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Performance determinants and leg kinematics in the BMX supercross start

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Abstract

In competitive BMX racing, a fast start is crucial for obtaining a favorable position early in the race and the best possible final ranking. This study aimed to evaluate technical (effectiveness of preparatory slingshot maneuver), neuromuscular (torque, cadence and power) and quasi-anthropometric factors for their relative importance in determining starting performance in competitive BMX racers. Starting performance was defined by two criteria: 1) the elapsed time between the gate drop and the rider reaching the end of the ramp (t_{start}), or the corresponding mean velocity ($\overline{v}_{start}$), and 2) the rider's velocity at the end of the ramp (v_{end}). Also, this study describes basic leg kinematics during the first few pedal strokes of the starting phase. Subjects performed simulated race starts on a supercross ramp while various kinetic and kinematic parameters were obtained using a modified SRM powermeter and a Vicon 3D motion-capture system. Parameters were analyzed using linear regression with starting performance (i.e., mean and end velocity, separately) as the output. The results show that gathering forward velocity early and prior to the gate drop with a slingshot maneuver (countermovement) and generating a powerful first pedal stroke, with both a high torque and cadence, have the most influence on $\overline{v}_{start}$ and v_{end}. Regarding leg kinematics, evidence for a stretch-shortening cycle of the front knee during the slingshot maneuver, as well as cycle-mean extension velocities thereafter of 100 – 300 °/s for the knees and 100 – 200°/s for the hips were found. Thus, BMX racers should focus training on a quick and early slingshot maneuver and developing strength and power at relatively high loads.

Keywords: bicycle motocross, leg motion, torque, power, joint angles, joint power, kinematic, kinetic.

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Introduction

Importance of a fast start

In competitive BMX racing, eight riders compete directly against one another on a technically demanding and relatively narrow track. Considering the typical race duration of only 35 – 45 s (Rylands and Roberts 2014) and the relatively high risk and difficulty of overtaking, a fast start becomes crucial for obtaining a favorable position early in the race and the best possible final ranking. Getting out of the gate quicker than his opponents allows a rider to have the best choice of line through the track and reduces the risk of crashing due to contact with other riders. In addition to these logical arguments, empirical evidence for the importance of a fast start is found in a few published studies (Rylands and Roberts 2014; Zabala et al. 2009). Rylands and Roberts analyzed the relative positions of riders at four intermediate checkpoints of 175 UCI World Cup races and found significant correlations with eventual placing already at the first checkpoint, ~8 s into the race. Expectedly, correlations increased for later checkpoints, implying that some changes in position occurred throughout the race; nonetheless, their results clearly show the importance of attaining a good position early on, especially when contending for a spot on the podium. In the study conducted by Zabala and co-workers (2009), Spanish national team riders participated in an intervention, which led to improvements in starting time in the order of 100 – 200 ms, and these reportedly led to improved race results in the subsequent competitive season.

Determinants of a fast start

The BMX start is a complex performance task, which relies on various technical, neuromuscular and anthropometric factors. One of the technical factors reported by Zabala and co-workers to be important for a fast start is the "slingshot" maneuver, prior to the gate drop: a countermovement with which riders leave their ready position, putting themselves into a position to apply power to the pedals and accelerate the bike forward. During this maneuver, riders rapidly shift their bodies forward and down toward the handlebar. As a result, the bike moves backward, which creates space for gathering forward velocity before the gate drop, and the front wheel to lifts slightly, which facilitates better gate clearance of the front wheel (Zabala et al. 2009). As these authors write, the slingshot should be timed such that forward velocity is attained before the gate has fully dropped and such that the forward-moving front wheel almost scrapes the gate as it drops (Zabala et al. 2009). The sooner a rider begins to gather forward velocity, the greater his velocity can potentially be when the gate drops. Further, the maneuver must be timed such that the rider's velocity is in the forward direction and his position relative to the starting line at gate drop is neither too far forward (risk of running into the gate) nor too far back (increased distance to cover).

Figure 1, which breaks down starting performance into fundamental, objective parameters, depicts the distance travelled between the instant the gate begins to open and the bike becoming even with the starting line, as $|d|_{t_0}$. Figure 1 also shows how the forward velocity prior to gate drop, is the product of forward acceleration (discussed below) and forward acceleration time, where forward acceleration time is indicated by the time point of velocity becoming positive (t_{v_0}). Thus, these two criteria objectively characterize the effectiveness of the slingshot maneuver.

In addition to technical skill, neuromuscular factors such as maximal cycling power output ($\boldsymbol{P}$) are highly important for developing a fast start in BMX (Bertucci et al. 2007). Accordingly, elite BMX racers have been shown to generate peak power ($\boldsymbol{P}_{peak}$) of over 2000 W in on-bike field tests (Herman et al. 2009). Further, in addition to a high $\boldsymbol{P}_{peak}$, riders must be able to produce high $\boldsymbol{P}$ over a wide range of pedaling cadences (*Cad*) as they descend the starting ramp. Due to the ramp's slope—especially on the steeper 'supercross' ramps used in international competitions—and the impracticality of shifting gears, *Cad* increases rapidly in the course of a BMX start, from zero to near maximal (>200 rev·min^{-1}) within ~6 m (2–3 revolutions, Herman et al. 2009). Moreover, the rapid increase in speed, and thus *Cad*, is dictated to a large extent by the slope of the ramp itself, independent of pedaling $\boldsymbol{P}$ (Mateo et al. 2011). This feasibly makes the ability to adopt the quickly changing *Cad* and continually apply high torque ($\boldsymbol{M}$) an important performance-determining factor, independent of $\boldsymbol{P}_{peak}$.

Figure 1 shows how mean pedaling $\boldsymbol{P}$ ($\overline{\boldsymbol{P}}$) is the neuromuscular factor that determines mean acceleration (thus affecting starting performance), and that $\overline{\boldsymbol{P}}$ is a function of the power produced in each individual pedal stroke. The power produced in individual pedal strokes of changing cadence are a function of a rider's characteristic torque-cadence ($\boldsymbol{M}$-Cad) profile (Dorel et al. 2005; Gardner et al. 2007). Since the $\boldsymbol{M}$-Cad relationship in cyclists is linear (Dorel et al. 2005; Gardner et al. 2007), the development of $\boldsymbol{M}$ and Cad throughout the BMX start is bound by the constraints set by the $\boldsymbol{M}$ and Cad components of the slowest (i.e., the first) and fastest pedal strokes, as represented in Figure 1. Thus, four parameters—the $\boldsymbol{M}$ and Cad components of the first ($\boldsymbol{M}_{peak}$, $Cad_{\boldsymbol{M}_{peak}}$) and fastest ($Cad_{peak}$, $\boldsymbol{M}_{Cad_{peak}}$) pedal strokes—summarize the neuromuscular aspect of the BMX start.

