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Allometric scaling of peak power output accurately predicts time trial performance and maximal oxygen consumption in trained cyclists

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ABSTRACT

Objective The purpose of this study was to determine if peak power output (PPO) adjusted for body mass$^{0.32}$ is able to accurately predict 40-km time trial (40-km TT) performance.

Methods 45 trained male cyclists completed after familiarisation, a PPO test including respiratory gas analysis, and a 40-km TT. PPO, maximal oxygen consumption (VO_{2max}) and 40-km TT time were measured. Relationships between 40-km TT performance and (I) absolute PPO (W) and VO_{2max} (l/min), (II) relative PPO (W/kg) and VO_{2max} (ml/min/kg) and (III) PPO and VO_{2max} adjusted for body mass (W/kg$^{0.32}$ and ml/min/kg$^{0.32}$, respectively) were studied.

Results The continuous ramp protocol resulted in a similar relationship between PPO and VO_{2max} (r=0.96, p<0.0001) compared with a stepwise testing protocol but was associated with a lower standard error of the estimated when predicting VO_{2max}. PPO adjusted for body mass (W/kg$^{0.32}$) had the strongest relationship with 40-km TT performance (s) (r=−0.96, p<0.0001). Although significant relationships were also found between absolute (W) and/or relative PPO (W/kg) and 40-km TT performance (s), these relationships were significantly weaker than the relationship between 40-km TT performance and PPO adjusted for body mass (W/kg$^{0.32}$) (p<0.0001).

Conclusions VO_{2max} can be accurately predicted from PPO when using a continuous ramp protocol, possibly even more accurately than when using a stepwise testing protocol. 40-km TT performance (s) in trained cyclists can be predicted most accurately by PPO adjusted for body mass (W/kg$^{0.32}$). As both VO_{2max} and 40-km TT performance can be accurately predicted from a PPO test, this suggests that (well)-trained cyclists can possibly be monitored more frequently and with fewer tests.

INTRODUCTION

Performance tests which measure a cyclist's training status and are used to prescribe training have been used since the early 1900s.[1–5] As maximal oxygen consumption (VO_{2max}) is related to exercise capacity,[6] VO_{2max} has rapidly become the most popular measurement to determine training status in athletes, such as runners and cyclists.[7–10] However, this parameter loses its accuracy to predict training status in a homogeneous group of well-trained cyclists.[11 12] In response, the measurement of peak power output (PPO) has gained popularity as a marker of training status.[7 13 14] PPO can either be expressed as an absolute (W) or relatively to body mass (W/kg), the latter being a predictor of a climbing capacity.[7] In addition, a cyclist's endurance capacity is normally tested by performing a laboratory-based time trial.[14] The 40-km time trial (40-km TT) test has shown to be reliable[12 15] and able to detect small meaningful changes in well-trained and elite cyclists.[16–18]

Although the performance parameters measured during these tests are valuable and potentially could assist in refining training programmes, these tests (VO_{2max}, PPO and 40-km TT) are strenuous and are therefore not practical for monitoring purposes. As a consequence, these tests are normally only performed twice or three times per season.[19] However, if one test could accurately predict other performance indicators, the volume of testing per session could decrease and possibly allow more frequent testing (monitoring). Accordingly, Hawley and Noakes[11] developed a stepwise protocol and reported a strong relationship between PPO and VO_{2max} (r=0.97), which allows the prediction of VO_{2max} from PPO. In addition, Hawley and Noakes[11] also reported a good relationship between PPO and 20-km TT time (r=−0.91) in a small group of male and female cyclists (n=19), suggesting that PPO can also predict endurance cycling capacity. However, when PPO within this study was expressed in relative terms, the relationship between PPO (W/kg) and 20-km TT performance became substantially weaker (r=−0.67). A similar finding was reported by Balmer *et al*[20] who reported a strong relationship between absolute PPO (W) and mean power measured during a 16.1-km flat time trial (r=0.99, n=16), but when 40-km TT time was compared with PPO, a significantly weaker relationship was found (r=−0.46). A possible explanation for these discrepancies could be that the effect of body mass was not considered appropriately when determining the relationships between PPO and time trial performance.

