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Original investigation

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Abstract

A large number of power meters were produced on the market for nearly 20 years and according to user requirements. **Purpose:** This study aimed to determine the validity, sensitivity, reproducibility and robustness of the Powertap (PWT), Stages (STG) and Garmin Vector (VCT) power meters in comparison with the SRM device. **Methods:** A national-level male competitive cyclist was required to complete three laboratory cycling tests that included a sub-maximal incremental test, a sub-maximal 30-min continuous test and a sprint test. Two additional tests were performed: the first on vibration exposures in the laboratory and the second in the field. **Results:** The VCT provided a significantly lower 5 s power output (PO) during the sprint test with a low gear ratio compared with the PO_{SRM} (-36.9%). The PO_{STG} was significantly lower than the PO_{SRM} within the heavy exercise intensity zone (zone 2, -5.1%) and the low part of the severe intensity zone (zone 3, -4.9%). The PO_{VCT} was significantly lower than the PO_{SRM} only within zone 2 (-4.5%). The PO_{STG} was significantly lower in standing position than in the seated position (-4.4%). The reproducibility of the PWT, STG and VCT was similar to that of the SRM system. The PO_{STG} and PO_{VCT} were significantly decreased from a vibration frequency of 48 Hz and 52 Hz, respectively. **Conclusions:** The PWT, STG and the VCT systems appear to be reproducible, but the validity, sensitivity and robustness of the STG and VCT systems should be treated with some caution according to the conditions of measurement.

Keywords: Mobile power meter, power output, comparison, laboratory, field, cycling.

Introduction

A large number of power meters were produced on the market for nearly 20 years and according to user requirements. The use of power meters enables the assessment of cyclists' training¹ and racing² intensity zones according to their skills and thus to their race performance profile³. These data enable the coach and athlete to have measurements of intensity in real cycling locomotion in the field, thus allowing training programs to be optimised using power output (PO). To be used, power meters should provide a valid, sensitive, reproducible and robust PO⁴. Validity is the ability of power meters to reflect what it is designed to measure⁵. Sensitivity is the smallest measurement change that can be detected by power meters. Reproducibility refers to the variation in measurements made on power meters under changing conditions⁶. Finally, robustness is the ability of power meters to remain unaffected by small variations of experimental factors.

The SRM power meter (SRM, Schoberer Rad Messtechnik, Julich, Germany) is the most commonly used system in cycling, particularly in professional and amateur racing. Indeed, eight of the 2016 UCI WorldTeams use the SRM power meter while seven different power meters (Pioneer, Rotor, Quarq, 4iiii, Power2Max, Stages and Shimano) are used in the remaining ten WorldTeams. The SRM system is a crankset that includes a number of strain gauges (4-20 depending on the model used) located between the crank axle and the chainring. The SRM is considered as a gold standard measurement system due to its high validity, reliability and sensitivity during the measure ($\pm 1\%$ average error after calibration procedure performed under standard environmental conditions)^{7,8}. This 1% average error represents changes in PO measurements of 2 W in endurance (200 W) and 20 W during sprints (2000 W). Additionally, the SRM is one of the few power meters that can be calibrated by the user to increase the accuracy of the PO measurement. However, the high cost of the SRM has led manufacturers to develop less expensive mobile cycling power meters. Some of them have

been studied for their validity and reliability (Powertap⁴, Max one⁹, Polar S710¹⁰, Ergomo¹¹ and Look Keo Power¹²), but other newer power meters have not yet been studied. As a valid and reliable device, the SRM has been used as a reference system to validate previous mobile power meters and stationary ergometers, such as the Kingcycle cycle ergometer¹³ and the Axiom Powertrain cycle ergometer¹⁴.

The Powertap (PWT, Saris Cycling Group, Madison, USA) is also considered a valid and reliable power meter when compared with the SRM⁴ or a dynamic calibration rig⁷. The PWT device measures the PO with strain gauges located in the hub of the rear wheel. The new Stages (STG, Stages Cycling, Saddleback Ltd., UK) and Garmin Vector (VCT, Olathe, USA) power meters are less known power meters. The STG power meter uses only the left crank arm for the PO measurement. The strain gauges are integrated into a small plastic case bonded to the rear side of the left crank arm. As the crank measures the PO on the left side only, the algorithm for power calculation doubles this value to obtain a complete reading for both the left and right sides¹⁵. In the VCT power meter, PO is measured at the pedals where force is applied. The VCT measures the slight deflection of the pedal spindle though the entire pedal stroke as well as the 2D force vectors; these data are used to calculate power. The force sensors are housed in both pedals, so that they can independently measure power from each leg and report the total PO considering the balance between both left and right legs.