Finally and also as seen in Figure 1, starting performance is affected by quasi-anthropometric factors, namely the rider's frontal area (A) and mass (m), as well as the mass of his equipment, since these factors influence the net acceleration resulting from gravity and air resistance. Although BMX rider m has been considered in a few studies with regards to the $\boldsymbol{P}$-to-m ratio (e.g., Bertucci et al. 2007), this potentially influential parameter has often been ignored (Herman et al. 2009; Mateo et al. 2011; Rylands et al. 2015). Aerodynamics in BMX has also been essentially neglected in the scientific literature, and serious attention to this factor by riders and coaches has been somewhat discouraged by the international cycling federation's regulations on material and clothing (UCI 2017). Nonetheless, in addition to technical and neuromuscular factors, total m and A have the potential to affect starting performance.

So far, it is not clear how the various factors discussed above and highlighted in Figure 1 relate to BMX starting performance. Therefore, the first aim of the present study was to explore the relative importance of these possible performance indicators for individual starting performance in competitive BMX riders. In the current study, starting performance was defined by two criteria: 1) the elapsed time between the opening of the gate (gate drop) and the rider reaching the end of the ramp (t_{start}), represented also as mean starting velocity ($\overline{\boldsymbol{v}}_{start}$, see methods for calculation), and 2) the velocity at the end of this phase (end velocity, $\boldsymbol{v}_{end}$). In addition to the most obvious performance criterion ($\overline{\boldsymbol{v}}_{start}$), $\boldsymbol{v}_{end}$ was also considered because this represents the velocity a rider carries into the main portion of the race. It was hypothesized that starting performance would benefit from an effective slingshot maneuver, characterized by greater forward acceleration time prior to gate drop due to an early initiation of forward movement (t_{v_0}), and which minimizes the distance covered by the

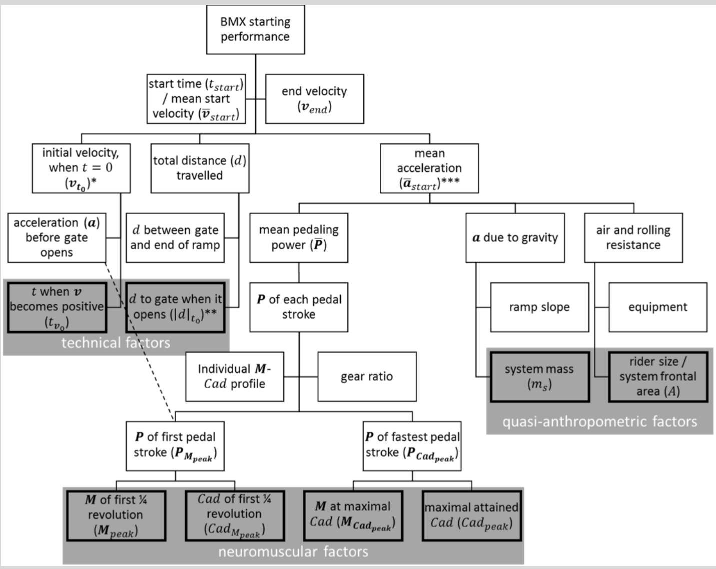

Figure 1. Hierarchical model (Bartlett 2007) of BMX starting performance, identifying eight potential performance determinants (grey shaded boxes). *t=0: time at the beginning of the gate drop. **scalar distance including movement away from the gate if velocity is directed backward at t=0. ***mean acceleration calculated beyond t=0. $\mathbf{M}$: crank torque. $\mathbf{Cad}$: pedaling cadence.

bike behind the starting line after gate drop ($|d|_{t_0}$). Further, it was hypothesized that larger $\boldsymbol{M}$ and pedaling Cad spectra between the first and fastest pedal strokes (i.e., higher $\boldsymbol{M}_{peak}$, $Cad_{\boldsymbol{M}_{peak}}$, Cad_{peak}, and $\boldsymbol{M}_{Cad_{peak}}$) would be positively related to starting performance. Finally, the m and estimated A of the rider and his equipment were hypothesized to affect performance negatively, although to a relatively small degree. For clarity, the eight factors addressed by these hypotheses are highlighted by the grey boxes in Figure 1.

The second aim of this study was to describe the kinematics of the knee and hip joints and the bike's crank during the first few pedal strokes of the BMX start. Such data have not yet been reported, but could be potentially useful when selecting off-bike training exercises for BMX racers.

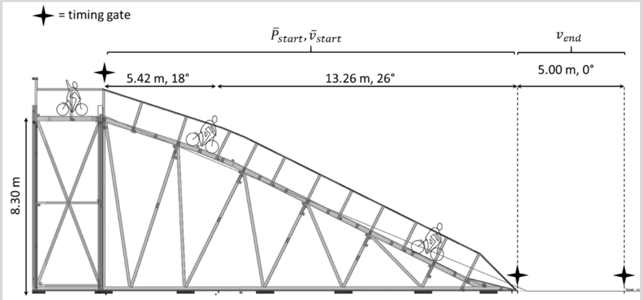

Figure 2. Diagram of the BMX 'supercross' starting ramp used during the study, showing the segments designated to determine mean starting velocity ($\bar{\mathbf{v}}_{\mathbf{start}}$) and power ($\bar{\mathbf{P}}_{\mathbf{start}}$) and for end velocity ($\mathbf{v}_{\mathbf{end}}$).

Figure 3. One subject immediately prior to performing a start.

Materials and methods

Subjects

Twelve BMX riders belonging to the junior or senior Swiss national team selection pool (two females, 10 males) participated in the study. Descriptive subject data are displayed in Table 1. Subjects (and for those under 18, their parents) received an information pamphlet in advance regarding the aims and procedures of the study and gave their written consent to participate. All study procedures were approved by the ethical review board of the Swiss Federal Office of Sport and conformed with the ethical standards of this journal (Harriss and Atkinson 2009).

Upon arriving to the lab, subjects' body mass (m_b) without shoes was attained using a force plate (MLDStation Evo2, SP Sport, Austria) and their body height was measured. Further, subjects' bikes were massed and the combined mass of bike and rider (system mass, m_s) was attained. Subjects' approximate frontal area (A) while on the bike was calculated based on m_b and height using the formula proposed by Heil (2001) and assumed seat tube and trunk angles of 90° for out-of-the-saddle sprinting (Table 1). Finally, the distance covered with one full rotation of the rear wheel (wheel circumference) was measured in the lab with the rider on the bike, and the bike's gear ratio was noted.

