the PRIMSA process).

Descriptive findings

As illustrated in Table 1, of the 17 articles included in the review, 16 of the studies adopted quantitative research designs and one was not stated due to it being a written synopsis. In total, 41% of the studies were observational, 35 % either experimental or correlation studies, 17% were descriptive studies with a single study being descriptive (Cowell et al., 2012b). In addition, only 35 % of the studies included female riders (*n* = 6) and all riders were recruited from elite/national standard populations. The sample sizes of the studies were notably low (*n* = 13) ten participants or fewer (*n* = 2) 26 participants, (*n* = 1) 348 participants and one study included no participants. The majority of the studies were from European countries (*n* = *14*), with (*n* = 2) studies from New Zealand (Cowell et al., 2012ab) and one from north America (Herman et al., 2009). The setting for the studies varied between BMX track (*n* = 7) laboratory (*n* = 3), BMX track and laboratory (*n* = 1),

Table 1. BMX studies included in the review.

Reference	Study aim	*N*	Skill level	Sex	Design	Research environment	Summary of findings
Chiementin et al. (2012)	Analysis of a pedalling action and identification of the sequence of power production during a pedal revolution.	4	Elite	M	Observational	Not stated	A section of the pedal revolution was identified by the authors where relatively lower power was produced. To reduce this effect, the authors recommended a fluid pedalling action would aid alleviate this reduction in power
Bertucci and Hourde (2011)	Comparison of peak power and force-velocity relationships between a laboratory and field environment.	26	17 Amateur (National) 9 Elite	M	Descriptive	Laboratory and BMX track	The authors identified that power from the lower limbs contributes between 41- 66 % of a riders' power during the initial part of a ride (straight 1).
Cowell et al. (2012a)	Analysis of the dominant movement patterns and techniques during a BMX race.	26	Elite	16M 10F	Descriptive	BMX track	Identified techniques predominantly performed when riding specific sections of the BMX track. establish position. The start was a key element of overall lap time.
Cowell et al. (2012b)	Synopsis of existing research on the strength training considerations for BMX.	None	N/A	M	Not stated	N/A	Presented methods of strength and conditioning training. Predominantly focusing on strength development in the lower limbs.
Debraux and Bertucci (2011a)	Analysis of the relationship between torque – velocity and power- velocity.	7	Elite	4M 3F	Observational	Semi- field test environment -80m flat ground.	Authors theorised the optimal pedalling rate that elicits optimal power-velocity and torque-velocity relationships). The theorised relationships were ascertained using linear data in a regression analysis.
Debraux and Bertucci (2011b)	Analysis of relationship between maximal strength and power.	10	National level	M	Observational	Laboratory	Maximal strength is a muscular determinant of BMX performance, but the start of a BMX race needs a high amount of force in a short time. Maximal strength is not necessarily associated with an optimal start.
Debraux et al (2013)	Analysis of the relationship between power, torque and cadence.	7	Elite	5M 2F	Experimental	Semi- field test environment -80m flat ground.	From a regression analysis the optimal torque, power and pedal rate was presented
Herman et al. (2009)	Analysis of peak power, power to weight ratio and cadence in a field and semi field environment (paved outdoor surface)	5	Elite	M	Observational	BMX Track	The authors presented power data from elite riders in a field study and compared this data to a semi field environment. It was noted that the peak power within the first 2 s in field studies contrasts lab data.