This study aimed to assess the validity, sensitivity, reproducibility and robustness of the PWT, STG and VCT power meters during both laboratory and field cycling tests in comparison with the SRM device considered to be the gold standard. We hypothesised that the PO measured by the four systems would be different considering that the force was measured at different locations on the bicycle (pedals, crank, crankset and rear hub). The highest PO would be measured at the pedals, whereas the lowest PO would be measured at

the rear wheel hub, which does not take into account the mechanical loss in the chain drive system. Moreover, the four power meters would be considered as sensitive, reproducible and robust.

Methods

Participant

A national-level male competitive cyclist (age: 23 years old, height: 1.88 m, body mass: 80 kg) with a very low asymmetry index (4%)¹⁶, measured by combining intensity and duration with the SRM torque analysis system in our laboratory (personal data), volunteered as the subject for this study. Prior to testing and after having received a full explanation of the nature and purpose of the study, the subject gave his written informed consent. The study was approved by the ethics committee of the institute. Before experimenting, the subject underwent several habituation sessions to get used to the testing procedure.

Experimental design

All testing sessions were performed with the same road-racing bicycle. The bicycle tire pressure was inflated to 700 kPa. The bicycle was fitted with an SRM crankset, a rear wheel composed of the PWT G3 hub, the STG power crank and the VCT pedals. The SRM power meter was paired with a SRM power control whereas PWT, STG and VCT power meters were paired with Garmin power controls. To ensure accurate measures of the SRM power meter, a static calibration was applied before the study¹⁷ and the zero offset frequency was adjusted according to the manufacturer's instructions. The PO was measured continuously at a frequency of 1 Hz for all power meters. A short acceleration (six pedalling cycles) was realised at the beginning of each testing session to facilitate data synchronisation.

The validity of the PWT, STG and VCT power meters was investigated in the field and in the laboratory at submaximal and maximal intensities from three experimental

protocols: 1) a sub-maximal incremental test, 2) a sub-maximal 30-min continuous test and 3) a sprint test. The incremental and continuous sub-maximal tests were performed on a motorised treadmill (S 1930, HEF Techmachine, Andrezieux-Bouthéon, France) of 3.8 m length and 1.8 m width, and the sprint test was performed on a Cateye ergometer (CS-1000, Cateye, Osaka, Japan). The subject performed the three protocols on the same day and repeated each protocol three times on three different days to assess reproducibility. Sensitivity was studied in the laboratory during the sub-maximal incremental test by using three different pedalling cadences (60, 80 and 100 rpm) and by measuring the difference in PO between seated and standing positions¹⁸. Robustness was investigated in the laboratory by using twelve different vibration frequencies (vibration test).

Sub-maximal incremental test

A sub-maximal incremental test was performed on a motorised treadmill at speeds of 19.5, 21, 22.5, 24 and 25.5 km.h⁻¹ (150-350 W). The mass of the system (subject + bicycle) contributes to the PO required to ride on a treadmill at a given velocity. We controlled this parameter by adding or removing water from two bottles in the bottle cages of the bicycle⁴. At each velocity, both the pedalling cadence (60, 80 and 100 rpm) and the position (seated and standing) effects on the PO were tested in randomized order. The combinations of the different velocities, pedalling cadences and positions resulted in 30 different data sets (5 velocities, 3 pedalling cadences and 2 positions), each data set lasting 30 seconds.

Sub-maximal continuous test

A 30-min continuous exercise test was performed in a seated position at 21 km.h⁻¹ on a 3% slope with a pedalling cadence of 80 rpm.

