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ORIGINAL INVESTIGATION

Accuracy of Indirect Estimation of Power Output From Uphill Performance in Cycling

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Purpose: To use measurement by cycling power meters (P_{mes}) to evaluate the accuracy of commonly used models for estimating uphill cycling power (P_{est}). Experiments were designed to explore the influence of wind speed and steepness of climb on accuracy of P_{est}. The authors hypothesized that the random error in P_{est} would be largely influenced by the windy conditions, the bias would be diminished in steeper climbs, and windy conditions would induce larger bias in P_{est}. ***Methods:*** Sixteen well-trained cyclists performed 15 uphill-cycling trials (range: length 1.3–6.3 km, slope 4.4–10.7%) in a random order. Trials included different riding position in a group (lead or follow) and different wind speeds. P_{mes} was quantified using a power meter, and P_{est} was calculated with a methodology used by journalists reporting on the Tour de France. ***Results:*** Overall, the difference between P_{mes} and P_{est} was –0.95% (95%CI: –10.4%, +8.5%) for all trials and 0.24% (–6.1%, +6.6%) in conditions without wind (<2 m/s). The relationship between percent slope and the error between P_{est} and P_{mes} were considered trivial. ***Conclusions:*** Aerodynamic drag (affected by wind velocity and orientation, frontal area, drafting, and speed) is the most confounding factor. The mean estimated values are close to the power-output values measured by power meters, but the random error is between ±6% and ±10%. Moreover, at the power outputs (>400 W) produced by professional riders, this error is likely to be higher. This observation calls into question the validity of releasing individual values without reporting the range of random errors.

Keywords: speed, gradient, climbing uphill, Tour de France

It has become popular for journalists, coaches, and sport scientists to use mathematical models to estimate uphill-cycling power output (PO) based on the characteristics of the climb (% grade) and cycling speed. These estimates have been used for a variety of purposes including documenting demands of competition, research linked to climbing power,[1] and speculating whether a cyclist's climbing performance was "unrealistic" and therefore suspicious. Many popular professional cyclists have recently confessed that they have been involved in doping. These revelations may be encouraging speculation by journalists as to whether any current successful professional cyclists are doping, and in their attempts to provide substance to allegations some have turned to estimating climbing power output based on speed and gradient (*Le Monde,* France[2]; *The Guardian,* UK[3]; *The New York Times,* USA[4]). Although many professional cyclists are known to race with power meters, rarely are these data published in a format that would enable the accuracy of predictive models to be evaluated.

PO is now widely used as a training and competition tool in professional cycling. For example, a model based on measured power (P_{mes}), the record power profile, has recently been proposed for monitoring the physical potential of a cyclist through the relationship between the record PO and time.[5,6] There is little doubt that P_{mes} has garnered the greatest interest, and in fact, the most commonly used mobile power meter mounted on bikes (SRM Professional Training System, Schoberer Rad Messtechnik, Jülich, Germany) has demonstrated good accuracy (±2%) when well calibrated.[6]

The values obtained for estimated power (P_{est}) are based on a simple and well-known biomechanical model[7] that incorporates the summing of the POs against the aerodynamic drag (P_{aer}), gravity (P_{grav}), and rolling resistances (P_{roll}), in addition to the friction of the mechanical elements of the bicycle (P_{fri}; Friction Fact Company, www.friction-facts.com), as follows:

$$P_{est} = P_{aer} + P_{grav} + P_{roll} + P_{fri} \qquad \text{(Eq 1)}$$

$$P_{est} = [0.5\rho\, ACd(V_d + V_w)^2 V_d + (M\, g\, h/d)V_d + Cr\, M\, g \cos \alpha Vd] + F_b \qquad \text{(Eq 2)}$$

where ρ is the air density (kg/m^3), ACd is the effective frontal area (m^2), V_d is the cyclist's speed (m/s), V_w is the wind velocity (m/s), M is the total mass of cyclist plus bicycle (kg), h is the total elevation (m), d is the distance covered (m), Cr is the rolling coefficient, g is gravity (9.81 m/s^2), cos α is the angle of the slope, and F_b is the friction associated with drive-train transmission. It is important to note that more sophisticated cycling-performance models have been proposed in the literature.[8–10]

While some of these variables can be measured accurately (V_d, h, d, cos α, F_b), most of them are estimated with variable accuracy (ρ, Cr, M) and are likely to vary during the climb (ACd, V_w).