Table 1. Continued

Kalichová et al. (2013)	**3D technique analysis of a BMX start**	**2**	**Elite**	**1M 1F**	**Observational**	**Not stated**	**The authors noted angle characteristics in elbow, shoulder, hip and knee joints when performing a start technique from a start gate were presented.**
Mateo et al. (2011)	Analysis of the relationship between power, speed and technique whilst riding various technically difficulty track.	9	Elite	M	Observational	BMX track	The authors stated that power is dependent on the level of difficulty of the track. The greater the technical level of the track, the less the possibility of developing power.
Mateo et al. (2012)	Comparison of technique using a notational analysis on two different tracks.	8	Elite	M	Descriptive	BMX track	The authors suggest that the international level BMX tracks differ significantly from national level tracks and are technically more challenging for riders.
Rylands et al. (2017b)	Ascertain optimal gear ratio that can elicit peak power and reduce time to peak power	8	Elite	M	Correlational	Laboratory	Three gear ratios were analysed in the study: a standard 43/16 tooth gear ratio, which was compared to a higher (45/16) and lower (41/16) ratio. The study ascertained that a larger than standard gear ratio (45/16) enabled riders to produce higher peak power without adversely effecting time to peak power, as no significant effect on time to peak power was ascertained.
Rylands et al. (2017a)	The study was to determine if a technique upper body has an effect on performance using a technique called 'pumping'.	10	National Standard	M	Experimental	BMX track	Riders performed three laps of a Riders rode a BMX track using the pumping technique and the recorded time was compared to riders time reframing from performing the technique. The study identified that upper body does contribute significantly to velocity production through the implementation of the pumping technique. The lap times recorded for the pumping trials were 19.50 ± 4.25 % lower than the non-pumping.
Rylands et al. (2014)	Ascertain if the start of a BMX race has an impact on overall race outcome.	348	Elite	240M 108F	Correlational	BMX Track	The authors found a strong correlation exists between riders position 8-10 s into a race. Therefore, focusing on a riders' ability to gain placings at the start of a race will have an effect on their finish line position.
Rylands et al. (2017c)	The aims of this study were to analyse the optimal cadence for peak power production and time to peak power in bicycle motocross (BMX) riders	6	Elite	M	Correlational	Laboratory	Four cadences (80, 100, 120 and 140 revs·min^{-1}) were chosen based on research from various cycling disciplines that had stated the optimal cadence for a specific discipline. The results indicate that the optimal cadence for producing peak power output and reducing the time to peak power output are attained at comparatively low cadences (120 revs · min^{-1}) for sprint cycling.
Rylands et al. (2013)	The aim of this study was to analyze the production of velocity in bicycle motocross (BMX) compared to other cycling disciplines.	6	Elite	5M 1F	Observational	Flat ground asphalt	The authors noted a key finding was the relationship of cycling cadence (rev·min^{-1}), peak power (Watts) and velocity (mi·h^{-1}). This relationship suggests once a BMX rider achieves peak power their pedalling cadence becomes the major contributory factor to velocity production.
Zabala et al. (2009)	Analysis of the effect of feedback on skill development in BMX cycling.	6	Elite	M	Experimental	BMX track	Audio-visual feedback and cognitive training of BMX skill can result in a significant improvement in the execution of the gate start technique in BMX cycling.

flat ground environment (*n* = 3), the remaining three studies did not specify the testing environment.

The 17 studies recorded in this scoping review were classified into two performance characteristic sub-categories. The first category, physical performance characteristics included ten studies. Two studies (Rylands et al., 2017a; Mateo et al., 2011) reported that the upper body might impact on performance to a greater degree than previously thought. Two studies concluded that the reliability of the power data could have been increased by using an SRM power meter (Debraux et al., 2013; Mateo et al., 2011), rather than a PowerTap power meter. The remaining six studies (Bertucci & Hourde, 2011; Cowell et al., 2012b; Herman et al., 2009; Rylands et al., 2013; Rylands et al., 2017b; Rylands et al., 2017c) focused on identifying torque, cadence, and peak power physical performance characteristics. These studies placed an emphasis on peak power and its relationship with peak velocity and the time to attaining peak power and its importance at the start of a race.

The second category related to technical attributes. Three of the seven studies focused on the development and identification of an effective gate start technique (Chiementin et al.,2012; Kalichová et al., 2013; Zabala et al., 2009). The remaining four studies analysed techniques that were deemed important during a BMX race (Cowell et al 2012a; Mateo et al., 2012; Rylands & Roberts., 2014; Rylands et al., 2017a).

Discussion

The aim of this scoping review was to synthesise retrospective performance characteristic studies between 2000 and 2017. The review identified seventeen performance characteristic studies in BMX cycling. Thirteen studies were coded as physical performance studies, and four were coded as technique performance characteristics (Table 1). Perhaps most significantly, the results from the present review highlight the need for a greater consideration of reliability and future direction of research in BMX research. The discussion will be presented under 4 broad themes: 1) equipment accuracy and ecological reliability issues, 2) physical performance characteristics, 3) technique characteristics and 4) Future directions of performance characteristics research in BMX.

Equipment accuracy, and ecological reliability issues

The reliability of the studies recorded in this review are condensed into two main areas, which includes the equipment used to test the riders and the actual testing environment. These are important consideration as credibility of data is essential especially when this data is used by coaches to quantify if a training adaptation has occurred or as bench marking against another athletes' performance (Hopkins et al, 2001). For example, when examing variation in power and speed on a number of BMX tracks with varying levels of riding technical difficulty, Mateo et al. (2011) reported that power and speed were lower on tracks that were defined as being more technical and requiring greater skill to ride them. However, the authors also noted that the equipment (i.e. PowerTap) used may have underestimated values. Mateo et al. (2011) noted that future studies using an SRM or a G-Cog power meter would be '*interesting*' as the peak power and time to peak power data in their study may have been underestimated estimated using the PowerTap power meter.