Sprint test

The sprint test consisted of three 8 s sprints in a seated position to determine the maximal 1 s PO (PO_{max}) and 5 s PO. The magnetic resistance of the Cateye ergometer was set to a simulated grade of 7%. Three different gear ratios were used (53/15, 53/17 and 53/19) to determine the three different maximal pedalling cadences and the levels of applied force. Sprints were separated by 5 min of active recovery at low intensity (<150 W).

Vibration test

The frequencies used during the vibration test corresponded to vibrations measured in road cycling¹⁹. The test consisted of a 30 sec ramp exercise bouts on vibrating plates (Globus, Physioplate FIT, Italy) by mean steps of 4 Hz increasing from 12 to 56 Hz (amplitude of 4 mm) and decreasing from 56 to 12 Hz. The exercise was performed at 200 W with a pedalling cadence of 80 rpm. The bicycle was fixed on an ergo-trainer (Tacx, Netherlands).

Field test

The field test consisted of a 2 h road cycling session on a hilly terrain including the different laboratorial experimental conditions (seated and standing positions, different pedalling cadences and different velocities) at an average temperature of 20.9 °C. The Record Power Profile (RPP) was used to compare the four power meters according to the exercise intensity zones determined by Pinot and Grappe³ and defined as follows: zone 1 (between 1 and 4 h; moderate exercise intensity), zone 2 (between 20 and 60 min; heavy exercise intensity), zone 3 (between 5 and 20 min; low part of the severe intensity zone), zone 4 (between 30 and 5 min; high part of the severe intensity zone) and zone 5 (between 1 and 30 s; force – velocity zone).

Statistical analysis

Descriptive statistics were used, and all data were expressed as mean \pm standard deviation. Statistical analysis was performed using SigmaPlot 12.0 software (Systat Inc. San Jose, USA). Bland-Altman plots and 95% limits of agreement²⁰ were applied to assess the agreement among PO_{PWT} , PO_{STG} , PO_{VCT} and PO_{SRM} during the sub-maximal incremental test. The data of the submaximal incremental tests were checked for heteroscedasticity by calculating the heteroscedasticity correlation between 1) the absolute differences between PO_{PWT} , PO_{STG} , PO_{VCT} and PO_{SRM} and 2) the mean PO as described by Atkinson and Nevill⁵. Although this analysis showed that heteroscedasticity was not present, the data were logarithmically transformed according to the recommendations of Nevill and Atkinson²¹. The data of the sub-maximal incremental test, sub-maximal continuous test and sprint test were not normally distributed. Thus, the analysis of the differences among the PO_{PWT} , PO_{STG} , PO_{VCT} and PO_{SRM} of each protocol was conducted with the non-parametric Kruskal-Wallis test. An initial two-way ANOVA (power meters *vs.* exercise intensity zones) was used to analyse the influence of the exercise intensity zones on the power meters. The pedalling cadence and cycling position effects on PO_{PWT} , PO_{STG} , PO_{VCT} and PO_{SRM} during the sub-maximal incremental test were evaluated with the non-parametric Kruskal-Wallis test. To assess reproducibility, the non-parametric Kruskal-Wallis test was also used for the sub-maximal incremental test, and the mean coefficient of variation (CV) was calculated for all conditions. A second two-way ANOVA (power meters *vs.* vibration frequency) was used to analyse the influence of the vibration frequency on the power meters. Significance was set to $p < 0.05$ in all statistical tests.

Results

Validity

During the sub-maximal incremental test (150-350 W), strong correlations were found between PO_{SRM} and PO_{PWT} (0.997, $p < 0.001$), PO_{STG} ($r = 0.985$, $p < 0.001$) and PO_{VCT} ($r = 0.996$, $p < 0.001$). The mean PO from 19.5 to 25.5 km.h⁻¹ was not significantly different among the four systems. The ratio limits of agreement of the PO differences were $1.007 \times \div 1.056$ between PO_{SRM} and PO_{PWT} , $0.945 \times \div 1.110$ between PO_{SRM} and PO_{STG} and $1.004 \times \div 1.051$ between PO_{SRM} and PO_{VCT} . The Bland-Altman analysis (Figure 1) shows that the mean bias between PO_{SRM} and PO_{PWT} was 1.3 ± 6.0 W (95% CI: -10.4 and 13.0 W). Additionally, the mean bias between PO_{SRM} and PO_{STG} was -13.7 ± 12.4 W (95% CI: -37.9 and 10.6 W) and 0.6 ± 6.2 W (95% CI: -11.6 and 12.7 W) with the PO_{VCT} .