Procedures

Start procedure

Riders performed five starts on a supercross ramp (Grenchen, Switzerland), whose dimensions can be seen in Figure 2. Starts were performed with the same electronic, standardized start command and randomized gate used in international competition, with no other riders on the ramp (Figure 3). Riders were instructed to start as fast as possible until passing the last timing gate (see Figure 2).

Data collection

Three electronic timing gates (TC Timing System, Brower, Salt Lake City, USA) were installed between the gate and the first obstacle (Figure 2). The first timing gate was initiated by the dropping of the starting gate itself, the others by the rider's front wheel passing through. The start time (t_{start}) as well as mean starting velocity ($\bar{\boldsymbol{v}}_{start}$) and power output ($\bar{\boldsymbol{P}}_{start}$) were taken for the phase between the first and second timing gates. The average speed for the 5-m section between the second and third gates was used to represent $\boldsymbol{v}_{end}$. Recovery between starts was 5 – 6 minutes, which is more than enough to maintain maximal short sprint cycling power output (Phillips et al. 2014).

Table 1. Descriptive data of subjects (females *n*=2, males *n*=10).

	age	**height**	**body mass (m_b)**	**system mass (m_s)***	**frontal area (A)****
	[y]	**[cm]**	**[kg]**	**[kg]**	**[m^2]**
mean ± *sd*	19 ± 3	175 ± 8	74 ± 11	82 ± 11	0.38 ± 0.04
range	16 – 26	160 – 187	56 – 95	64 – 103	0.31 – 0.46

*combined mass of rider and bicycle. **estimate based on the formula of Heil (2001) with assumed seat tube and trunk angles of 90°: $A = 0.00433 \cdot 90^{0.172} \cdot 90^{0.096} \cdot {m_b}^{0.762}$

Riders performed the starts using their own racing bikes with their usual competition gear ratio and tires. Before the tests, each bike was equipped with a modified crank-based powermeter. The powermeter (Shimano DXR with SRM spider, SRM, Jülich Germany) was modified with a high-frequency gyroscope (Axiamo GmbH, Biel, Switzerland), which measured crank angular velocity, intercepted the analog torque signal from the SRM, and recorded the synchronized data streams at 100 Hz (Figure 4). Crank angular velocity was converted to an equivalent cadence (Cad) and combined with the torque ($\boldsymbol{M}$) to calculate pedaling power ($\boldsymbol{P}$). Further, Cad was divided by 60, then multiplied by the gear ratio and the wheel circumference to produce a continuous bike velocity signal (in m/s), which was then integrated to obtain a continuous bike displacement signal to be used for data synchronization (see below). Using the time points of peaks and nadirs in the torque signal, means of $\boldsymbol{M}$, Cad, and $\boldsymbol{P}$ were calculated over pedal stroke, i.e., the first quarter revolution (approximately, because cranks are initially horizontal) and each subsequent half revolution (between top and bottom of pedal cycle). The principal parameters used for hypothesis testing were mean $\boldsymbol{M}$ and Cad of the first (approximately ¼ revolution) and the fastest pedal strokes (typically the last complete ½ revolution).

For a subset of the subjects (*n*=9), three-dimensional kinematic motion of the rider and bike were captured using an opto-electronic system (Vicon, Oxford Metrics Group, Oxford, UK) operating at 100 Hz. During the measurements, riders wore skin-tight clothing, upon which reflective markers were placed prior to warm-up. The plug-in gait marker set (Vicon Documentation) was used, with additional markers placed on the bike's handlebar, frame, crank axle, pedals, and front and rear hubs. For data acquisition, 20 cameras (T160) were affixed to the walls of the starting ramp or tripods on the ground and connected to a computer running corresponding software (Vicon Nexus, Version 1.8.5). The Vicon system was calibrated and the origin was set before the measurement session in the morning and the afternoon. This was done with the help of a handheld device with multiple LEDs (Vicon Wand) according to the manufacturer's guidelines and with at least 3000 frames.

Data processing

Motion-capture data were processed initially using Vicon Nexus 2 software, then exported for parametrization and further analysis with the calculation program MatLab (Version R2014b, The MathWorks, Inc., Natick, USA). In MatLab, the initial position of the bike in the ready position and with the front wheel against the gate was defined for each start. Then, the time point of the initiation of gate drop (t=0) was defined by movement of the marker placed on the gate (velocity threshold 0.1 m/s). Relative to this time point, the onset of definitive forward bike velocity (t_{v_0}), the bike velocity at the onset of gate drop ($\boldsymbol{v}_{t_0}$), and the absolute distance traveled behind the gate after the onset of gate drop ($|d|_{t_0}$) were extracted based on movement of the markers on the bike's rear hub. Additionally, leg kinematic parameters were computed using the markers placed on the rider's body. Mechanical raw data were exported and processed using either Microsoft Excel (2013) or MatLab to obtain $\boldsymbol{M}_{peak}$, $Cad_{\boldsymbol{M}_{peak}}$, Cad_{peak}, and $\boldsymbol{M}_{Cad_{peak}}$, as well as mean starting velocity, acceleration, and power ($\bar{\boldsymbol{v}}_{start}$, $\bar{\boldsymbol{a}}_{start}$, $\bar{\boldsymbol{P}}_{start}$) after onset of gate drop. $\bar{\boldsymbol{v}}_{start}$ was calculated as $\frac{18.68\ m}{t_{start}}$, where 18.68 m is the distance between the gate and the end of the ramp (first and second timing gates in Figure 2) and t_{start} is the elapsed time between the initiation of gate drop and the bike's front wheel passing through the second timing gate. $\bar{\boldsymbol{a}}_{start}$ was calculated with the formula $\bar{a} = \frac{2(d - v_{t_0} \cdot t_{start})}{{t_{start}}^2}$, where d=18.68 m. $\bar{\boldsymbol{P}}_{start}$ was simply the average $\boldsymbol{P}$ during the phase corresponding to t_{start}.

Synchronization of motion-capture and mechanical data was achieved by visually aligning the displacement data of the rear wheel from both measurement systems.

Statistical analysis

Initially, in order to decide how $\boldsymbol{P}$ and $\boldsymbol{M}$ data would be best scaled for hypothesis testing, correlations to $\bar{\boldsymbol{v}}_{start}$ were compared for absolute and ratio scaled (to body mass) $\bar{\boldsymbol{P}}_{start}$ data, as well as $\bar{\boldsymbol{P}}_{start}$ data scaled allometrically to body mass$^{2/3}$ (Stone et al. 2004). Pearson correlations were all significant (r=0.91, 0.88, and 0.94, respectively, all p<0.01). Although, based on Fisher *r*-to-*z* transformation, correlations were not significantly different from one another, it was decided that hypothesis testing would be performed using absolute and allometrically scaled $\boldsymbol{P}$ and $\boldsymbol{M}$ data. Some ratio scaled data were applied for comparisons with other published studies.