In support of this, Swain has shown that body mass is an advantage when performing a flat time trial and is a disadvantage for climbing cycling capacity.[21 22] Based on these findings, Swain has suggested that body mass should be adjusted to the power of 0.32 when predicting flat time trial performance.[21 22] Subsequently, Mujika and Padilla[9] have used this allometric scaling method profiling 24 professional road cyclists. This study showed that PPO adjusted for body mass (W/kg$^{0.32}$) was the strongest predictor of time trial specialists, which supports Swain's allometric scaling method to predicting endurance cycling capacity.

Although this method has the potential to predict endurance cycling capacity, to our knowledge no study has confirmed the accuracy of this method in a large group of trained cyclists. Therefore, the aim of this study was to determine whether PPO or VO_{2max} adjusted for body mass ($W/kg^{0.32}$, $ml/min/kg^{0.32}$, respectively) is able to more accurately predict 40-km TT performance than absolute PPO (W) or VO_{2max} (l/min) or relative PPO (W/kg) or VO_{2max} (ml/min/kg). A secondary aim was to confirm whether VO_{2max} can also be accurately predicted from PPO when using a continuous ramp protocol.

METHODS

Forty-five competitive male cyclists of varying training status were recruited for this study. Subjects had a competitive cycling history of 8±5 years, ranging from 2 to 21 years, and trained on average 10±3 h per week, ranging from 5 to 20 h per week. Prior to participation, all cyclists completed a Physical Activity Readiness Questionnaire (PAR-Q)[23] and signed a written informed consent. Ethical approval for the study was provided by the Research and Ethics Committee of the Faculty of Health Sciences of the University of Cape Town. The principles of the World Medical Association Declaration of Helsinki and the American College of Sports Medicine Guidelines for Use of Human Subjects were adopted in this study.[24]

In the 2 weeks before the performance tests, all subjects completed a PPO test, including gas analysis, and the 40-km TT test for familiarisation purposes. Subjects were asked to refrain from eating for 2 h before the test and from drinking any caffeine 3 h before the test. Measurements including height, weight and seven skinfolds (triceps, biceps, supra-iliac, subscapular, calf, thigh and abdomen)[25] were performed at the start of the study while body fat percentage was calculated.[26] All tests were performed on Computrainer cycle ergometers (Computrainer Pro 3D; RacerMate, Seattle, Washington, USA), which were calibrated before each test as recommended and described previously.[12] The 40-km TT test was performed 72 h after the PPO test. All performance tests were conducted under stable environmental laboratory conditions (21.9±1.0°C, 51±4% relative humidity, 102.1±0.7 kPa).

PPO test

The PPO test, which included respiratory gas analysis, was started 8 min after a standardised warm-up period, known as the Lamberts and Lambert Submaximal Cycle Test (LSCT).[12 19] The starting work rate of the PPO test was set at 2.50 W/kg and was thereafter increased continuously at a rate of 20 W/min.[12] The end of the PPO test was defined as the point where the cyclist could no longer maintain a cadence higher than 70 revolutions per min (rpm). The online breath-by-breath gas analyzer (Oxycon pro, Viasis, Hoechberg, Germany), which has been shown to be valid and accurate,[27] was warmed-up and calibrated as prescribed by the manufacturer. Data were collected over 15-s intervals, while VO_{2max} was determined as the highest recorded reading for 30 s. PPO was determined as the mean power output during the final minute of the PPO test. PPO and VO_{2max} adjusted for body mass to the power of 0.32 were expressed as $PPO^{0.32}$ ($W/kg^{0.32}$) and $VO_{2max}{}^{0.32}$ ($ml/min/kg^{0.32}$), respectively. For example, a subject who weighs 70 kg and has a PPO of 350 W has a relative power of 350/70 = 5.0 W/kg and a $PPO^{0.32}$ of $350/70^{0.32} = 89.9\ W/kg^{0.32}$.