No significant difference was measured among the mean POs during the 30 min continuous test, and the mean CVs were 2.8%, 3.6%, 3.6% and 2.0% for PO_{SRM} , PO_{PWT} , PO_{STG} and PO_{VCT} , respectively.

No significant difference was found in PO_{max} among the four power meters. However, the 5 s PO_{VCT} was lower than that of PO_{SRM} (-36.9%, $p < 0.05$) during the sprint test with a low gear ratio (Figure 2).

Significant differences were found within certain intensity zones among the power meters. Figure 3 shows the RPP according to the different power meters and the exercise intensity zones. The two-way ANOVA indicated that PO_{STG} was lower ($p < 0.05$) than PO_{SRM} within zones 2 (-5.1%) and 3 (-4.9%). PO_{VCT} was lower ($p < 0.05$) than PO_{SRM} within zone 2 (-4.5%).

Sensitivity

The pedalling cadence had no effect on PO among the different power meters. However, cycling position had an effect ($p < 0.001$) on PO_{SRM} , PO_{PWT} and PO_{STG} . For the same velocity on the treadmill, the PO was higher in the standing position for both the SRM (+2.1%, $p < 0.001$) and the PWT (+2.4%, $p < 0.001$) power meters. By contrast, PO_{STG} was lower in the standing position (-4.4%, $p < 0.001$).

Reproducibility

No significant difference was detected in all the incremental tests with the Kruskal-Wallis analysis. The mean CVs (Table 1) for all the cycling conditions (5 velocities, 3 pedalling cadences and 2 pedalling postures) were $1.9 \pm 1.3\%$ for PO_{SRM} , $2.6 \pm 1.5\%$ for PO_{PWT} , $3.0 \pm 1.9\%$ for PO_{STG} and $2.5 \pm 1.3\%$ for PO_{VCT} .

Robustness

Figure 4 shows that both STG and VCT power meters are sensitive to high vibration frequencies. PO_{STG} and PO_{VCT} were decreased from a vibration frequency of 48 Hz ($p < 0.001$) and 52 Hz ($p < 0.001$), respectively, whereas vibrations did not influence the SRM and PWT power meters.

Discussion

This study is the first to analyse the validity, sensitivity, reproducibility and robustness of the PWT, STG and VCT power meters in comparison with the SRM device during laboratory and field cycling exercises.

The results of the PWT power meter demonstrated a narrow CI (23.4 W) and non-significant differences compared with the results of the SRM device. The PWT device was considered valid. However, the CI reported by Bertucci *et al.*⁴ was narrower (12.9 W) during the sub-maximal incremental test.

A large CI (48.5 W) was reported for the STG power meter, thus rendering this system invalid during the sub-maximal incremental test. This power meter also significantly underestimated the PO during the field test within zone 2 (-5.1%) and zone 3 (-4.9%) compared with the SRM device. Despite the fact that no significant difference was detected, PO_{STG} was markedly lower within zones 4 (-10.2%) and 5 (-5.0%) than PO_{SRM} . Our results are in accordance with those of Hurst *et al.*¹⁵, who reported that the STG device did not show any agreement with the SRM power meter and underestimated the PO by an average of 8% during off-road cycling tasks. Miller *et al.*²² also reported that the STG device underestimated the PO in downhill and flat field sections in comparison with the PWT device.

The VCT power meter had a valid PO during the sub-maximal exercise in laboratory. However, it underestimated the PO during the sprints with a low gear ratio (-36.9%) and the field test within zone 2 (-4.5%) compared with the SRM device. Even if no significant difference was detected, PO_{VCT} was markedly lower within zones 4 (-12.7%) and 5 (-6.3%) than PO_{SRM} . Furthermore, a poor reproducibility of the VCT system was demonstrated by a high standard deviation during the sprints with a low gear ratio. A recent study²³ showed that the VCT device slightly overestimated the PO during laboratory efforts when compared with the SRM system.