First, the importance of the eight potential determining factors (identified in Figure 1) was evaluated using stepwise linear regression with $\bar{\boldsymbol{v}}_{start}$ or $\boldsymbol{v}_{end}$ as the output. Additionally, the relative importance for starting performance of some intermediate parameters were evaluated using linear regression as described, or Pearson's correlation coefficients (r), which were compared using Fischer transformation.

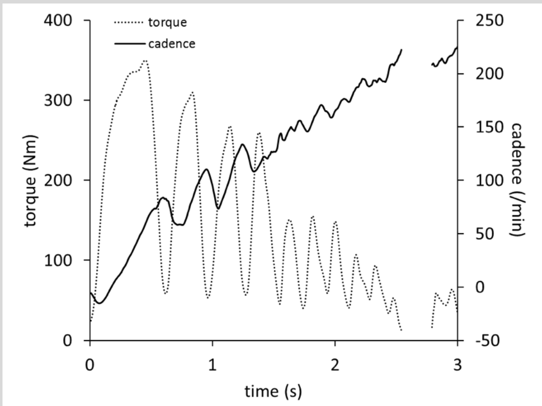

Figure 4. Example recording from a modified powermeter. Torque was measured with an SRM spider while pedaling cadence was measured with a gyroscope within an Axiamo data logger, which recorded both signals at 100 Hz.

For regression and correlation analyses, data from individual trials were used. Also, based on mean $\overline{\boldsymbol{v}}_{start}$ for each individual rider, two groups (the six fastest and the six slowest) were created for comparison of several mechanical and kinematic parameters, including leg kinematics. Comparison were performed using Student's *t*-test. Regression and correlation analyses and *t*-tests were performed using SPSS (Version 24, IBM Corp., Armonk, NY), with a significance threshold of $p<0.05$. Descriptive data are displayed as mean ± standard deviation.

Results

In all, start times, velocity ($\overline{\boldsymbol{v}}_{start}$, $\boldsymbol{v}_{end}$) and crank-based ($\boldsymbol{M}$, Cad, $\boldsymbol{P}$) data from 57 starts (12 subjects) as well as motion-capture data ($\boldsymbol{v}_{t_0}, t_{v_0}, |d|_{t_0}$, leg kinematics) from 45 starts (from nine of these subjects) were available for analysis. Descriptive data from the starts are displayed for the faster and slower groups separately in Table 2. There were several significant differences between the faster and slower subgroups, particularly for $\boldsymbol{P}$ and $\boldsymbol{M}$ parameters.

First aim

Using absolute data, the following regression equations were derived:

(1) $\overline{\boldsymbol{v}}_{start} = 2.83 - 0.206m\cdot_s + 53.014 \cdot A - 3.918 \cdot t_{v_0} + 0.004 \cdot \boldsymbol{M}_{peak} + 0.008 \cdot Cad_{\boldsymbol{M}_{peak}}$
(r=0.971, r^2=0.944),

(2) $\boldsymbol{v}_{end} = 12.025 + 0.052 \cdot Cad_{\mathrm{M}_{peak}} - 3.873 \cdot t_{v_0}$
(r=0.841, r^2=0.708)

Using allometrically scaled data, the following regression equations were derived:

(3) $\overline{\boldsymbol{v}}_{start} = 2.052 - 0.217 \cdot m_s + 57.639 \cdot A - 3.895 \cdot t_{v_0} + 0.057 \cdot \boldsymbol{M}_{peak} + 0.008 \cdot Cad_{\boldsymbol{M}_{peak}}$
(r=0.971, r^2=0.943)

(4) $\boldsymbol{v}_{end} = 12.025 + 0.052 \cdot Cad_{M_{peak}} - 3.873 \cdot t_{v_0}$
(r=0.841, r^2=0.708)

where $\overline{\boldsymbol{v}}_{start}$ is mean velocity after the onset of gate drop, $\boldsymbol{v}_{end}$ is the velocity at the end of the starting ramp, m_s is the combined mass of bike and rider, A is approximate frontal area, t_{v_0} is the time point of definitive forward velocity, $\boldsymbol{M}_{peak}$ and $Cad_{\boldsymbol{M}_{peak}}$ are the torque and cadence of the first pedal stroke, and

Table 2. Descriptive data from starts.

			mean (± *s*)			range	TE	(T%E)
			faster subgroup (*n*=6)		**slower subgroup (*n*=6)**			
starting time	t_{start}	[s]	2.47 ± 0.04	*	2.62 ± 0.11	2.40 – 2.92	0.03	1.2%
mean starting $\boldsymbol{v}$	$\overline{\boldsymbol{v}}_{start}$	[m·s^{-1}]	7.57 ± 0.13	*	7.14 ± 0.28	6.4 – 7.8	0.1	1.3%
$\boldsymbol{v}$ at end of start	$\boldsymbol{v}_{end}$	[m·s^{-1}]	15.2 ± 0.4	*	14.2 ± 1.9	4.9 – 16.2	1.1	7.2%
$\boldsymbol{v}$ at gate drop	$\boldsymbol{v}_{t_0}$	[m·s^{-1}]	0.67 ± 0.26		0.43 ± 0.78	-0.86 – 1.33	0.15	20%
t at initiation of forward $\boldsymbol{v}$	t_{v_0}	[s]	-0.01 ± 0.02		0.02 ± 0.05	-0.05 – 0.10	0.01	40%
d to gate at gate drop	$\lvert d\rvert_{t_0}$	[m]	0.28 ± 0.04	*	0.21 ± 0.07	0.06 – 0.34	0.03	11%
mean starting $\boldsymbol{a}$	$\overline{\boldsymbol{a}}_{start}$	[m·s^{-2}]	5.6 ± 0.2	*	5.1 ± 0.3	4.6 – 5.9	0.2	3.1%
mean starting $\boldsymbol{P}$	$\overline{\boldsymbol{P}}_{start}$	[W]	1660 ± 250	*	1170 ± 230	720 – 1940	93	6.8%
		[W·kg$^{2/3}$]	88 ± 8	*	70 ± 11	45 – 103	5.2	6.6%
peak $\boldsymbol{P}$ during start	$\boldsymbol{P}_{peak}$	[W]	2000 ± 260	*	1460 ± 240	1110 – 2360	111	6.6%
		[W·kg$^{2/3}$]	107 ± 8	*	88 ± 11	68 – 125	6	6.2%
peak $\boldsymbol{M}$ over one pedal stroke	$\boldsymbol{M}_{peak}$	[Nm]	232 ± 24	*	195 ± 27	140 – 270	12	5.9%
		[Nm·kg$^{2/3}$]	12.5 ± 0.8	*	11.8 ± 1.4	9.1 – 14.7	0.7	5.9%
Cad at $\boldsymbol{M}_{peak}$	$Cad_{\boldsymbol{M}_{peak}}$	[rev·min^{-1}]	57.6 ± 2.4	*	49.5 ± 6.5	26.8 – 62.5	3	5.0%
peak Cad over one pedal stroke	Cad_{peak}	[rev·min^{-1}]	204 ± 16	*	190 ± 13	172 – 228	10	6.3%
$\boldsymbol{M}$ at Cad_{peak}	$\boldsymbol{M}_{Cad_{peak}}$	[Nm]	70 ± 26		61 ± 23	21 – 140	9	15%
		[Nm·kg$^{2/3}$]	3.7 ± 1.2		3.7 ± 1.2	1.4 – 6.7	0.5	15%
$\boldsymbol{P}$ at $\boldsymbol{M}_{peak}$	$\boldsymbol{P}_{M_{peak}}$	[W]	1287 ± 235	*	980 ± 286	470 – 2078	223	20%
		[W·kg$^{2/3}$]	69 ± 10	*	59 ± 17	31 – 100	13	20%
$\boldsymbol{P}$ at Cad_{peak}	$\boldsymbol{P}_{Cad_{peak}}$	[W]	1383 ± 396	*	1179 ± 300	435 – 2241	127	10%
		[W·kg$^{2/3}$]	74 ± 18		71 ± 15	28 – 108	8	11%