40-km time trial test

The 40-km time trial (40-km TT test) was performed on a simulated 40-km flat time trial course, which was created on the Computrainer system and was started 3 min after a standardised warm-up period (LSCT).[12 19] Subjects were allowed to drink water *ad libitum* and were asked to complete the distance as fast as possible. In an attempt to control for any pacing strategies, the subjects were only given their completed distance and were not given any feedback about other aspects of their performance, such as power output, time or speed. No verbal encouragement was given during the time trial, except for the last kilometre when the distance was counted down in 100-m sections and during the last 100 m in 10-m sections.

Power output, speed, cadence and elapsed time were measured and stored by the Computrainer software at a rate of 34 Hz. Heart rate data during these tests were captured continuously with Suunto T6 heart rate monitors (Suunto Oy, Vantaa, Finland) and calculated into 2-s averages. Analysis of performance data was performed using CyclingPeaks analysis software (WKO+ edition, Version 2.1, 2006, Lafayette, Colorado, USA) and the Computrainer coaching Software (Version 1.5.308; RacerMate). Heart rate data were analysed with Suunto Training Manager (Version 2.1.0.3; Suunto Oy).

Statistical analysis was performed using STATISTICA version 10.0 (Stat-soft, Tulsa, Oklahoma, USA). All data are expressed as mean±SD. Relationships between PPO and VO_{2max} and 40-km TT were assessed with Pearson's product–moment correlation (GraphPad Prism version 5.02 for Windows, GraphPad Software, San Diego, California, USA). In addition, 95% CI were calculated for all relationships. Statistical differences between the slopes of relationships were analysed with the use of Graphpad software.

RESULTS

The general characteristics and performance parameters of the 45 trained cyclists are shown in table 1.

The relationships between absolute PPO (W) and absolute VO_{2max} (l/min) and relative PPO (W/kg) and relative VO_{2max} (ml/min/kg) are shown in figure 1. Significant relationships were found between absolute PPO and VO_{2max} (r=0.96 (95% CI 0.93 to 0.98), p<0.0001) and relative PPO and VO_{2max} (r=0.94 (95% CI 0.89 to 0.97), p<0.0001).

Table 1 Descriptive and performance data of the 45 trained cyclists

Variable	Mean±SD	Range
Descriptive data		
Age (years)	32±6	20–45
Height (cm)	180.7±7.4	167.0–194.0
Body mass (kg)	76.8±7.5	58.5–92.0
Body fat (%)	14.4±2.6	9.4–19.9
Sum of skinfolds (mm)	66.2±13.8	43.3–95.6
Training hours per week	10±3	5–20
Training years	8±5	2–21
Peak power output test		
PPO (W)	381±42	265–470
PPO (W/kg)	5.0±0.5	3.8–6.1
PPO ($W/kg^{0.32}$)	95.1±9.4	72.1–155.1
VO_{2max} (l/min)	4.4±0.5	2.9–5.6
VO_{2max} (ml/min/kg)	57.3±6.2	45.3–72.5
VO_{2max} ($ml/min/kg^{0.32}$)	1093.9±121.5	782.8–1375.2
Respiratory exchange ratio $_{max}$	1.22±0.04	1.15–1.32
40-km time trial test		
Time (s)	3964±181	3584–4471
Average power (W)	254±32	166–331
Cadence (rpm)	92±6	82–107

PPO, peak power output; rpm, revolutions per minute; VO_{2max}, maximal oxygen consumption; W, wattage.