PO_{STG} was significantly lower in the standing position than in the seated position probably because of the left-crank-only measurement. The algorithm used to determine power for the STG system simply doubles the value determined at the left crank and then creates an average. This process may create problems in situations in which a contralateral force production imbalance is present. Bilateral asymmetries have been studied among cyclists²⁴⁻²⁶, and the results show that asymmetries are reduced with an increase in workload. As asymmetries depend on the subject, further studies must be conducted on several cyclists

controlling this parameter with the STG device in both laboratory and field cycling conditions.

The VCT system did not measure the PO change between the seated and standing positions. This could be due to some technological limits of the system that will be discussed below. Both STG and VCT power meters were not considered sensitive because PO_{SRM} and PO_{PWT} were significantly higher in standing position than in the seated position. These results are in accordance with those of Bouillod *et al.*¹⁸ who measured a systematic increase in PO in the standing position because of the mechanical deformation of the tires and the bike frame.

The importance of reproducible power meters to detect small changes in performance has been emphasised in a review²⁷. The detectable change in performance represents a magnitude of less than 2% in elite athletes. The mean CVs obtained with the PWT, STG and VCT devices are slightly higher than 2%, but the statistical analysis indicates that the four power meters provide reproducible PO during submaximal tests in the laboratory. Additionally, Van Praagh *et al.*²⁸ proposed a 5% margin of error to consider power meters as reproducible, but this margin is too wide to detect a small change in performance. Considering an elite athlete with a maximal aerobic power of 400 W, the margin of error represents 20 W. Supposing that the claimed accuracy of the SRM is correct, our results indicate that the PWT, STG and VCT have an accuracy of $\pm 2\text{-}3\%$ for PO between 150 and 350 W. This value slightly exceeds the manufacturers' claimed accuracies of $\pm 1.5\%$ for PWT and 2.0% for STG and VCT. In comparing the results of the present study with those of previous research in the agreement between cycling power meters, the CVs were similar to those previously reported for the Powertap hub system (CV = 2.1%), Polar S710 (CV = 2.2%) and Ergomo Pro (CV = 4.1%)^{4,10,11}. Hurst *et al.*¹⁵ reported higher CV for both the STG (CV = 5.5%) and SRM (CV = 5.1%) power meters, but this result was biased by trail vibrations and a small variation in pacing in the different trials. Higher CVs were also

reported for the G-Cog BMX^{29,30} and the Look Keo Power¹² power meters than those of the power meters measured in the present study.

The effect of vibration frequencies on the four power meters demonstrated that PO_{STG} and PO_{VCT} significantly stalled with high vibrations (48 Hz and 52 Hz, respectively), whereas PO_{SRM} and PO_{PWT} were not affected by vibrations. It is important to specify that the actual cycling condition on cobblestones induce successive shocks that cover a great range of frequencies and enlarge the density of the frequency spectrum principally from 0 to 200 Hz (personal data). This condition is different than in the laboratory vibrating platform where the vibration plate generate excitation without shocks at specific frequencies designed by the experimenter. For a cyclist riding on a granular rough road (26 to 36 km/h), 88% of the road excitation power falls within a 10–50 Hz frequency bandwidth¹⁹. According to Chiementin *et al.*³¹, the mean excitations frequencies on cobblestones (120 ± 11 mm of length) for speeds from 20 to 35 km/h were from 35 to 65 Hz, respectively. These results suggest that the robustness of the STG and VCT could alter the validity of the PO measurement on roads with cobblestones or with high macrotecture surfaces. Also, PO_{STG} and PO_{VCT} stall could be due to the use of accelerometers to measure PO. The accelerometers could be out of range of measurement especially when the road conditions involve severe vibratory exposure from 48 Hz. These results indicate that the STG and VCT power meters are not suitable for practice with strong vibrations, such as mountain biking and cobblestone roads.

Note that this study is limited to only one participant. Nevertheless, the study design provided a large number of measurement over a variety of exercise intensities and conditions of cycling. This variety enabled the assessment of PO typically generated by elite athletes³ (PO ranging between 1223 and 1454 W for the sprint test and between 150 and 350 W for the sub-maximal incremental tests).