Several methods have been used to measure rolling and aerodynamic resistances in cycling with estimated reproducibility ranging from 1% to 10%[11]: decelerative,[12] coasting down or towing techniques,[13] wind tunnel,[14] velodrome,[15] or cycling treadmill.[16] It is beyond the scope of this article to report in details all methods. However, it seems clear that slight changes—probably very difficult to observe—can greatly affect both rolling and aerodynamic resistances. According to the technique used by the cyclists, the position on the bike can vary during the climb. Three positions

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may be used according to the environmental conditions, pedaling technique, and/or fatigue: upright (trunk straightened and arms outstretched), aero (elbows bent and head back), and standing (on the pedals). When changing from upright to aero position, the ACd may decrease to 20% (0.34–0.27 m^2). A small lowering of the head in these positions can determine a 5% decrease of the ACd. Varying upright to standing position may increase the ACd up to 20%.[12] The decrease in tire pressure from 10 to 7 kPa can decrease the Cr by 16%.[17] Moreover, during a 5- to 6-hour race between the start and the finish, the decrease in tire pressure can be ~1 kPa. The total PO distribution can be approximated in a 7% climb at an average PO of 350 W as follows (from Eq 1): 9% for P_{aer}, 86% for P_{grav}, 3% for P_{roll}, and 2% for P_{fri}. Therefore, because of the difficulties in quantifying these variables, P_{est} is less likely to be accurate than P_{mes}. However, to the best of our knowledge, the differences between P_{mes} and P_{est} in different environmental conditions are not known, and there is to date no scientific publication assessing the reliability and accuracy of P_{est}. Hence, we used a method published in a 2002 book[18] and, more recently, in a magazine[19] that, although never validated, has been used to determine calculated P_{est} values published in many French newspaper articles.

We hypothesized that the random error in P_{est} estimated by this method would largely be influenced by the environmental conditions of the uphill trial evaluated. Because the component that is likely the most difficult to assess externally is P_{aer}, we also hypothesized that the error would be smaller for steeper climbs (slope >6%), where P_{aer} is reduced due to the decrease in Vd, and that windy conditions (high V_w) would induce greater error in P_{est}.

Methods

Subjects

Sixteen well-trained male cyclists (mean ± SD: age 21 ± 4 y, body mass 67.8 ± 6.6 kg, height 177.8 ± 5.8 cm, peak power output 373 ± 43 W, training volume 12,687 ± 5313 km/y) participated in the study. The study was approved by the institutional ethics committee, and all subjects provided written, voluntary, informed consent before participation.

Experimental Design

Cyclists performed 15 uphill trials (range: length 1.3–6.3 km, slope 4.4–10.7%) in a randomized order with their own bikes under various conditions: alone versus in a small or large group; all in sitting position, all in standing position, or alternating these 2 positions; at constant or irregular velocities. For each trial, the number of cyclists was different (ranging from 10 to 14) and the time was recorded for each subject. Overall, 10 different slopes were used in different windy conditions. Five trials were performed in a small group (n < 4), 5 in a large group (4–14), and 5 alone. Five trials were performed with a voluntary very irregular pacing. Three trials were performed standing. The temperature, barometric pressure, and wind speed, measured by an anemometer (Alba, Silva, Sweden) at the middle of the trial at 1.5 m from the ground, were also recorded.

Each bike was equipped with a mobile power meter (SRM Professional Training System, Schoberer Rad Messtechnik, Jülich, Germany). Subjects were accustomed to using the SRM power meter. The slope of calibration for each SRM was verified using static calibration to determine the relationship between the torque (Nm) and frequency (Hz).[20] The cyclists performed the zero-offset frequency procedure before each trial to obtain accurate PO data.[21] However, despite this zeroing, one cannot rule out that the 15 SRMs may not agree exactly with regard to measuring PO. The accuracy of this device has been reported to be excellent (±2%[21] or ±1.5%[22]).

The data from each trial were transferred from the SRM to a computer using SRM Software (Schoberer Rad Messtechnik, Germany), and the average value of PO (P_{mes}) was calculated.