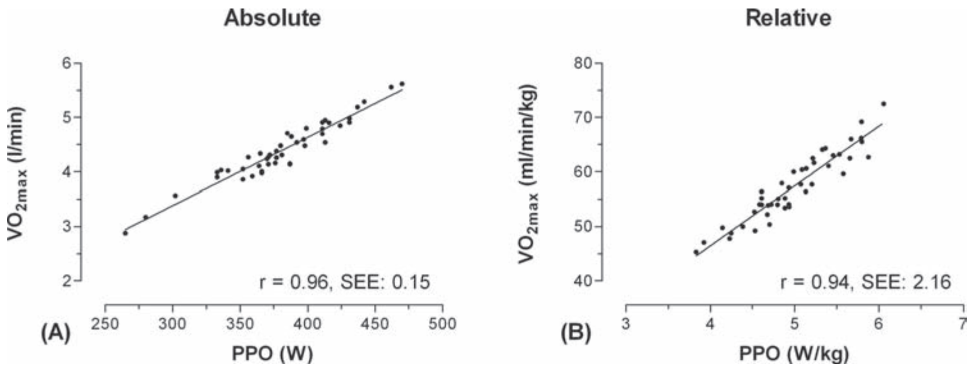

Figure 1 The relationship between absolute peak power output (PPO) and absolute VO_{2max} (A) and relative PPO and relative VO_{2max} (B).

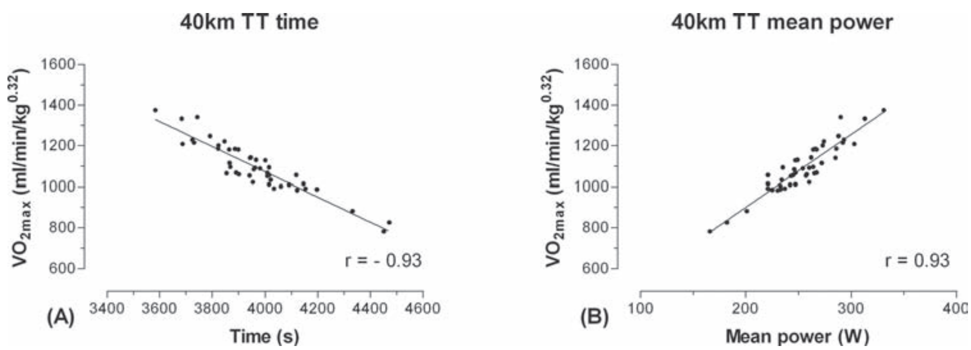

Figure 2 The relationship between adjusted relative VO_{2max} (ml/min/kg$^{0.32}$) and 40-km time trial (40-km TT) time (A) and mean power output during the 40-km TT (B).

Both relationships between PPO and VO_{2max} were linear and are characterised by the following regression equations:

Absolute

VO_{2max} (l/min) = [0.01251 × PPO (W)] − 0.3680

The SEE of VO_{2max} (l/min) from PPO (W) is 0.15 l/min.

Relative

VO_{2max} (ml/min/kg) = [10.97 × PPO (W/kg)] + 2.598

The SEE of VO_{2max} (ml/min/kg) from PPO (W/kg) is 2.16 ml/min/kg.

VO_{2max} adjusted for body mass ($VO_{2max}^{0.32}$) and 40-km TT performance

The relationships between VO_{2max} adjusted for body mass (ml/min/kg$^{0.32}$) and 40-km TT performance expressed as time or as mean power (PO) are shown in figure 2A,B, respectively. Significant relationships were found between both $VO_{2max}^{0.32}$ and 40-km TT time ($r=-0.93$ (95% CI −0.88 to −0.96), $p<0.0001$) and $VO_{2max}^{0.32}$ and average 40-km TT PO ($r=0.93$ (95% CI 0.88 to 0.96), $p<0.0001$).

The relationship between $VO_{2max}^{0.32}$ and 40-km TT time and mean 40-km TT PO were characterised by the following regression equations:

40-km TT time

40-km TT time (s) = [−1.398 × $VO_{2max}^{0.32}$ (ml/min/kg$^{0.32}$)] + 5496

The SEE of 40-km TT time (s) from $VO_{2max}^{0.32}$ is 70 s.