Main sources of error encountered in power meters

Our results show that the theoretical mechanical losses from the PO measurements between the pedals and the rear hub are not verified. These results can be explained by 1) the strain gauges' sensitivity and their number included in each system, 2) the environmental temperature, 3) the fatigue of certain components, 4) the signal processing (amplification, filtering, analog to digital conversion and data analysis), 5) the calibration methods and 6) the elapsed time since the last calibration (PO measurement drift). Thus, it appears that the mechanical properties of the strain gauges inside the system are very important to consider. Indeed, all the power meters include force measurement which is obtained using semiconductor strain gauge rosettes as sensors. After signal conditioning (impedance bridge and amplification/filtering), the resultant voltage is converted 1) into a digital signal (by an Analog to Digital converter) and processed by a microcontroller (Figure 5) and 2) into a frequency signal by Pulse Width Modulation (PWM) before sending it to a power control (SRM), in which the microcontroller processes data after the demodulation step (Figure 6). Operating principles of the STG and VCT power meters have not been presented because we had not the opportunity to disassemble the two systems. In both detailed cases (PWT and SRM), the angular velocity of the wheel and of the crankset (obtained by reed switches) is necessary to compute power data. Temperature effect, mechanical fatigue, misalignment errors, Wheatstone Bridge Nonlinearity, electronic components' noise (Amplifier, A/D converter) and testing cell fatigue (long-time effect) were identified as the main sources of error in strain gauges measurements. To compensate for some of these errors, it is necessary to calibrate the system.

According to standard instructions of calibration recommended by the manufacturers, PO_{VCT} and PO_{STG} should be higher than PO_{SRM} , whereas PO_{PWT} should be lower than PO_{SRM} considering the measurement location and the mechanical losses in the bicycle components.

Practical Applications and Conclusions

This study confirms that the PWT power meter can be considered a suitable and valuable device for PO measurement during cycling. However, both the STG and VCT systems should be treated with some caution given the presence of significant differences when they are compared with the SRM device. The use of accurate devices such as SRM and PWT is required for coaches and scientists to enable the assessment of cyclists’ intensity zones and to establish a long-term power profile of individual performance. Among the four power meters tested in this study, only the SRM device can be calibrated by the user, thus making it a useful system for coaches and scientists.

Our study demonstrates that the PWT, STG and VCT systems are reproducible mobile power meters compared with SRM device. However, the validity, sensitivity and robustness of the STG and VCT systems should be treated with some caution as they may limit the potential application of the crank and pedal systems for researchers. To date, SRM and PWT remain the most reliable systems for sport scientists and coaches. To be as reliable as the SRM and PWT power meters, the STG and VCT systems should improve their signal processing in some assessment conditions.

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References

1. Jobson SA, Passfield L, Atkinson G, Barton G, Scarf P. The analysis and utilization of cycling training data. *Sports Medicine*. 2009;39(10):833-844.
2. Vogt S, Heinrich L, Schumacher YO, et al. Power output during stage racing in professional road cycling. *Medicine and Science in Sports and Exercise*. 2006;38(1):147-151.
3. Pinot J, Grappe F. The record power profile to assess performance in elite cyclists. *International Journal of Sports Medicine*. 2011;32(11):839-844.
4. Bertucci W, Duc S, Villerius V, Pernin JN, Grappe F. Validity and reliability of the PowerTap mobile cycling powermeter when compared with the SRM Device. *International Journal of Sports Medicine*. 2005;26(10):868-873.
5. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*. 1998;26(4):217-238.
6. Bartlett J, Frost C. Reliability, repeatability and reproducibility: analysis of measurement errors in continuous variables. *Ultrasound in Obstetrics & Gynecology*. 2008;31(4):466-475.
7. Gardner AS, Stephens S, Martin DT, Lawton E, Lee H, Jenkins D. Accuracy of SRM and power tap power monitoring systems for bicycling. *Medicine and Science in Sports and Exercise*. 2004;36(7):1252-1258.
8. Paton CD, Hopkins WG. Tests of cycling performance. *Sports Medicine*. 2001;31(7):489-496.
9. Grappe F, Candau R, Belli A, Rouillon J-D. Aerodynamic drag in field cycling with special reference to the Obree's position. *Ergonomics*. 1997;40(12):1299-1311.
10. Millet GP, Tronche C, Fuster N, Bentley DJ, Candau R. Validity and reliability of the Polar S710 mobile cycling powermeter. *International Journal of Sports Medicine*. 2003;24(3):156-161.
11. Duc S. Validity and reproductibility of the ergomo pro power meter compared with the SRM and Powertap power meters. *International Journal of Sports Physiology and Performance*. 2007.
12. Sparks SA, Dove B, Bridge CA, Midgely AW, McNaughton LR. Validity and reliability of the look Keo power pedal system for measuring power output during incremental and repeated sprint cycling. *International Journal of Sports Physiology and Performance*. 2015;10(1):39-45.
13. Balmer J, Davison RC, Coleman DA, Bird SR. The validity of power output recorded during exercise performance tests using a Kingcycle air-braked cycle ergometer when compared with an SRM powermeter. *International Journal of Sports Medicine*. 2000;21(3):195-199.