During the Tour de France, the analyst usually estimates P_{est} from TV records (time at the bottom and top of the climb for Vd, position of the cyclist for estimation of ACd, pacing, and quality of the road surface for Cr), detailed maps (distance, lowest and highest altitudes for h), meteorological records (wind velocity, temperature, barometric pressure, and hygrometry for estimation of ρ), and information obtained from the media (body mass of the cyclist and mass of the bicycle for M).

During the study, the following accurate data were provided to the same experienced analyst: height and M of each rider, duration of the ascent and location of both the start and end of each trial, and temperature and barometric pressure. The analyst was present but did not directly observe the conditions of each trial. However, it was possible for him to see the cyclists seated on their bikes (visual estimation of ACd) and to estimate the wind (V_w) and the road surface (Cr). The analyst determined the distance and elevation from maps (d and h). From these data, he calculated individual P_{est} for each trial as reported[18,19] that were, therefore, as close as possible to the "real world" conditions used for PO estimation during the Tour de France.

Of note, the calculation of P_{mes} and estimation of P_{est} were performed by independent researchers who were blinded to each other's findings.

Statistical Analyses

All variables are presented as mean ± SD. The relationships between P_{mes} and P_{est} were assessed by Pearson product–moment correlation coefficient. The level of determination of agreement between P_{mes} and P_{est} was defined using the method of Bland and Altman.[23] The differences between the measurements performed with the 2 devices were drawn in relation to the mean values, and 95% of the differences were expected to lie between the 2 limits of agreement (95% confidence interval [95% CI]) that were the mean difference ± 2 SD of the differences, expressed as bias ×/÷ random error. The statistical analyses were performed using SigmaPlot 11.0 software (SSI, San Jose, CA, USA). For all variables, statistical significance was accepted at $P < .05$.

Results

For the 15 different trials overall, 161 individual data points were analyzed. P_{mes} versus P_{est} values are PO = 273.8 ± 45.5 versus 271.1 ± 44.2 W, d = 3.51 ± 1.40 versus 3.54 ± 1.40 km, and V_d = 15.7 ± 2.8 versus 15.8 ± 2.9 km/h

Logically, because the duration of the ascent and the location of both start and end of each trial were provided to the analyst, there were high ($r > .995$) correlations between measured and estimated d and V_d. Similarly, there was high correlation ($r = .96$, $P < .001$) between P_{mes} and P_{est} (Figure 1). However, in the current study, the range for PO values was very high (200–400 W; Figure 1), which by definition inflates r^2 to a degree that is not representative of the variability in professional riders' values, which is likely to be much smaller. We performed recalculations on a subsample of all PO values >300 W, and, as might be expected, the strength of the relationships between P_{mes} and P_{est} was reduced ($r^2 = .83$).

Overall, the difference between P_{mes} and P_{est} was –0.95% (95% CI –10.4%, +8.5%) for all trials (Figure 2) and 0.24% (–6.1%, +6.6%) for conditions without wind ($V_w < 2$ m/s; Figure 3). Table 1 shows the bias and the 95% CI between the power measured by SRM and that estimated in various conditions, for example, with low versus high winds, on low versus high slopes, and in slower versus faster riders.

In contradiction to our second hypothesis, we did not find any relationship between bias and percent slope of the trials or any difference in bias (–1.5% vs 0.6%, NS) between high (>6.4%) versus low (<6.4%) slopes.

P_{mes} and P_{est} were not significantly different except in 3 (most windy, $V_w > 5$ m/s) of the 15 trials. However, we did not find a significant relationship between V_w and bias. Finally, we did not find any difference in bias between different conditions of body position (seated vs standing) or grouping (cycling alone vs in small or large groups).