Mean 40-km TT PO

40-km TT PO (W) = [0.2416 × $VO_{2max}^{0.32}$ (ml/min/kg$^{0.32}$)] − 9.864

The SEE of mean 40-km PO (W) from $VO_{2max}^{0.32}$ is 12 W.

PPO adjusted for body mass ($PPO^{0.32}$) and 40-km TT performance

In figure 3A,B, the relationships between PPO adjusted for body mass (W/kg$^{0.32}$) and 40-km TT time and mean 40-km TT PO are shown. Even stronger relationships were found between the relative $PPO^{0.32}$ and 40-km TT time ($r=-0.96$, 95% CI −0.93 to −0.98, $p<0.0001$) and average 40-km TT power ($r=0.92$, 95% CI 0.86 to 0.96, $p<0.0001$).

The relationships between $PPO^{0.32}$ and 40-km TT time and mean PO were characterised by the following regression equations:

40-km TT time

40-km TT PO (W) = [−18.56 × $PPO^{0.32}$ (W/kg$^{0.32}$)] + 5740

The SEE of 40-km TT time (s) from $PPO^{0.32}$ is 52 s.

Mean 40-km TT power

Mean 40-km TT power (W) = [3.102 × $PPO^{0.32}$ (W/kg$^{0.32}$)] − 40.53

The SEE of mean 40-km Power (W) from $VO_{2max}^{0.32}$ is 12 W.

Other findings

Significant differences in slope ($p<0.01$) showed that $PPO^{0.32}$ is able to predict 40-km TT performance more accurately than $VO_{2max}^{0.32}$. In addition to $PPO^{0.32}$, the relationships between