14. Bertucci W, Duc S, Villerius V, Grappe F. Validity and reliability of the Axiom PowerTrain cycle ergometer when compared with an SRM powermeter. *International Journal of Sports Medicine*. 2005;26(1):59-65.
15. Hurst HT, Atkins S, Sinclair J, Metcalfe J. Agreement between the stages cycling and SRM powermeter systems during field-based off-road climbing. *Journal of Science and Cycling*. 2015;4(1):21-27.
16. Carpes FP, Mota CB, Faria IE. On the bilateral asymmetry during running and cycling - A review considering leg preference. *Physical Therapy in Sport*. 2010;11(4):136-142.
17. Wooles AL, Robinson AJ, Keen PS. A static method for obtaining a calibration factor for SRM bicycle power cranks. *Sports Engineering*. 2005;8:137-144.
18. Bouillod A, Pinot J, Valade A, Cassirame J, Soto-Romero G, Grappe F. Gross efficiency is improved in standing position with an increase of the power output. *Journal of Science and Cycling*. 2014;3(2):6.
19. Lépine J, Champoux Y, Drouet JM. A Laboratory Excitation Technique to Test Road Bike Vibration Transmission. *Experimental Techniques*. 2013.
20. Bland JM, Altman DG. Comparing methods of measurement: why plotting difference against standard method is misleading. *Lancet*. 1995;346(8982):1085-1087.
21. Nevill AM, Atkinson G. Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *British Journal of Sports Medicine*. 1997;31(4):314-318.
22. Miller MC, Macdermid PW, Fink PW, Stannard SR. Agreement between Powertap, Quarq and Stages power meters for cross-country mountain biking. *Sports Technology*. 2016:1-7.
23. Novak AR, Dascombe BJ. Agreement of Power Measures between Garmin Vector and SRM Cycle Power Meters. *Measurement in Physical Education and Exercise Science*. 2016:1-6.
24. Smak W, Neptune RR, Hull ML. The influence of pedaling rate on bilateral asymmetry in cycling. *Journal of Biomechanics*. 1999;32(9):899-906.
25. Bini RR, Hume PA. Relationship between pedal force asymmetry and performance in cycling time trial. *Journal of Sports Medicine and Physical Fitness*. 2015;55(9):892-898.
26. Carpes FP, Rossato M, Faria IE, Bolli Mota C. Bilateral pedaling asymmetry during a simulated 40-km cycling time-trial. *Journal of Sports Medicine and Physical Fitness*. 2007;47(1):51-57.
27. Hopkins WG, Schabert EJ, Hawley JA. Reliability of power in physical performance tests. *Sports Medicine*. 2001;31(3):211-234.

28. Van Praagh E, Bedu M, Roddier P, Coudert J. A simple calibration method for mechanically braked cycle ergometers. *International Journal of Sports Medicine*. 1992;13(1):27-30.
29. Chiementin X, Crequy S, Bertucci W. Validity and reliability of the G-Cog device for kinematic measurements. *International Journal of Sports Medicine*. 2013;34(11):945-949.
30. Bertucci W, Crequy S, Chiementin X. Validity and reliability of the G-Cog BMX Powermeter. *International Journal of Sports Medicine*. 2013;34(6):538-543.
31. Chiementin X, Rigaut M, Crequy S, Bolaers F, Bertucci W. Hand-arm vibration in cycling. *Journal of Vibration and Control*. 2012;19(16):2551-2560.

