Journal of Sports Sciences

ISSN: 0264-0414 (Print) 1466-447X (Online) Journal homepage: http://www.tandfonline.com/loi/rjsp20

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JOURNAL OF SPORTS SCIENCES, 2017
http://dx.doi.org/10.1080/02640414.2017.1287935

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Reliability of the virtual elevation method to evaluate rolling resistance of different mountain bike cross-country tyres

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ABSTRACT

Although a low rolling resistance is advantageous in mountain bike cross-country racing, no studies have used the virtual elevation method to compare tyres from different manufacturers as used in international competitions so far. The aims of this study were to assess the reliability of this method, to compare the off-road rolling resistance between tyres and to calculate the influence on off-road speed. Nine 29-in. mountain bike cross-country tyres were tested on a course representing typical ground surface conditions 5 or 6 times. The coefficient of rolling resistance was estimated with the virtual elevation method by 3 investigators and corresponding off-road speeds were calculated.

The virtual elevation method was highly reliable (typical error = 0.0006, 2.8%; limits of agreement <0.0005, $r \geq 0.98$). The mean coefficient of rolling resistance was 0.0219 and differed from 0.0205 to 0.0237 ($P < 0.001$) between tyres. The calculated differences in off-road speed amounted to 2.9–3.2% (0% slope) and 2.3–2.4% (10% slope) between the slowest and the fastest tyre.

The reliability of the method and the differences in rolling resistance between the tyres illustrate the value of testing tyres for important competitions on a representative ground surface using the virtual elevation method.

ARTICLE HISTORY
Accepted 24 January 2017

KEYWORDS
Off-road cycling; mathematical model; aerodynamic drag

Introduction

The main resistive forces during cycling are aerodynamic drag, rolling resistance and gravity; furthermore, inertia is counteracting accelerations (Olds, Norton, & Craig, 1993). In mountain bike cross-country (MTB XC), a low rolling resistance seems particularly crucial to performance, as it can amount to up to 69% of the total resistance on a rough ground surface like grass (Bertucci & Rogier, 2012; Bertucci, Rogier, & Reiser II, 2013). Rolling resistance is defined as the opposing force against lateral displacement of the bike rolling over a surface under a compressing force like gravity. It is usually modelled as $F_r = C_r\, m\, g$ on level ground, where C_r is the ground surface-specific but dimensionless coefficient of rolling resistance, m is the total mass and g is the standard gravity.

Early attempts to quantify the rolling resistance of a bicycle have been made on the road by towing cyclists behind a car with a dynamometer (Di Prampero, Cortili, Mognoni, & Saibene, 1979). Newer studies have used deceleration trials (Candau et al., 1999; Macdermid, Fink, & Stannard, 2015; Steyn & Warnich, 2014), fixed power uphill tests (Macdermid et al., 2015), mean riding power (Bertucci et al., 2013) or regression models using power output and speed (Bertucci & Rogier, 2012; Lim et al., 2011). The methods used to assess resistive forces in road cycling are often problematic when used on off-road terrain, highlighting the necessity for a new method to estimate rolling resistance in MTB XC (Macdermid et al., 2015). A promising candidate is the virtual elevation method (Chung, 2012), which allows for the use of diverse and, thus, specific test courses. Nonetheless, the method uses an optical fitting procedure to solve a mathematical model, potentially impairing the reliability through inter-rater disagreement.

Whereas numerous studies have analysed the rolling resistance of road bike tyres, the literature on MTB XC tyres is rather small (Bertucci & Rogier, 2012; Bertucci et al., 2013; Macdermid et al., 2015; Steyn & Warnich, 2014). Variables associated with the C_r of a tyre include the mass, tyre pressure, width, volume, tread area, tread depth, rubber compound, casing construction and tyre–surface interaction. Tyres with a smooth tread area have been shown to have a lower C_r than the ones with a rough tread area (Bertucci et al., 2013), and depending on the ground surface, mean values between 0.007 and 0.037 have been reported (Bertucci & Rogier, 2012). Furthermore, there seems to be an interaction effect between tyre pressure and ground surface on the C_r: while a higher pressure reduces the C_r on a flat road surface, it increases the C_r on a bumpy grass surface (Bertucci & Rogier, 2012). A recent study concluded that an optimal rolling MTB XC tyre for a hard packed mud ground surface should be light, high in volume and with a low tread surface area and tread depth (Macdermid et al., 2015).