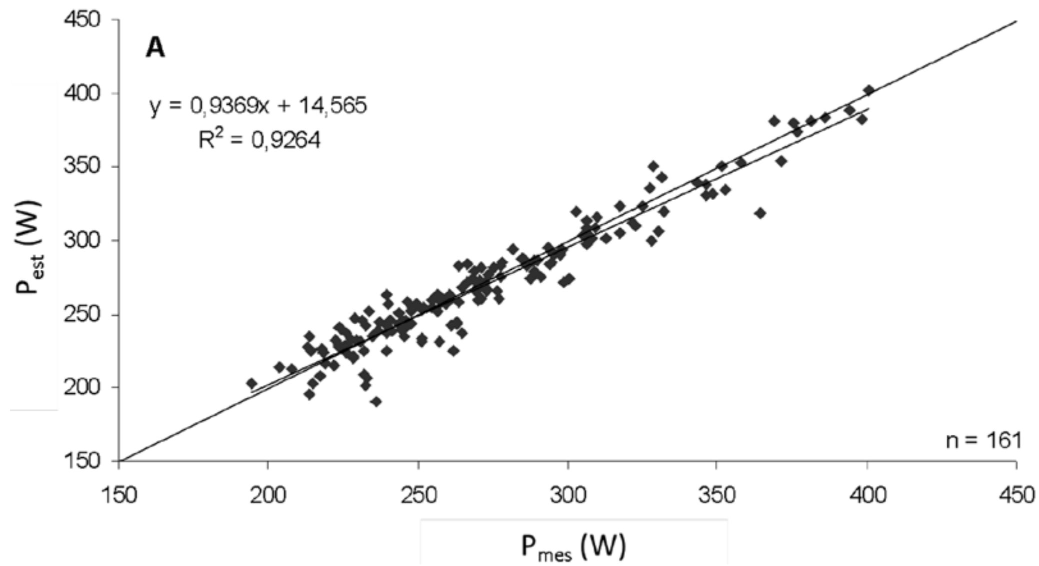

Figure 1 — Relationships between power measured by SRM power meter (P_{mes}) and estimated power output (P_{est}).