In addition, Debraux et al. (2011a & 2013) tested seven elite BMX riders' peak power and cadence. The tests were performed on a flat 80-meter surface using a PowerTap power meter. The reported data suggested an optimal peak power and cadence relationship for a BMX rider. However, the reliability of the apparatus used is once again called into question as peak power and time to peak power may not have been registered accurately (Mateo et al, 2011) using a PowerTap power meter. Furthermore, Bertucci et al. (2005) noted a large degree of error (8 %) when recording power, especially peak power during sprinting. Debraux et al. (2011a & 2013) also reported a mean peak power output of 1631 watt (SD 368) and this was used to ascertain a theoretical peak power/cadence relationship, even though the data used in the calculations was likely to have a large degree of error due to the reliability of the PowerTap power meter. This is not to criticise the work we reviewed, as the equipment used in these studies was the only equipment available to the researchers. Advancements in power meters may have alleviate the reliability issues, but future studies would have to be conducted to establish this assumption.

Another consideration is that of ecological validity - as some studies conducted trials in environments not considered regulation BMX (Debraux et al. 2011a & 2013). This is an important point, because if the environment in which a BMX rider is tested can elicit a variation in results (i.e. Bertucci & Hourde, 2011. Herman et al, 2009. Rylands et al, 2015), then previous laboratory studies may have limited transferability to the BMX track. For instance, Bertucci and Hourde (2011) recognised that the environment in which BMX riders are tested might have an effect on the transference of the results. Their study attempted to ascertain variations when testing peak power in a laboratory compared to a field environment. Bertucci and Hourde (2011) tested 17 riders from the French national BMX team on a static indoor cycle ergometer and on a European standard BMX track using a standard 20" BMX bike. The results suggested differences existed between the two environments with mean peak power outputs in the laboratory of 819 watts (SD 108) compared to the field test mean of 1340 watts (SD 240). However, the authors stated that the variation in their results could have been due to the equipment used in the study (PowerTap power meter). In a study not included in this review Rylands et al. (2015) compared peak power and time to peak power in a laboratory and a BMX track using SRM power meter. The authors found a 34 ± 9% higher peak power and reduced time of power production of 105 ± 24% when comparing the field environment (indoor BMX track) to the laboratory. The findings from the study suggest that BMX performance characteristic data compared between the two environments may have limited transference. As a result, the data of 10 of the studies may not be comparable to race data as only seven of the studies were performed on a BMX track.

Physical performance characteristic

A number of the studies examined in this review reported physical performance characteristics of BMX cycling (i.e. Cowell et al., 2012a; 2012b) and included power as a performance characteristic (Herman et al., 2009; Chiementin et al., 2012; Debraux et al., 2011b; Debraux et al., 2013). Chiementin et al. (2012) used a G-cog power meter, to analyse pedalling technique. The authors noted the high sampling frequency allowed Chiementin et al. (2012) to analyse what the authors termed a 'dead centre' in a single pedal revolution. A dead centre is the point of transition from pulling up on a pedal to pushing down; at this point a lower level of power was produced. The authors concluded that an optimisation of the pedalling technique could result in a smaller loss of power. Rylands et al (2017b, 2017c) looked at the optimisation of pedalling technique through ascertaining an optimal cadence. Although Debraux et al. (2011a & 2013) had previously looked at the cadence /power relationship there were issues around reliability due to the relationship being estimated using a correlation analysis and a powerTap power meter which had been previously inferred as having potential reliability issues. Rylands et al, (2017c) addressed the reliability issues by using an SRM cycle ergometer and measuring the actual relationship rather than predicting the relationship. The maximal cadence a rider could achieve was restricted using the laboratory SRM cycle ergometer and the optimal cadence recorded. The optimal relationship was presented as the cadence that enabled the rider to produce the highest peak power in the shortest time. Although the low sample size (six male elite BMX) may have had an impact on the strength of the statistical analysis. The study found that a cadence of 120 revs · min^{-1} elicited peak power and the optimal time to peak power. Rylands et al. (2017c) used the finding from this study to ascertain if equipment could be manipulated to enhance the power/ cadence relationship. The authors analysed the effect of gear ratio manipulating on peak power and reducing the time to peak power. Most cycling disciplines have a gear changing system, which will enable a rider to indirectly alter their cadence, thereby decreasing or increasing the production of power. BMX riders use a single gear ratio, which they choose and fit to their bikes prior to a race. A gear ratio is a combination of the size of a front and rear chain ring that can be used to measure the distance that a bicycle can travel as a result of a single pedal revolution. A gear ratio is expressed as the number of teeth a chain ring has. For example, a 43/ 16 means a bike has a 43 tooth on the front of the bike and a 16 at the rear. The choice of gear ratio is crucial, as a low gear ratio will enable a rider to produce high cadence and low force, whereas a comparatively high gear ratio will result in lower cadence, but greater applied force at the pedal. In theory, a lower gear ratio should enable a rider to accelerate quickly, but limit peak velocity, and a higher gear ratio will result in a slower start, but higher power and a theoretical higher velocity (Debraux et al, 2013) Rylands et al (2017b) analyse three gear ratios: a standard 43/16 tooth gear ratio, which was compared to a higher (45/16) and lower (41/16) ratio. An SRM power meter to measure peak power, cadence at peak power and time of power. The study ascertained that a larger than standard gear ratio (45/16) enabled riders to produce higher peak power without adversely effecting time to peak power. The authors noted that this could have a positive impact on the start of a race.