$\boldsymbol{v}$: velocity. t: time point relative to gate drop (t_0). d: distance in both backward and forward directions. $\boldsymbol{a}$: acceleration. $\boldsymbol{P}$: pedaling power. $\boldsymbol{M}$: pedaling torque. Cad: pedaling cadence. TE: typical error, calculated across the five starts. T%E: typical percent error. Subgroups "faster" and "slower" were formed based on individuals' average $\overline{v}_{start}$. * indicates significant differences (p<0.05) between subgroups.

$\boldsymbol{M}_{Cad_{peak}}$ and Cad_{peak} are torque and cadence of the fastest pedal stroke.

Significant bivariate correlations with starting performance existed for $|d|_{t0}$ (r=0.66 and r=0.70 for $\bar{\boldsymbol{v}}_{start}$ and $\boldsymbol{v}_{end}$, respectively, both p<0.01) but these were not independent of the more strongly correlated parameters included in the regression equations 1 – 4. The parameter $\boldsymbol{v}_{t_0}$was significantly more strongly correlated with t_{v_0} (-0.94, p<0.01) than with $|d|_{t0}$ (0.48, p<0.01). Subjects' m_b correlated significantly with $\bar{\boldsymbol{v}}_{start}$ (r=0.65, p<0.01) but not with $\boldsymbol{v}_{end}$ (r=0.12, p=0.38). As expected, the correlation between $\bar{\boldsymbol{a}}_{start}$ and $\bar{\boldsymbol{v}}_{start}$ was significant (r=0.45, p<0.01); however, it was weaker (Fisher transformation: p=0.23) than the correlation between $\boldsymbol{v}_{t_0}$ and $\bar{\boldsymbol{v}}_{start}$ (r=0.70, p<0.01). The correlations with $\boldsymbol{v}_{end}$ were similar for $\bar{\boldsymbol{a}}_{start}$ and $\boldsymbol{v}_{t_0}$ (r= 0.47 and r=0.52, respectively, p<0.01). Correlations with $\bar{\boldsymbol{v}}_{start}$ were significantly higher for $\boldsymbol{P}_{M_{peak}}$ (r=0.58 – 0.72, p<0.01) than for $\boldsymbol{P}_{Cad_{peak}}$ (r=0.18 – 0.37, p=0.01 – 0.19). The correlation between m_b and $\bar{\boldsymbol{v}}_{start}$ was high and significant (r=0.84, p<0.01). Additionally, the following regression equations were derived:

with absolute data:

(5) $\bar{\boldsymbol{v}}_{start} = 6.448 + 0.239 \cdot \boldsymbol{v}_{t_0} + 0.001 \cdot \boldsymbol{P}_{M_{peak}}$
(r=0.960, r^2=0.922)

(6) $\boldsymbol{v}_f = 13.410 + 0.252 \cdot \boldsymbol{v}_{t_0} + 0.001 \cdot \boldsymbol{P}_{M_{peak}}$
(r=0.811, r^2=0.657)

with allometrically scaled data:

(7) $\bar{\boldsymbol{v}}_{start} = 6.271 + 0.280 \cdot \boldsymbol{v}_{t_0} + 0.012 \cdot \boldsymbol{P}_{M_{peak}}$
(r=0.963, r^2=0.927)

(8) $\boldsymbol{v}_f = 13.092 + 0.313 \cdot \boldsymbol{v}_{t_0} + 0.02 \cdot \boldsymbol{P}_{M_{peak}}$
(r=0.826, r^2=0.682)

Second aim

Descriptive leg and crank kinematic data are displayed in Table 3 and Figures 5 and 6.

About half of the knee and hip angle minima and maxima for the first four unilateral pedal strokes (~2 complete revolutions) differed significantly between groups, mostly due to smaller peak angles (extension) of both joints by the faster starters, particularly beyond the first pedal revolution. All time points of minima and maxima differed significantly between groups, due to a leftward shift (shorter reaction time) for the faster riders. For the first five pedal strokes, most mean and peak angular velocity values differed significantly between groups, but there was no consistent pattern for the direction of these differences. Finally, the following significant relationship between Cad and mean knee angular velocity ($\bar{\omega}$) was found:

(1) $\bar{\omega} = 1.22 \cdot Cad + 85.7$
(r^2=0.75)

where angular velocity is in °/s and Cad is in rev/min.

Table 3. Leg and crank angles during the preparatory "slingshot" maneuver of the BMX racing start.

	first instance of forward acceleration	first instance of forward velocity*
front knee angle	138 ± 4°	123 ± 7°
front hip angle	99 ± 8°	108 ± 6°
crank angle	9 ± 7°	8 ± 7°

For leg joint angles, full extension is defined as 180°. For crank angle, front pedal forward and horizontal is defined as 0°; positive values (<90°) indicate the front pedal above the horizontal. *because the preparation maneuver typically includes a countermovement (slingshot) behind the gate, the first forward acceleration occurs with backward (negative) velocity and the first instance of forward velocity occurs at a slightly later time point.