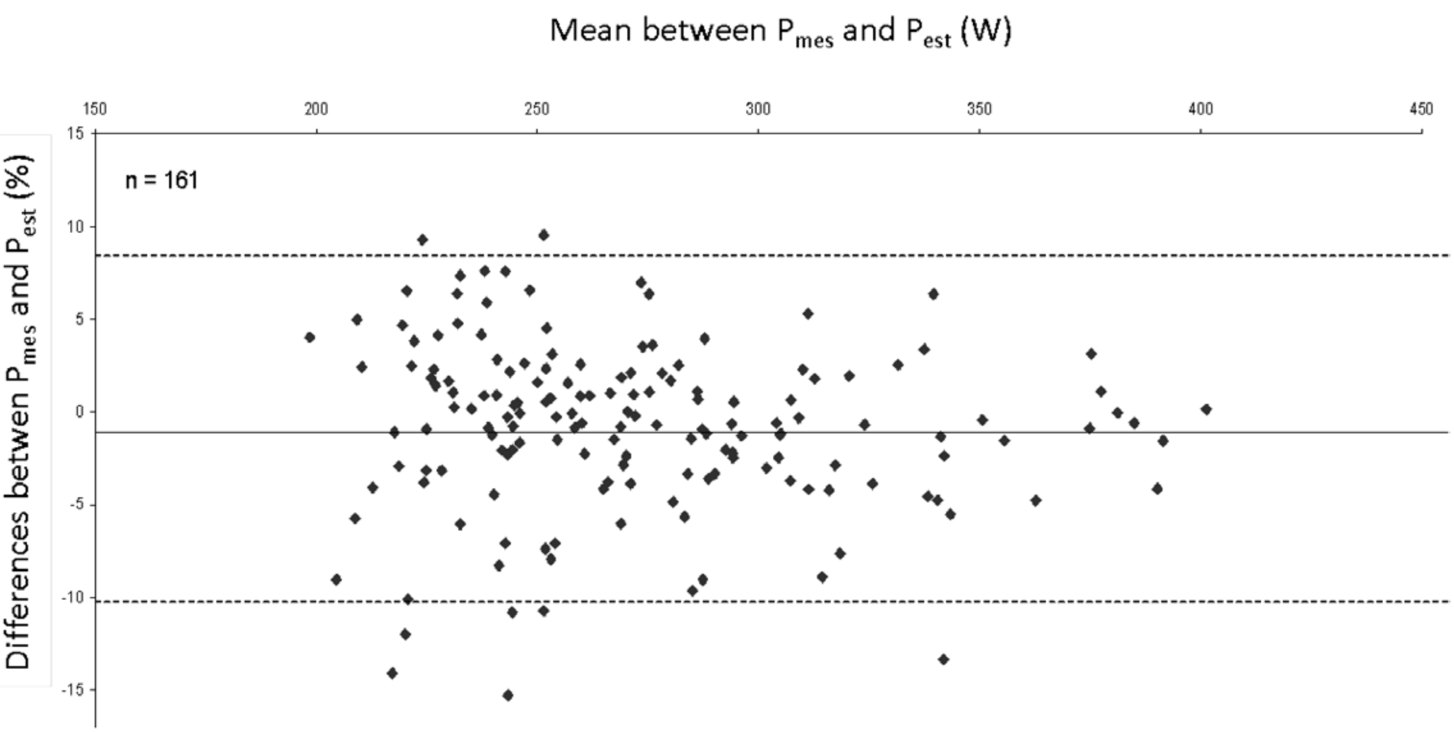

Figure 2 — Bland-Altman plot showing the relationship between the mean measured values for power and the differences (expressed in percentage) in power measured by SRM power meter (P_{mes}) and in estimated power (P_{est}; bias ± random error) in all trials.

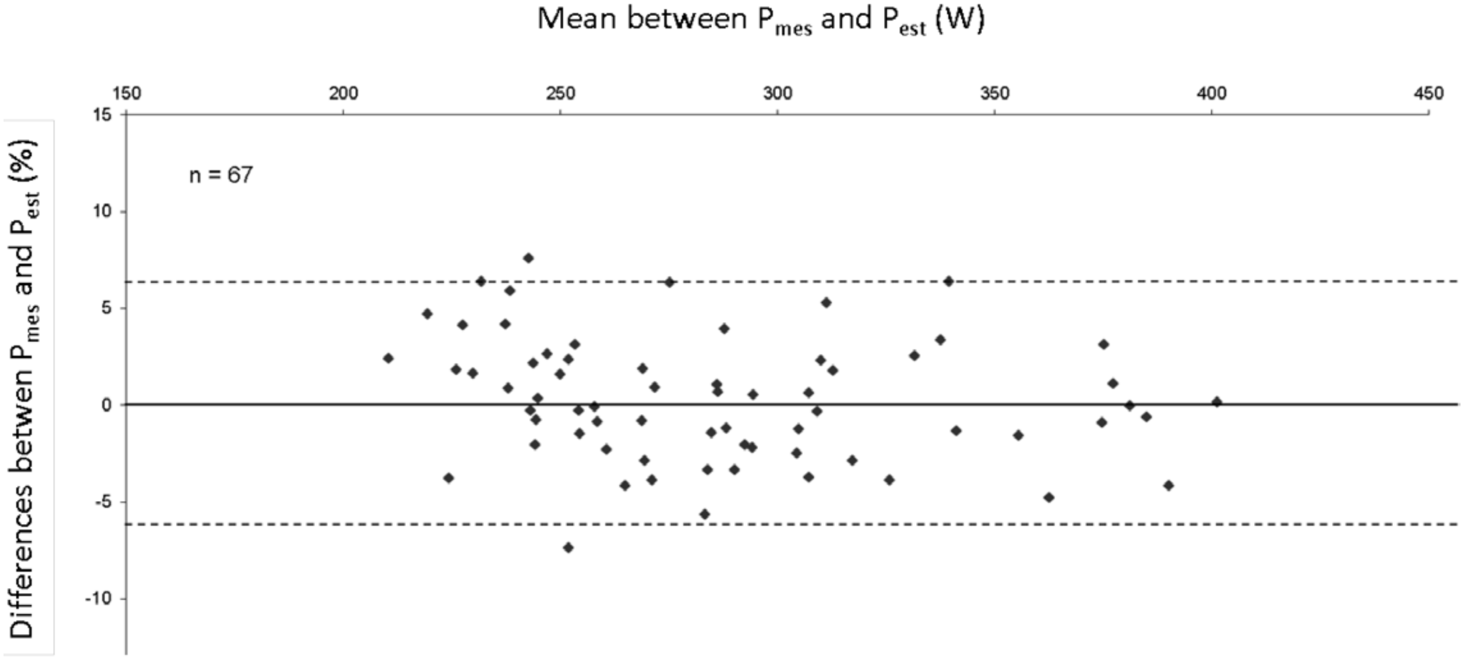

Figure 3 — Bland-Altman plot showing the relationship between the mean measured values for power and the differences (expressed in percentage) in power measured by SRM power meter (P_{mes}) and in estimated power (P_{est}; bias ± random error) in trials without wind (wind velocities <2 m/s).