In today's MTB XC competitions, athletes use numerous different manufacturers and models of tyres in an attempt to lower the rolling resistance while maintaining enough grip, cornering control and puncture protection for technical sections. Athletes typically choose tubeless mounted tyres, inflated with a low pressure of around 0.29 psi · kg^{-1} of total

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mass (participant + bike + accessories), with a width of around 2.1 in. and a low tread depth (cross-country race tread).

No studies have been conducted so far analysing the use of the virtual elevation method to compare the off-road rolling resistance between MTB XC tyres from different manufacturers as used in international competitions. Furthermore, there is limited data on the influence of rolling resistance on actual off-road speed (Bertucci et al., 2013).

The aims of this study were to assess the reliability of the virtual elevation method, to compare the off-road rolling resistance between 9 MTB XC tyres as used in international competitions, and to calculate the influence of rolling resistance on off-road speed.

Method

Tyres and participant

Nine 29-in. MTB XC tyres suitable for all-round dry conditions were tested (Table 1). Eight tyres represented the top model of the respective manufacturer as used in international competitions; 1 tyre was a newly developed prototype. One new set (front and rear) of each tyre model was provided by different international MTB XC teams and stored for 1 month under dry conditions before testing.

An experienced mountain biker (height = 1.75 m, mass = 71 kg) volunteered to participate in the study. The study was accepted by the institutional review board (Swiss Federal Institute of Sport) and written informed consent was obtained.

Study design

The data collection was conducted within 1 week in July 2015. The first day was used as a familiarisation day, during which the participant used all tyres and the test course for the first time.

Subsequently, 50 C_r tests were conducted during 5 days with a randomised order of the tyres, resulting in 5–6 tests per tyre. For each test, the participant completed the C_r test protocol. On the last day, the participant additionally completed the effective frontal area (C_dA) test protocol 7 times.

Table 1. Description of studied tyres.

Manufacturer	Tyre model	Mounted	Dimension (in.)	Mass (g)	Volume (cm^3)	TPI
Bontrager	XR1	Tubeless	29 × 2.20	700	4269	120
Continental	Race King	Tubeless	29 × 2.20	512	4687	180
Dugast	Fast Bird	Tubular	29 × 2.00	620	3834	N/A
Dugast	Prototype	Tubular	29 × 2.00	645	3652	N/A
Hutchinson	Black Mamba	Tubeless	29 × 2.00	479	3634	127
Maxxis	Ikon	Tubeless	29 × 2.20	542	4331	120
Ritchey	Shield	Tubeless	29 × 2.10	566	3749	120
Schwalbe	Racing Ralph	Tubeless	29 × 2.25	566	4346	127
Specialized	Renegade	Tubeless	29 × 2.10	488	3832	120

Volume was calculated as the product of measured cross-sectional area and mean circumference, TPI: threads per inch, N/A: not available.

C_r test protocol

The participant had to complete 5 laps on the test course in the seated position with minimal upper body movement. Before and afterwards, the following parameters were obtained: total mass, air pressure, humidity, tyre pressure and 0-offset of the power meter. Wind speed and temperature were recorded continuously.

Effective frontal area (C_dA) test protocol

The participant had to complete 6 laps on a 400-m athletics track in the seated position with minimal upper body movement, during which he accelerated steadily from around 10 km · h^{-1} to around 35 km · h^{-1}. Before and afterwards, the same parameters as in the C_r test protocol were obtained.

Test course

A course representing typical MTB XC ground surface conditions was chosen, located in Magglingen BE, Switzerland, at an altitude of 960 m. Its length amounted to 500 m with an altitude difference of 3 m (Figure 1). The course could be completed without using the brakes. Approximately 40% of the ground surface consisted of soil (grassland), 30% of soil (forest) and 30% of gravel road.

Bike setup

A 29-in.-wheel MTB XC bike (C29, Colnago, Cambiago, Italy) with front suspension (OPM O.D.L. 100 LTD Team Edition, DT