Nine of the seventeen studies (Table 1) in this review noted that the start of a BMX race was crucial and analysed performance characteristics that had the potential enhance a riders start. However, only one study looked at the supposition that a correlation existed between the start of a race and the final placing. Rylands et al. (2014) analysed data from 348 riders' results in 175 elite races in four BMX World Cup events during the 2012 season. The rider's relative position at each timing gate was individually compared to their finish line position at the end of a race. Therefore, if a rider were in first place at timing gate two where they in the same race position at the finish line. The study found that a significant correlation did exist between the start of a BMX race and the finishing position.

Technique performance characteristics

Another form of performance characteristic referred to as 'technique analysis' has seen a larger amount of BMX literature published in academic journals and text books in the last few years (Cowel et al., 2012; Kalichová et al., 2013; Mateo et al., 2012; Zabala et al., 2009). Unlike the studies that analysed power, the technique analysis studies identified and prioritised key techniques that have an effect on BMX performance. For example, Kalichová et al. (2013) performed a 3D kinematic analysis of a BMX start and quantified the various phases of a BMX start that could be used by coaches and riders. Kalichová et al. (2013) identified five phases associated with an effective start: phase 1 reaction time, phase 2 preparation movement time, phase 3 first pedal stroke time, phase 4 dead point pedal passage time, phase 5 second pedal stroke. Kalichová et al., (2013) noted that poor technique in the first, second and fourth phases resulted in a poor transference of force to the pedals. Additionally, Cowell et al. (2012) identified various muscle groups associated with specific techniques, primarily lower body, providing coach and rider with information that could be used to develop strength and conditioning regimes. Zabala et al. (2009) and Mateo et al. (2012) identified the contribution of techniques that were essential during racing for performance, such as the technique required to use an electronic start gate and the importance of effective jumping technique. This body of knowledge concerning technique analysis has the potential to aid coach and rider in prioritising technique development but cannot be used to inform training methods.

Future Directions in Performance Characteristic BMX Research

In addition to providing a review of what is a surprisingly limited number of studies, this review did identify a number of key performance characteristics in BMX cycling. The future direction of research may look at intervention studies based on these performance characteristics. For example, how time to peak power can be developed, the effect of developing upper body strength on performance and developing the start in a race.

The review also highlighted the importance for future studies to consider more ecological research designs which places an emphasis on the interactions of the rider in their natural environment where actions are viewed as interconnected rather than separate (Palmer et al, 1996. Smith et al, 2001). Although logistically more complex than univariate approaches a consideration may be to adopt more multidimensional studies of performance characteristics to also include psychological factors (e.g. coping skills, confidence, determination etc.) and how psychological skills can be incorporated into performance BMX.

Practical applications

To the authors knowledge this is the first attempt to review performance characteristics in BMX. The findings of this scoping review suggest that there is a limited number of studies conducted over the past 17 years. The studies identified in this review reported reliability issues in collecting performance characteristic data, as well as issues surrounding transference of data from the laboratory to the BMX track. From a more positive perspective the studies revealed how the start of a BMX race is a vital aspect of BMX performance and can affect the outcome of a race. The scoping review also identified that time to peak power as physical performance characteristic maybe a have a major influence on performance based on its relationship to an effective start.

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Conflict of Interest

The manuscript has been read and approved by the authors and meets the requirements of authorship as specified in the Authorship Guidelines. We have no conflicts of interest to disclose.

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