Table 1 Bias (Differences Expressed as Percentages; Mean ± SD) and 95% Confidence Interval Between Power Measured by SRM Power Meter and Power Estimated Under Various Conditions

	Bias (95% confidence interval)
Low winds (<2 m/s)	0.2% ± 3.2% (–6.1%, +6.6%)
High winds (>5 m/s)	–4.4% ± 7.2% (–18.9%, 10.0%)
Low slopes (4.4–6.4%)	–1.2% ± 5.9% (–12.9%, +10.4%)
High slopes (8.2–10.7%)	–0.8% ± 3.3% (–7.3%, +5.6%)
Slow riders (n = 5)	–0.8% ± 3.9% (–8.4%, +6.9%)
Fast riders (n = 5)	–0.8% ± 5.1% (–10.8%, +9.2%)
All	–0.9% ± 4.8% (–10.4%, +8.5%)

Note: Slow and fast riders were determined on the fastest uphill section as the last and third tertiles in velocity, respectively.

Discussion

The most important findings of the current study are that (1) there is a high correlation between P_{mes} and P_{est} and no differences in nonwindy conditions for uphill trials (with a minimum slope >4.4%); (2) the estimation components of aerodynamic drag (eg, inaccurate estimation of the wind velocity and/or of ACd) are likely to be the most confounding factors, because we found a large increase in random errors in windy versus nonwindy conditions but no relationship between slope and bias; and, finally, (3) the determination of any individual value (in the 95% CI) could not be exact (at least with random errors of ±6%, eg, ±17 W in the current study; ~0.25 W/kg). For example, 1 outlier in Figure 3 had a P_{est} of 253 W for a P_{mes} of 233 W.

We found a high correlation between P_{mes} and P_{est} and no differences in nonwindy conditions. Moreover, the differences in the average values were <1%. These latter results clearly show that it is possible to monitor the changes in PO across a large group of cyclists and that P_{est} is a method with great potential for analyzing trends in cycling-performance changes. This might require a large number of observations (over decades rather than years), due to the low precision of the estimates, which may also change at the group level. In the current study, the range of PO values was high (200–400 W), which did not reflect the values of PO observed in professional cyclists. Recalculated on a subsample of PO values >300 W, the strength of the relationships between P_{mes} and P_{est} was reduced (r^2 = .83). This is a limitation of the current study, and it is likely that in professional cyclists the bias and random errors between P_{mes} and P_{est} would be larger.

In the current study, the analyst estimated P_{est} with the exact M of the subjects. In actual conditions, the inaccuracy in the estimation of M can be ~2% to 3% because the weight of a cyclist is unknown at the exact time of the ascent, especially if it is at the end of a long stage. It is unlikely that the morning weight of a cyclist would change to a great extent during the Tour de France, because the caloric intake is known to provide for the energy expenditure (4000–6000 kcal/day) in Tour de France cyclists.[24] However, during long stages, large decreases in body mass have been reported due to dehydration and/or glycogen depletion (eg, 2.1–4.5 kg, or ~3–5%[25] and 1.2–3.5%,[26] respectively). In addition, the weight of the bike (with bottles) and rider clothing (eg, helmet, shoes, jersey) is approximated.

In the current study, the analyst was also provided with the exact starting and finishing locations of each trial. Therefore, the distance and elevation—and therefore the gradient—traveled by the cyclists were exactly similar for P_{mes} and P_{est}. In real-life situations, it is likely that these data would always be accessible (as in television coverage, for example) and would need to be found elsewhere, which may potentially increase the bias. This is paramount since gradient has a powerful influence on PO. In fact, very good accuracy can be obtained for estimates of distance, start and finish altitudes, and therefore elevation and gradient by using maps or Google Earth. Finally, the analyst was also provided with the exact duration of each trial. In actual conditions, this variable is sometimes not 100% clear and has to be approximated. This would increase the bias to a larger extent than in the current study's conditions.