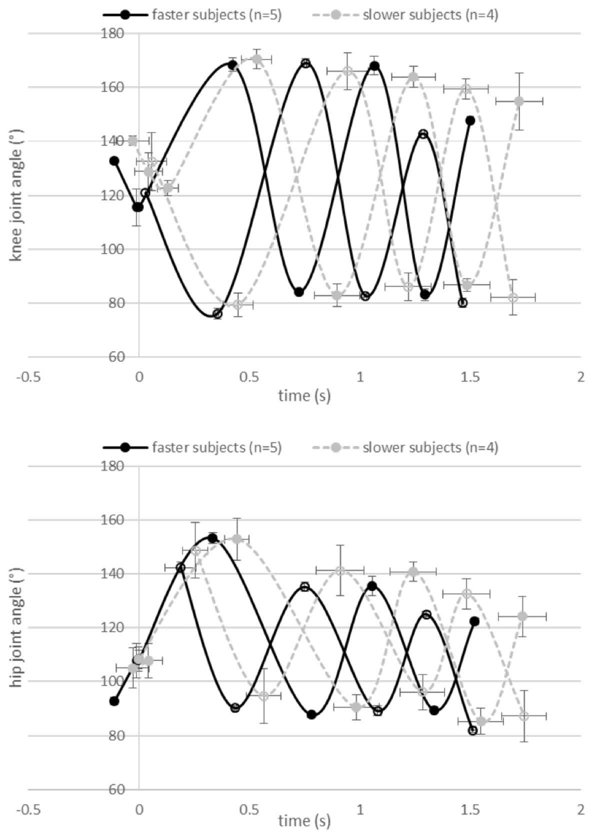

Figure 5. Knee (upper panel) and hip (lower panel) angle minima and maxima during BMX starts on a 'supercross' ramp. The first

Discussion

First aim

The first aim of this study was to evaluate eight potential performance determinants (Figure 1) for their relative importance of a BMX starting performance. These included two technical, four neuromuscular, and two quasi-anthropometric factors.

Effectiveness of slingshot maneuver

The two technical parameters evaluated in this study ($t_{v_0}$and $|d|_{t_0}$) characterize the effectiveness of the preparatory slingshot maneuver prior to the gate drop.

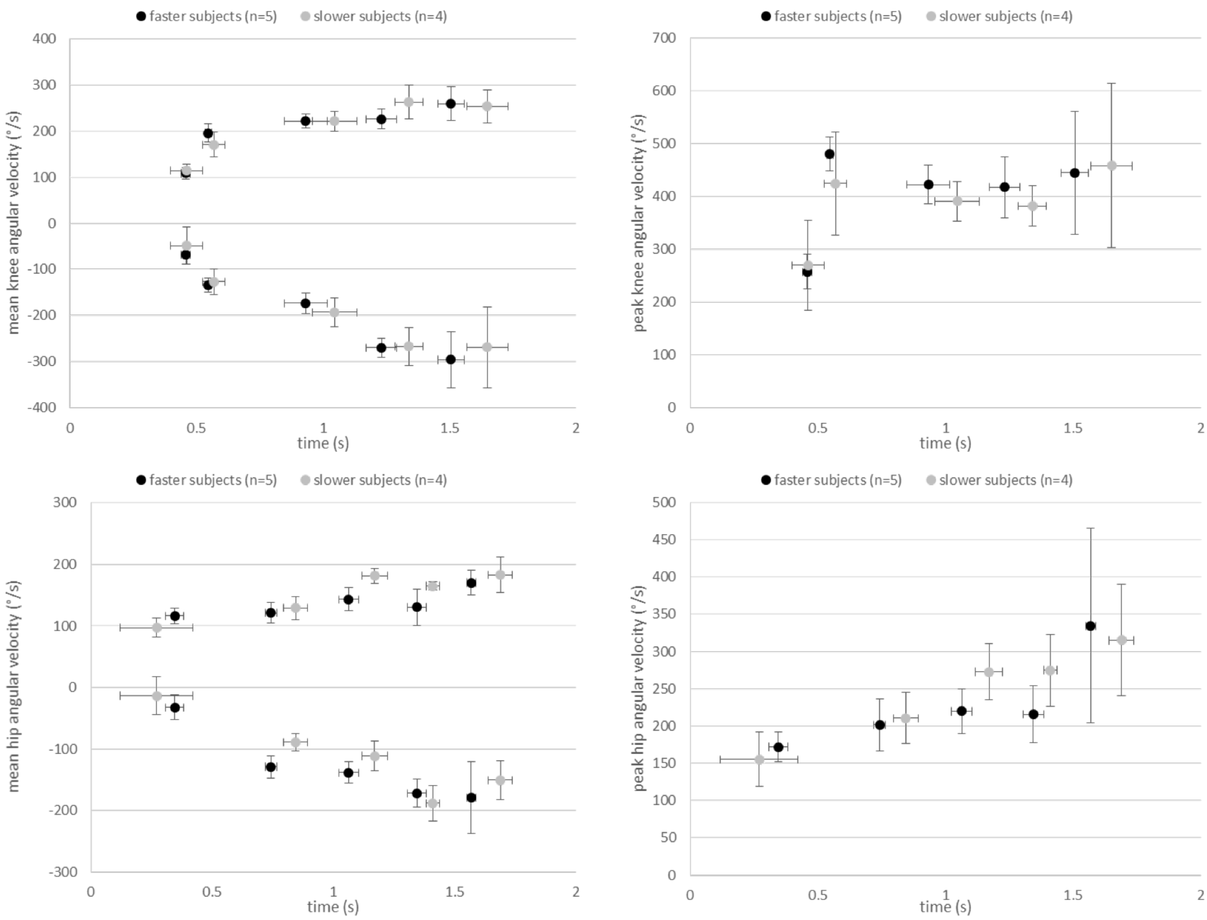

Figure 6. Mean (left panels) and peak (right panels) joint angular velocities for knee (upper panels) and hip (lower panels) during BMX starts on a 'supercross' ramp. The first extension with the front leg (simultaneous flexion of the back leg) occur over approximately one quarter crank revolution, whereas successive flexion-extension cycles occur over half revolutions. The time point 0 is defined as the instant where the starting gate begins to drop. Time points for mean angular velocities indicate the middle

The appearance of t_{v_0} but not $|d|_{t_0}$ in equations 1 and 3 suggest that an early initiation of forward velocity is more directly related to starting performance than is proximity to the gate when it drops. This could be because the relationship between $|d|_{t_0}$and performance is probably not perfectly linear, as mentioned before (because $|d|_{t_0}$ should be neither too large nor too small). Another consideration, although this was not investigated explicitly, is that reaching the backward-most position in the slingshot maneuver early allows technically savvy riders to finely modulate the forward thrust thereafter in order to achieve the best balance between forward velocity and gate clearance. Mainly, however, an early t_{v_0} extends the forward acceleration time prior to gate drop, and as a result, t_{v_0} values further below zero were closely related to a relatively high velocity at gate drop (effectively a head start) and significantly improved starting performance. Indeed, the overwhelming advantage of speed gathered before the gate drop ($\boldsymbol{v}_{t_0}$) is made clear by the fact that this parameter correlated more strongly with $\bar{\boldsymbol{v}}_{start}$ than did mean acceleration after the gate drop ($\bar{a}_{start}$).