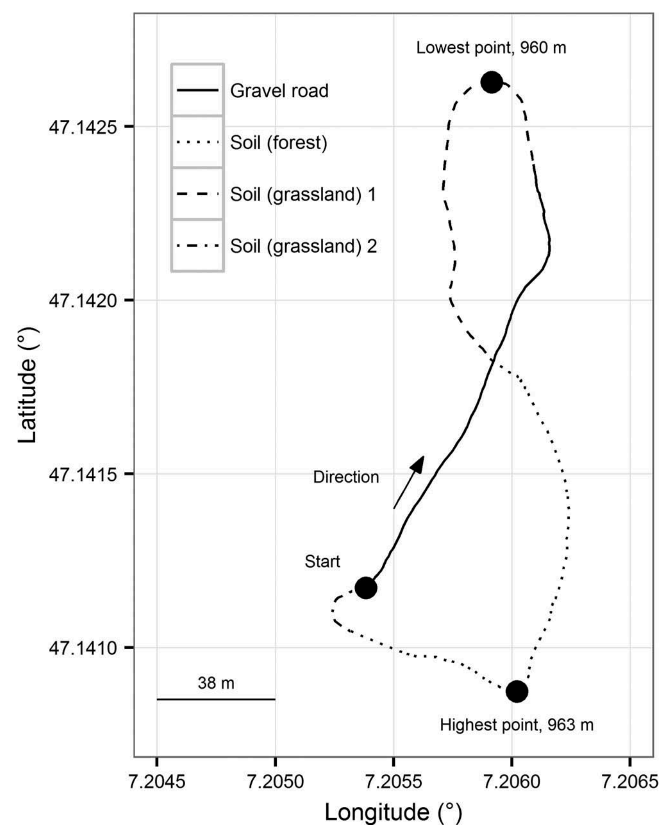

Figure 1. Map of the test course.

Swiss AG, Biel, Switzerland) was used. All tubeless tyres were mounted on the same wheels (XR 1501 Spline One 29, DT Swiss AG, Biel, Switzerland) with 100 mL of fluid sealant (Stan's Tire Sealant, Notubes, Big Flats NY, USA). The 2 tubular tyres were mounted on special carbon wheels (WH-M9000-TU, Shimano, Sakai, Japan). Tyre pressure was set to 0.28 psi $\cdot$ kg^{-1} of the total mass (participant + bike + accessories) after personal communication with several National Team athletes and controlled with a pressure gauge (Airmax Pro, Schwalbe, Reichshof, Germany). This setup represents the typical use in international competitions.

Power output was measured with a dynamically calibrated mobile power meter (SRM Shimano XT, SRM, Jülich, Germany). Speed was measured with a magnet-based speed sensor (GSC10, Garmin, Olathe KS, USA). Power output and speed were recorded with 1 Hz on a recording unit (Edge 510, Garmin, Olathe KS, USA). Wheel circumference of each tyre was assessed individually by loaded rollouts on a flat surface.

Environmental conditions

Weather conditions were sunny and dry throughout the data collection period. Environmental measurements were conducted at the start (Figure 1), corresponding with the location least sheltered against wind. Wind speed and temperature were recorded with a hot-wire thermo-anemometer (SDL350, Extech Instruments, Nashua NH, USA) and averaged for each test. Wind direction was monitored with a mechanical indicator (Windex 15, Windex Development AB, Bromma, Sweden). Humidity and air pressure were measured with a mobile weather station (WH1170, Conrad Electronic SE, Hirschau, Germany). Air density was calculated from temperature, humidity and air pressure (Davis, 1992). No differences in wind speed (mean = 0.8 $m \cdot s^{-1}$, SD = 0.3 $m \cdot s^{-1}$, P = 0.99) or air density (mean = 1.08 $kg \cdot m^{-3}$, SD = 0.01 $kg \cdot m^{-3}$, P = 0.50) were evident in the tests between the tyres.

Estimation of the C_r and the C_dA with the virtual elevation method

The key concept of the virtual elevation method (Chung, 2012) is to calculate an elevation profile from recorded power output and speed. After using a starting estimate for the C_r and the C_dA, they are adjusted iteratively until the modelled elevation profile optically fits the true one.

The mathematical model used is similar to previously published models (Di Prampero et al., 1979; Martin, Milliken, Cobb, McFadden, & Coggan, 1998; Olds et al., 1993), accounting for the power output to overcome rolling resistance, gravity, acceleration and aerodynamic drag (P = total required power output, η = drivetrain efficiency, v = speed, s = slope, a = acceleration, ρ = air density):

$$P\eta = C_r mgv + smgv + mav + 0.5C_dA\rho v^3$$

Solving the equation for the slope (and thereby modelling the elevation profile) yields:

$$s = \frac{P\eta}{mgv} - C_r - \frac{a}{g} - \frac{C_dA\rho v^2}{2mg}$$

Analysing multiple laps on a short course simplifies the optical fitting, as there is no net elevation change (Figure 2).