It is important to report that the random error is ±6% in the best conditions of no wind and is greatly increased (±10%) with significant wind. This result confirms our hypothesis that P_{aer} would be the most difficult component to be defined with precision. This is likely to be primarily due to the changes in V_w and direction (which are very difficult to accurately record in actual conditions) but may also be due to the changes in ACd caused by changes in position (seated vs out of saddle) and to the drafting effect.

Wind shielding has a large effect on PO, but measuring wind speed at 1 point in a race over a limited time may not be precise enough to fully capture the very important confounding potential of wind. Moreover, in competition, gaps between riders constantly change and it is difficult to account for this.

In our study, the highest velocity was 23 km/h and the highest PO was 401 W. It is likely that in professional cyclists who reach much higher V_d and PO, the approximation in P_{aer} would increase the bias reported in the current study, which examined lower-level cyclists. For example, the model[2] shows that for a given rider position, a 1-m/s increase in the front wind results in a 10-W increase in PO. In addition, a poor estimate of ACd can contribute to a large bias, as appeared to be the case with the ACd values used in a 2013 report.[19]

Contrary to our hypotheses, we did not detect greater accuracy in high (>6.4%) versus low (4.4–6.4%) slopes. The speed depends not only on the slope but also on the performance level of the cyclist, which appears highly influential because it directly affects the aerodynamic drag. Our experimental design did not allow us to determine at which level of slope the estimated method becomes unacceptably inaccurate. It is surprising that changes in group or body position did not modify the observed bias between P_{mes} and P_{est}. As a whole, our results support the idea that higher—but not satisfactory—accuracy is achieved in less windy conditions, as in a protected area (eg, a forest). Finally, the current "field" design did not allow us to quantify the errors coming from inaccurate Cr estimation.

The random error (±6%) observed with lower winds corresponds to ±25 W in professional cyclists, who can sustain 30-minute uphill bouts above 400 W. The current study underscores that it is impossible and dishonest to make comparisons between different cyclists and to release individual values such as PO without the corresponding range of random errors. This is an important limitation of the current use of such P_{est} methods as exemplified in the media-reported values for PO calculated from Tour de France ascents and presented as accurate (without any mention of the confidence interval). These values are produced to make comparisons between individual cyclists and feed the debate about the ongoing prevalence or decrease in doping in professional cycling. In our view, such comparisons between individuals are inaccurate. The P_{est} method, which takes into account a large number of observation points, could be used to compare groups of cyclists (eg, over various long cycling periods), but not when based on individual values.

Practical Applications

- In nonwindy conditions, the bias (mean ± SD; 95% CI) between the measured and estimated PO values from ascent performance in cycling based on a biomechanical model is 0.2% ± 3.2% (–6.1%, +6.6%).
- The slope, cyclist body position, and group size appear to have little influence on the accuracy of P_{est}, while the aerodynamic drag (eg, wind shielding dependent on wind velocity and orientation, ACd, drafting, and speed) is the most confounding factor.
- The mean estimated values are close to the PO values measured by power meters, but the random error is between ±6% and ±10%. This finding calls into question the validity of releasing individual values without also providing the range of random errors, but it does allow for the comparison of group values obtained from a large number of observation points.
- The systematic collection and analysis of P_{mes} values—at least on the main tours (Vuelta, Giro, Tour de France)—by independent experts would clarify the debate on performance evolution in professional cycling.

To conclude, when a relatively large group of well-trained cyclists ride uphill, the average PO for the group can be estimated with an acceptable level of accuracy (<0.25% error). However, this margin of error increases to ~1% during windy conditions, and, more important, in some cyclists the error between P_{mes} and P_{est} was greater than 6%. Although aerodynamic drag may have one of the biggest influences on the accuracy of P_{est}, it is also possible that rolling resistance, estimated mass, drive-train transmission efficiency, estimation of hill gradient, and total distance traveled could also influence accuracy. Those interested in better understanding hill-climbing PO need to recognize the many limitations associated with estimating uphill-cycling PO during important competitions such as the Tour de France.

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