Neuromuscular factors

Of the four neuromuscular factors investigated (Figure 1), torque and cadence in the first pedal stroke ($\boldsymbol{M}_{peak}$ and $Cad_{M_{peak}}$) were more important for $\bar{\boldsymbol{v}}_{start}$ than were torque and cadence occurring at the highest velocity further down the ramp (Cad_{peak} and $\boldsymbol{M}_{Cad_{peak}}$, equations 1 and 3). Further, the appearance of $Cad_{\boldsymbol{M}_{peak}}$ in the regressions for $\boldsymbol{v}_{end}$ (equations 2 and 4) suggests that even top speed itself was quite dependent on the first pedal stroke in the present study. In flat ground sprinting situations, it is evident that torque, and thus acceleration, decreases with increasing velocity and distance (Debraux et al. 2013; Gardner et al. 2007), making initial acceleration most important for short distances. In contrast, the increase in cadence (i.e., acceleration) on the supercross ramp is quite linear throughout the starting phase, despite a linear decrease in pedal-stroke mean torque (Figure 4). Thus, it appears that acceleration in the latter portion of the start is less heavily dependent on crank torque as it is at the beginning; rather, as the ramp becomes steeper (Figure 2), gravity plays an increasingly central role in the acceleration. Along this line of logic, pedaling $\boldsymbol{P}$ ($\boldsymbol{M}$ and Cad) have the greatest effect of bike velocity, and thus performance, during the initial portion of the start, where velocity and the ramp slope are lowest. Therefore, based on these findings, an explosive first pedal stroke,

characterized by high $\boldsymbol{M}$ and Cad, is the most crucial neuromuscular aspect of BMX starting performance.
Aside from these conclusions, it is important to note that Cad_{peak} represented the highest value attained during the start phase and not necessarily the individual maximum. Because the length of the start phase is short, the attained Cad_{peak} is rather dependent on the mean acceleration and thus the power output in the first few pedal strokes, because these strongly affect the velocity attained over the limited distance. This consideration agrees with the appearance of $Cad_{M_{peak}}$ in the regressions for $\boldsymbol{v}_{end}$ (equations 2 and 4), since Cad_{peak} and $\boldsymbol{v}_{end}$ are inevitably related. Hypothetically, the slower starters in the present study could have been capable of higher maximal Cad, but less able to exhaust their potential due to poor initial acceleration and the short starting distance.

Quasi-anthropometric factors
The two remaining, quasi-anthropometric parameters, frontal area (A) and system mass (m_s), both factored significantly into regression equations (1 – 4) for starting performance, although the former did so in a manner contrary to our hypothesis. Admittedly, the present study design was not well-suited to investigate the effects of aerodynamics on the BMX start due to the relatively low average velocity and the crude estimation of riders' A. Nonetheless, we decided to plug estimated A into the regression and, indeed, it was significantly related to starting performance in the present study, albeit in a positive manner, thus contrary to our hypothesis (equations 1 and 3). This finding that riders with greater estimated A displayed superior starting performance is also in contrast to the findings of Dorel and co-workers (2005), that an optimal ratio between power and frontal area was a key determinant of short sprinting performance of track cyclists. However, this discrepancy can be explained by the fact that the average velocity of a flying track sprint (19.2 m/s, Dorel et al. 2005) is much greater than that of a standing start in BMX (7.4 m/s in the present study), making A far more important in the former situation than in the latter, since aerodynamic drag increases quadratically with velocity. As for the BMX start, initial acceleration—prior to achieving the high speeds where aerodynamics become increasingly crucial—plays a much greater role than peak speed (see discussion above). In any case, based on the significant positive effect of A on starting performance in the present study, in spite of the inevitable relationship between A and air resistance (e.g., Dorel et al. 2005), we conclude that the larger riders in the present study (with greater estimated A) more than compensated for the greater air resistance they are assumed to have encountered with their ability to produce greater mechanical power.
In accord with our hypothesis, greater m_s, when considered independently from neuromuscular capacity, as it was in the regression analysis, was found to be detrimental to $\bar{\boldsymbol{v}}_{start}$ (negative coefficients in equations 1 and 3). As discussed above, the initial acceleration at the top of the ramp seems to be of greatest importance for $\bar{\boldsymbol{v}}_{start}$ and it is in this initial portion of the start, where the ramp is relatively flat, that the greater inertia associated with greater m_s would be most detrimental to performance. On the other hand, m_s was not significantly detrimental to $\boldsymbol{v}_{end}$ (absent in equations 2 and 4). This could be because greater m_s is of some benefit in the steeper portion of the ramp (Swain 1998) and that this benefit is able to blunt the negative effects of greater inertia. Notwithstanding these results from the regression analysis, there remained a significant positive relationship between body mass (m_b) and $\bar{\boldsymbol{v}}_{start}$ (but not $\boldsymbol{v}_{end}$), which, in light of the points discussed above regarding m_s, suggests that the heavier riders must have more than compensated for their greater inertia with even greater neuromuscular power. Thus, although greater m_b, m_s, and A are probably detrimental for a given amount of neuromuscular power, they tended to be associated with more than enough power to compensate, and thus with superior starting performance in the present study.
All things considered, the results reveals that 93 – 96% of the variation in $\bar{\boldsymbol{v}}_{start}$ can be explained by $\boldsymbol{v}_{t_0}$ and $\boldsymbol{P}$ of the first pedal stroke (the product of $\boldsymbol{M}_{peak}$ and $Cad_{\boldsymbol{M}_{peak}}$) alone.
Furthermore, we conclude that increasing absolute muscular power, even if this entails an increase in body mass (i.e., inertia) and body size (i.e., A), is beneficial for BMX starting performance. These findings highlight the predominant importance of a well-timed, technically clean preparatory slingshot maneuver, along with a powerful initial pedal stroke, for optimizing starting performance.