Using the virtual elevation method, the participant can vary his speed freely as long as he does not use the brakes.

In this study, we estimated both the C_r and the C_dA in the C_dA tests. Subsequently, the derived mean C_dA of 0.47 m^2 was used as a fixed parameter and only the C_r was estimated in the C_r tests. The drivetrain efficiency η was set to 0.977 for all estimations (Martin et al., 1998).

Calculation of off-road speed

To estimate the influence of the different C_r on MTB XC performance, corresponding off-road speeds were calculated. The same mathematical model of cycling power as in the virtual elevation method was used. Necessary input parameters (ρ, C_dA, m, η) were taken from this study. Two slopes of 0% and 10% were chosen to account for various MTB XC conditions (Impellizzeri & Marcora, 2007; Macdermid & Stannard, 2012).

Data analysis

No tests were excluded due to mean wind speed exceeding 2 $m \cdot s^{-1}$ (Bertucci et al., 2013).

Data analysis was conducted with a statistical software package (R 3.2.2, R Core Team, Vienna, Austria). Estimations of the C_r and the C_dA were conducted with the virtual elevation method implementation in a cycling performance software (Golden Cheetah 3.1, www.goldencheetah.org). All tests were analysed by 3 investigators blinded to the tyre model,

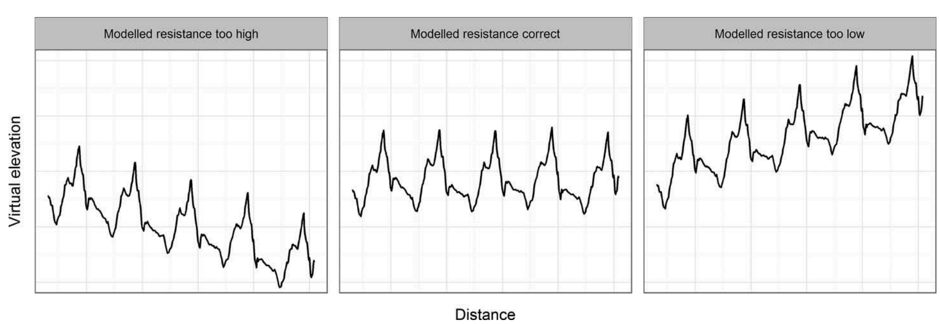

Figure 2. Qualitative visualisation of the virtual elevation method. Figure reproduced with permission from Chung (2012) with data from this study.

and their estimates were averaged for further analysis. Inter-rater agreement was assessed by Bland–Altman plots and Pearson correlations, and overall reliability of the method was calculated as typical error (Hopkins, 2000). Due to the small group sizes and their heteroscedasticity, differences between tyres were assessed with the non-parametric Kruskal–Wallis test (α = 0.05). If not otherwise stated, values are presented as mean [min–max].

Results

Reliability of the virtual elevation method

The overall reliability of a single C_r test (with a fixed C_dA) expressed as typical error was 0.0006 (2.8%). Figure 3 shows the agreement between the optical C_r estimations by the 3 investigators (limits of agreement <0.0005, $r \geq 0.98$).

C_r differences

The mean C_r of the tyres was 0.0219 [0.0205–0.0237] with significant differences between tyres ($P < 0.001$, Figure 4), whereas total mass (81.7 [80.1–82.9] kg, $P = 0.66$), mean power output (177 [151–197] W, $P = 0.06$) and mean speed (22.2 [20.4–23.0] km · h^{-1}, $P = 0.70$) did not differ between tyres in the tests. Furthermore, mean speed was not correlated with the C_r over all tests ($r = -0.08$, $P = 0.56$).