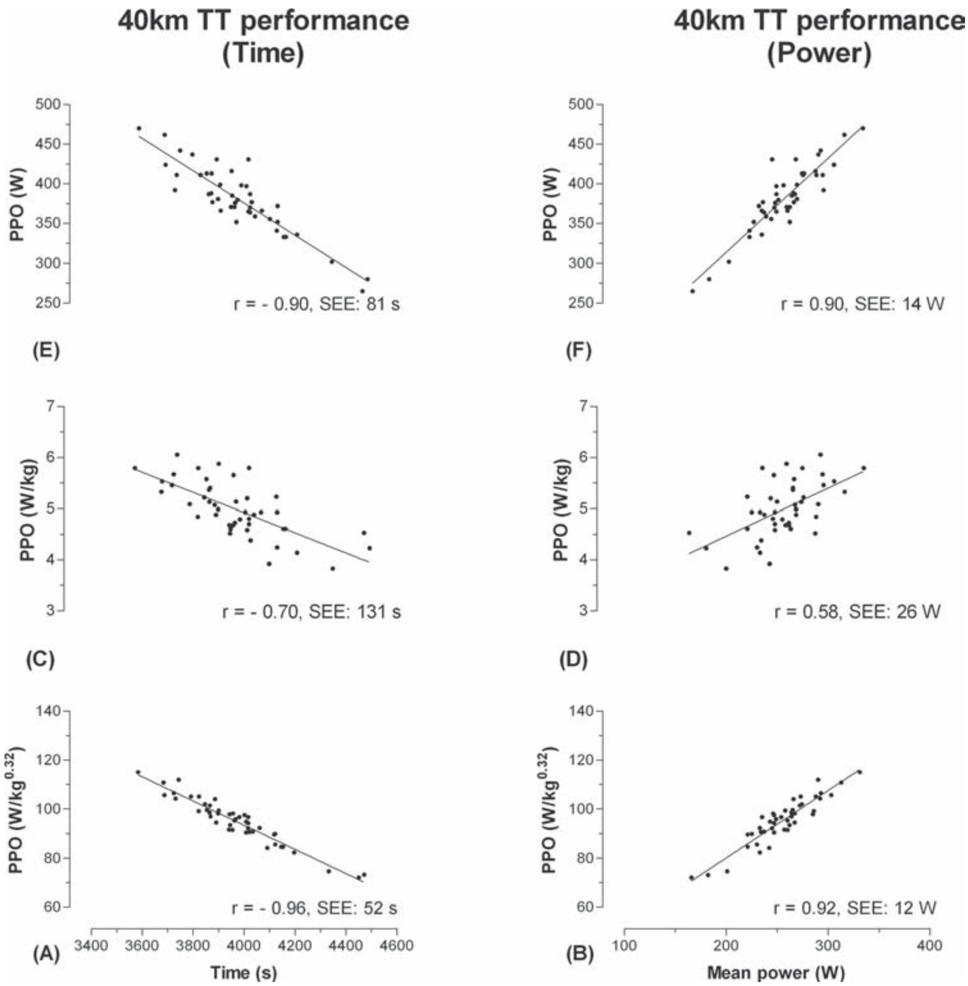

Figure 3 The relationship between adjusted relative peak power output (PPO) (W/kg$^{0.32}$) and 40-km time trial (40-km TT) time (A) and mean power output during the 40-km TT (B), relative PPO (W/kg) and 40-km TT time (C) and mean power output during the 40-km TT (D) and, absolute PPO (W) and 40-km TT time (E) and mean power output during the 40-km TT (F).

40-km TT performance and absolute and relative PPO were also determined (figure 3C–F). Significant relationship were found between absolute PPO (W) and 40-km TT performance (time: r=−0.90, 95% CI −0.83 to −0.95, p<0.0001, SEE: 81 s; mean power: r=0.90, 95% CI 0.83 to 0.95, p<0.0001, SEE: 14 W) (figure 3E,F) and, also relative PPO (W/kg) and 40-km TT performance (time: r=−0.70, 95% CI −0.51 to −0.82, p<0.0001, SEE: 131 s; mean power: r=0.58, 95% CI 0.35 to 0.75, p<0.0001, SEE: 26 W) (figure 3C,D). However, significant differences in slope revealed that the relationships between 40-km TT performance and absolute and relative PPO (both p<0.001), were weaker than the relationship between 40-km TT performance and PPO$^{0.32}$.

DISCUSSION

The first important finding of this study was the strong relationship between PPO and VO_{2max} either expressed in absolute (r=0.96 (l/min)) or relative (r=0.94 (ml/min/kg)) terms. These findings are similar to the findings by Hawley and Noakes,[11] who used a stepwise testing protocol instead of a continuous ramp protocol and reported a significant relationship between absolute PPO and VO_{2max} of r=0.97 (l/min). Although the regression equations are different, this finding confirms that VO_{2max} can be predicted from PPO determined by both a stepwise and/or continuous ramp protocol. As the standard error of estimate (SEE) of the predicted VO_{2max} in the current study (SEE 3%) is lower than the SEE in the study of Hawley and Noakes (SEE 6%), this finding suggests that PPO measured by a continuous ramp is slightly more reliable and able to predict VO_{2max} more accurately. However, other factors such as a different sample population or improved/new equipment for measuring PPO and/or VO_{2max} more accurately could also explain this finding.

The main finding of this study was that both $VO_{2max}{}^{0.32}$ and PPO$^{0.32}$ are able to accurately predict 40-km TT performance (r=−0.93 and r=−0.96, respectively). The strongest relationship and the lowest SEE when predicting 40-km TT performance was found when PPO was adjusted for body mass (W/kg$^{0.32}$) (r=−0.96, SEE: 52 s). This finding supports the allometric scaling method proposed by Swain.[21] In addition, Swain reported a strong relationship between 40-km TT time and 40-km TT PO (r=−0.94),[21] suggesting that both 40-km TT time and PO should be accurately predicted from PPO$^{0.32}$. This is similar to our findings, which show a strong relationship between PPO and both 40-km TT time (r=−0.96, 95% CI −0.93 to −0.98, p<0.0001) and 40-km TT PO (r=0.93, 95% CI 0.86 to 0.96, p<0.0001). The finding by Muijka and Padilla,[9] who reported that PPO$^{0.32}$ was the strongest predictor of time trial specialists, also support the proposed allometric scaling method of Swain to predict flat time trial performance. However, the