Second aim
A secondary aim of the present study was to describe basic leg kinematics during the BMX start. As seen in Table 3, the crank angle changes minutely, by only about 1° during the phase between the first positive acceleration and the initiation of forward velocity. During this phase, which last around 0.23 s, the front hip extends while the front knee undergoes flexion (Table 3, Figure 5). This finding of knee flexion in the preparatory phase, which is followed by explosive knee extension with the first pedal stroke, suggest that a stretch-shorting cycle is occurring to enhance knee-joint power, at least of the single-joint knee extensor *m. vastus intermedius*. This could be a novel finding, as cycling is typically thought of as comprising purely concentric actions of the leg muscles.
As for range motion, during the first quarter pedal revolution, the front knee goes through approximately the upper half of its range of motion (compared to the subsequent complete revolutions), whereas the hip goes through basically its entire range of motion. Knees reach near full extension and drop consistently below 90°, the overall range of motion decreasing somewhat with each of the first five half-revolutions. Hips never approach full extension and their range of motion has a smaller amplitude than that of the knees. Ranges of motion for

knee and hip are similar to that reported in a rare study on the biomechanics out-of-the-saddle cycling (Li and Caldwell 1998). Although not explicitly reported, the diagram in that study indicate that hips moved between about 75 and 125° while knees moved between about 85 and 155°.

Comparing the two rider subgroups, the faster starters tended toward smaller peak extension angles in the knee and hip joints compared to slower starters, particularly beyond the first pedal revolution (Figure 5). However, the most noticeable difference when comparing the leg kinematic sequences in Figure 5 was the quicker initiation of the first pedal stroke (leftward shift) seen in the faster starters.

As for joint angular velocities, comparable studies seem to be rare. McDaniel et al. (2014) reported knee and hip angular velocities associated with different Cad during maximal seated 'sprints'. At the lowest Cad (60 rev·min^{-1}), knee and hip angular velocities of approximately 100°·s^{-1} and 150°·s^{-1}, respectively, are comparable to the present results at the Cad of 55 rev·min^{-1} for the first quarter revolution. However, the present results seem to indicate that that knee and hip angular velocity level off a bit more with increasing cadence for standing BMX starts than for the seated sprints studied by McDaniel et al (McDaniel et al. 2014). This is conceivable as the upper body moves more freely in standing cycling and can therefore dampen the range of motion of the leg joints, thus requiring slightly lower angular velocities in these joints for a given Cad.

Based on these findings, it would be prudent for BMX riders to choose leg strength exercises that closely mimic the ranges of motion, extension velocities and joint moments encountered in the very important start phase of a race. This means leg press, squats and jumps, for example, should be performed out of knee angles slightly less than 90° and hip angles of ~90° (List et al. 2013; Lorenzetti et al. 2012; Schutz et al. 2014). These joint angles can be easily reached during normal squats (Lorenzetti et al. 2012). Regarding loading, there appear to be few helpful references available describing knee and hip angular velocities for common strength training exercises with different loads. One study (Jandacka et al. 2014) indicated that trained athletes performing squat jumps with and additional load of ~70% body mass displayed peak knee and hip angular velocities around 500°·s^{-1} and 300°·s^{-1}, respectively, which approximately correspond to the highest values attained by the present subjects in the course of the entire BMX start, at Cad_{peak} of 221 ± 39 rev·min^{-1}. Unpublished data from elite BMX riders from our lab indicate that squat jumps with an additional load equal to body mass (<50% 1-repetition max) attain mean knee angular velocities of 250 – 300°·s^{-1}, which also corresponds to the highest values attained on the starting ramp in the present study. On the other hand, unloaded squat jumps elicit peak knee angular velocities of ~800°·s^{-1} (Jandacka et al. 2014) and mean knee angular velocities of ~500°·s^{-1} (our lab). Based on regression equation 9, this could correspond to Cad of >300 rev·min^{-1}. This is much higher than the values we measured on the starting ramp, although it is not an unattainable value. In general, these results suggest knee angular velocities during the BMX start are probably slower than those encountered during unloaded squat jumps and probably compare better to jumps with additional loads of at least 70% of body mass. The importance of higher contraction velocities than those measured in the present study in later phases of a BMX race has yet to be addressed.

Comparison with other studies

Comparatively speaking, starting speed in the present study was highly correlated with mean pedaling power, in accord with a previous report (Bertucci et al. 2007). $\boldsymbol{P}_{\text{peak}}$ on the starting ramp for males in the present study (1810 W, 23.6 W·kg^{-1}), was higher than for the group of male racers (1340 W, 17.8 W·kg^{-1}) studied by Bertucci & Hourde (2011) but closer to the values reported for eight elite British male riders (1671 W, ~24 ·kg^{-1}) studied by Rylands et al. (2015), despite differences in data resolution. Similarly to the riders studied by Mateo et al. (2011), the present subjects attained $\boldsymbol{P}_{\text{peak}}$ after 1.4 ± 0.2 s during starts on the supercross ramp (usually in the latter half of the second pedal revolution).

Limitations

One limitation of the present study is that technical aspects beyond the gate were not considered. The most important of these is probably the 'pumping' maneuver at the apex of the ramp-ground transition or an additional pedal stoke that some riders manage between this transition and the first obstacle (5-m section over which $\boldsymbol{v}_{end}$ was measured). Similarly to a skateboarder in the halfpipe, riders can increase system energy by a vertical movement of their center of mass and, in this manner, potentially accelerate the bike independently of pedaling $\boldsymbol{P}$ (Rylands et al. 2017). Another minor limitation is that we defined t_{v_0}, $|d|_{t_0}$ and $\boldsymbol{v}_{t_0}$ based on the kinematics of the bike's rear wheel. It is conceivable that results would have varied had we considered the kinematics of the bike-rider system's center of mass. This was not possible, however, as the motion capture data of the upper body were too fragmented. Nonetheless, we believe our main conclusions would be remain unchanged had we based them on the system center of mass. A final limitation was our crude estimate of rider frontal area (A) using a formula not particular to BMX cycling. Indeed, more sophisticated methods exist (Debraux et al. 2009; Debraux et al. 2011), one of which would have been indispensable had we needed an exact, absolute value for A. As this was not the case, we employed the estimation method that seemed most appropriate (Debraux et al. 2011) and made the assumption that the estimated A was closely linked, though not exactly equal, to the true effective frontal area, and thus valid for the purpose of the present study (i.e, to addreass the relative importance of this factor).

Practical Applications

For practical purposes, it can be concluded that BMX racers should aim to improve starting performance by optimizing the preparatory slingshot maneuver in order to attain maximal forward velocity prior to gate drop. To this end, an early initiation of forward velocity appears to be of central importance. Additionally, since the power of the first pedal stroke seems to be of predominant importance for starting performance, maximal strength and power at high loads should be developed. To this end, riders should employ strength exercises using additional loads of at least 50% of the individual 1-repetition maximum.

Conflict of interest

The investigators in the present study have no conflicts of interest.

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