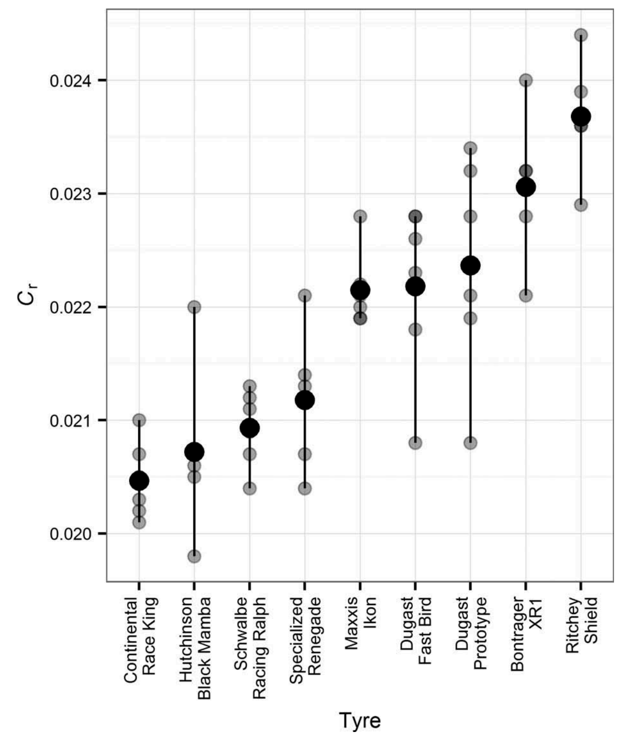

Figure 4. Coefficients of rolling resistance (C_r) by tyre. Transparent points: individual tests, black points: mean value. Main effect of tyre: $P < 0.001$.

Calculated off-road speed

With a slope of 0%, the calculated off-road speed showed an estimated difference, depending on power output, of 1.01–1.04 km · h^{-1} (2.9–3.2%) between the fastest and the slowest tyre. With a slope of 10%, the difference decreased to 0.29–0.32 km · h^{-1} (2.3–2.4%) (Figure 5).

Discussion

Our results showed that the virtual elevation method is a reliable tool to evaluate important differences in off-road rolling resistance between MTB XC tyres as used in international competitions (C_r ranging from 0.0205 to 0.0237). These C_r differences may translate to relevant differences in off-road speeds of up to 2.3–3.2%, depending on power output and slope.

Reliability of the virtual elevation method

The reliability of the virtual elevation method is not directly comparable to other methods, as different measures of off-road rolling resistance have been used (Macdermid et al., 2015). Convincingly, the current study's typical error of 2.8% is substantially lower than the differences between the tyres of 16%.

Apart from the high overall reliability and inter-rater agreement, the virtual elevation method enabled convenient measurements, as the participant could vary his speed freely as long as he did not use the brakes. Furthermore, a course with MTB XC-specific ground surface conditions, not restricted to a horizontal path, could be used.

C_r differences

The current study's mean C_r of 0.022 falls in the expected range for MTB XC tyres, as previous studies reported a ground

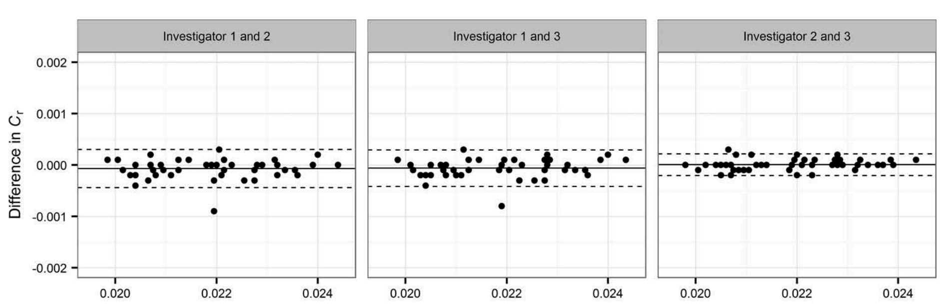

Figure 3. Agreement between the estimations of the coefficient of rolling resistance (C_r) with the virtual elevation method by the 3 investigators. Solid lines represent mean difference, dashed lines represent mean difference ± 1.96 SD of differences.