What is already known on this topic

Previous research has shown that there is a relationship between peak power output (PPO) and time trial performance. However, these findings seem to be inconclusive and vary when time trial performance is expressed in different units (eg, time or mean power). A possible explanation can be that the advantage of body mass is not correctly considered when determining the relationship between PPO and time trial performance. It has been suggested that PPO and maximal oxygen consumption (VO_{2max}) should be adjusted for body mass to the power of 0.32 to accurately predict flat time trial performance.

What this study adds

This study shows that PPO adjusted for body mass to the power of 0.32 ($W/kg^{0.32}$) predicts 40-km time trial performance more accurately than absolute (W) or relative PPO (W/kg). In addition both absolute and relative PPO were able to predict VO_{2max}, suggesting that a single PPO test can potentially be used to determine a cyclist's peak and endurance cycling capacity. As a PPO test is relatively easy to conduct (minimal amount of equipment and limited side effects on normal training and racing habits), the current established relationships possibly allow a more regular monitoring programme for well-trained and elite cyclists in addition to submaximal monitoring programmes.

current study is the first study to compare the relationships between 40-km TT performance and absolute PPO (W), relative PPO (W/kg) and $PPO^{0.32}$ ($W/kg^{0.32}$). As $PPO^{0.32}$ ($W/kg^{0.32}$) had a significantly better relationship with 40-km TT performance than absolute and relative PPO (both $p<0.001$), the allometric scaling method is able to more accurately predict flat 40-km TT performance in a heterogeneous group of trained cyclists.

As the current study only shows that $PPO^{0.32}$ is able to predict flat 40-km TT performance performed on a cycle ergometer, future research studies need to determine the capacity of $PPO^{0.32}$ to predict outdoor 40-km TT performance, as also suggested by Nevill *et al*.[28] However, as the main aim of 40-km TTs is to determine and monitor changes in the endurance cycling capacity, $PPO^{0.32}$ seems to be the most accurate prediction method. As we have conducted our research on a fairly heterogeneous group of trained cyclists (coefficient of variation for VO_{2max} was 11%), it is not known if the relationship between $PPO^{0.32}$ and 40-km TT is similar in a homogeneous group of elite cyclists, particularly since with this group other factors like cycling efficiency might also contribute to endurance cycling capacity.

In conclusion, the findings of this study show that in addition to PPO, both 40-km TT performance and VO_{2max} can be accurately predicted from a single PPO test. This suggests that the number of tests needed to determine a cyclist's cycling capacity (peak and endurance) can possibly be reduced to a PPO test. In addition, minimal equipment is needed to perform a PPO, the duration of a PPO test is short (in most cases ranging from 8 to 12 min) and a cyclist recovers relatively quickly from a PPO test (in comparison to a TT). Collectively, this suggests that a 20 W/min continuous ramp PPO protocol can be used more frequently to monitor changes in PPO, VO_{2max} and 40-km TT performance in (well)-trained and elite cyclists. However, it seems unlikely that it can fully replace submaximal cycle tests, such as the LSCT which can be performed on a weekly basis in elite cyclists.[19 29]

In summary, this study shows that $PPO^{0.32}$ ($W/kg^{0.32}$) is able to predict laboratory 40-km TT performance/endurance capacity in trained cyclists more accurately than absolute PPO (W) and/or relative PPO (W/kg). In addition, PPO (absolute and relative) determined during the same continuous ramp protocol PPO test, is able to accurately predict VO_{2max}. These findings suggest that in addition to PPO, both VO_{2max} and endurance cycling capacity can be predicted from a single PPO test.

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Competing interests None.

Ethics approval This study was conducted with the approval provided by the Research and Ethics Committee of the Faculty of Health Sciences of the University of Cape Town.

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