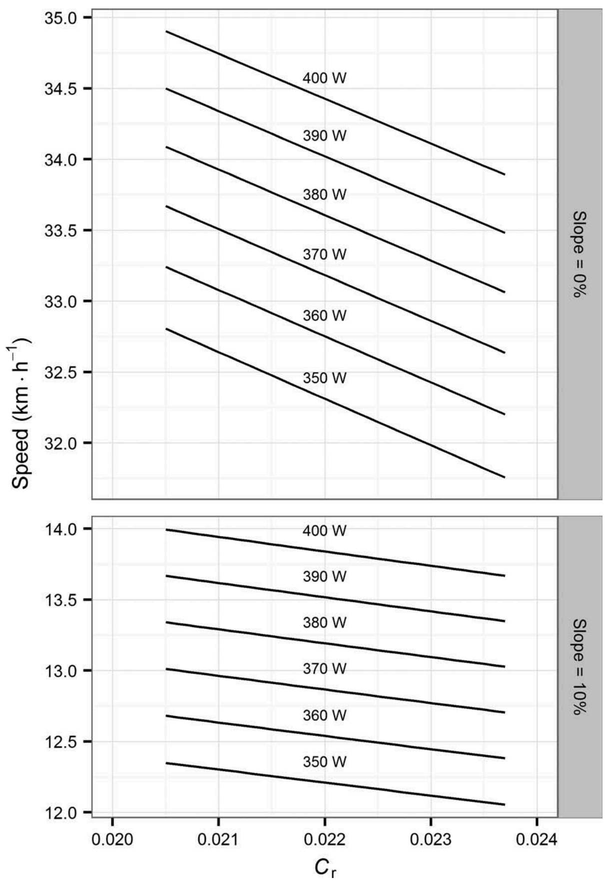

Figure 5. Calculated off-road speed as a function of the coefficient of rolling resistance (C_r) and power output.

surface dependant mean C_r of 0.007 on a road surface, 0.020 on sand and 0.037 on grass (Bertucci & Rogier, 2012) or 0.002–0.030 on various ground surfaces (Steyn & Warnich, 2014). The same authors reported a difference of 21% between the rolling resistance of tyres with a smooth and a rough tread area (Bertucci et al., 2013). Even though the current study tested a rather homogenous group of tyres, the C_r values differed by 16%. Another study, however, reported considerably lower values for the C_r (<0.001), but judged these as unrealistic in combination with very high C_dA values (>2.0 m^2) (Macdermid et al., 2015). In comparison to studies using road bikes, the current study's C_r values are, as expected, considerably higher due to the rougher tread area and ground surfaces (Candau et al., 1999; Grappe et al., 1999; Lim et al., 2011).

Whereas certain influencing factors on rolling resistance already have been studied (Bertucci & Rogier, 2012; Bertucci et al., 2013; Macdermid et al., 2015), future studies should investigate the influence of rubber compound and casing construction.

Calculated off-road speed

The estimated influence on off-road speed by differing C_r is highly relevant and in-line with previous calculations, which emphasises the importance of rolling resistance in MTB XC (Bertucci et al., 2013). Switching from the slowest to the fastest tyre is equivalent to increasing the power output by almost 10 W on a slope of 10%, where the proportion of the power output to overcome rolling resistance amounts to 16–18% of the total power output, according to the model. On a flat section (slope = 0%), the effect is even more pronounced, as over 20 W of additional power output are required to compensate the additional rolling resistance. In this scenario, a high proportion of the total power output (40–48%) is directed to counteract rolling resistance, as gravity is no longer an opposing force.

The influence of the tyre on off-road speed seems comparable to the effect of wheel size. Studies found an increase in speed of around 2–3% with the use of bigger 29-in. wheels in comparison to smaller 26-in. wheels (Macdermid, Fink, & Stannard, 2014; Steiner, Müller, Maier, & Wehrlin, 2016; Steyn & Warnich, 2014). It seems advantageous for performance to combine big wheels with fast rolling tyres.

Limitations

Due to the mathematical model of the virtual elevation method, the C_r and C_dA estimations affect each other. This study used a fixed C_dA for the C_r estimations to limit this source of variability. Furthermore, the mathematical model does not account for the tilted position of the participant when riding curves, potentially biasing the estimations of the resistance parameters.

The C_r values estimated in this study are specific for the test course used, with its different ground surface conditions, and as this study used only 1 set of tyres of every model, its results could be biased by manufacturing variations. Furthermore, the current study cannot explain the cause for the differences in rolling resistance between the tyres (e.g., volume, construction). Even though standardising the tyre pressure enabled to compare the tyres, this may not have resulted in an optimal tyre pressure for each individual tyre.

The calculations of off-road speed are limited to 2 specific conditions and, thereby, do not account for the highly variable nature of a MTB XC course. However, the calculations illustrate the practical differences between the tyres, apart from other important factors, such as the respective grip, cornering control and puncture protection of a tyre.

Conclusion

It can be concluded that the virtual elevation method is a reliable tool to evaluate the off-road rolling resistance of MTB XC tyres, as used in international competitions, on representative ground surface conditions. The differences in rolling resistance between these tyres may translate to relevant differences in off-road speeds of up to 2.3–3.2%, depending on power output and slope.

As new tyres enter the market regularly, testing and comparing them using the virtual elevation method is highly valuable for athletes and coaches before important competitions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by Swiss Cycling and the Swiss Federal Office of Sports, Magglingen.

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