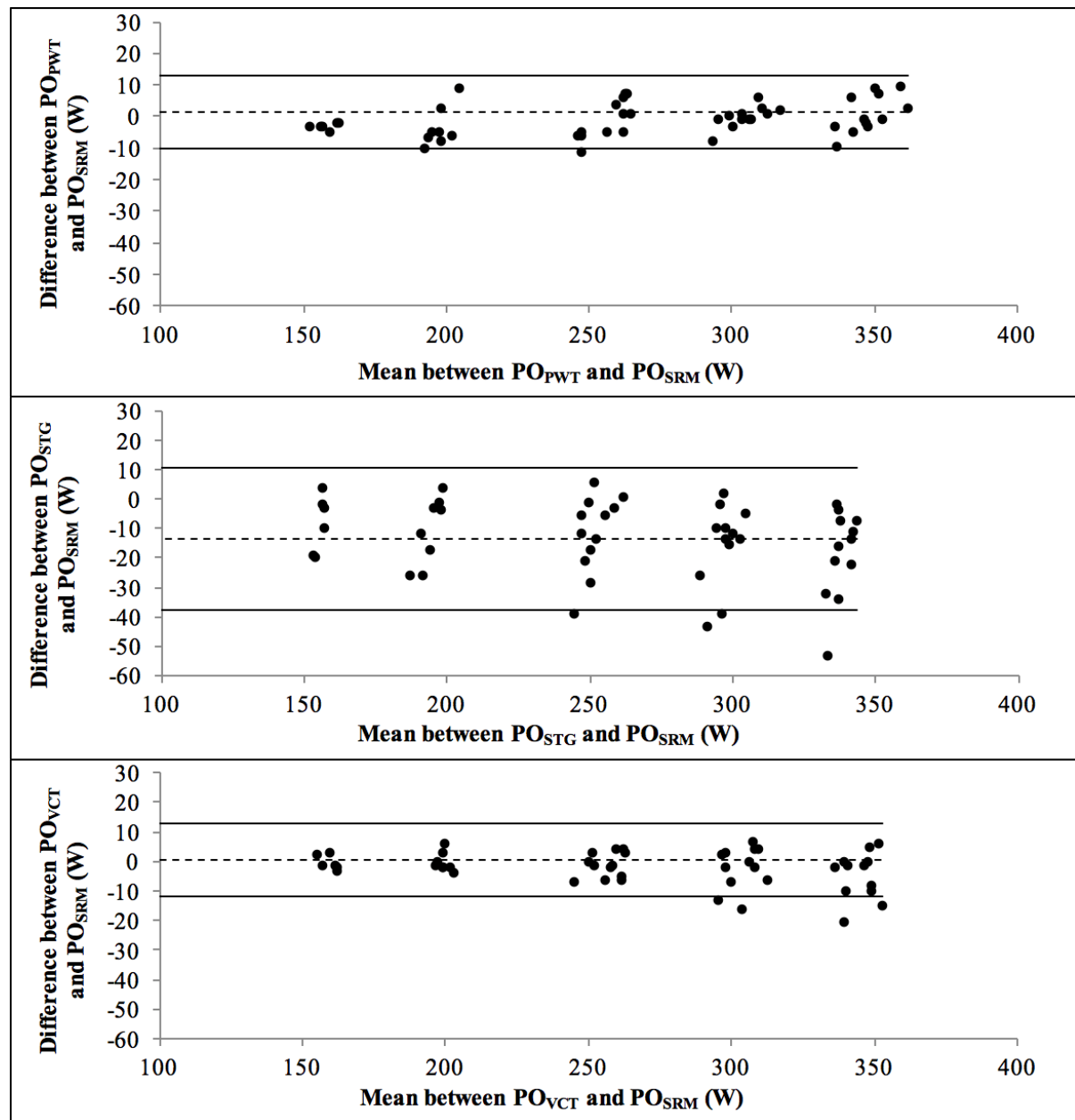


Figure 1. Bland-Altman plots of the differences between a) POSRM and POPWT, b) POSRM and POSTG and c) POSRM and POVCT power meters during the sub-maximal incremental test. The dashed line represents the bias whereas the solid lines represent the high and low 95% confidence interval (CI).

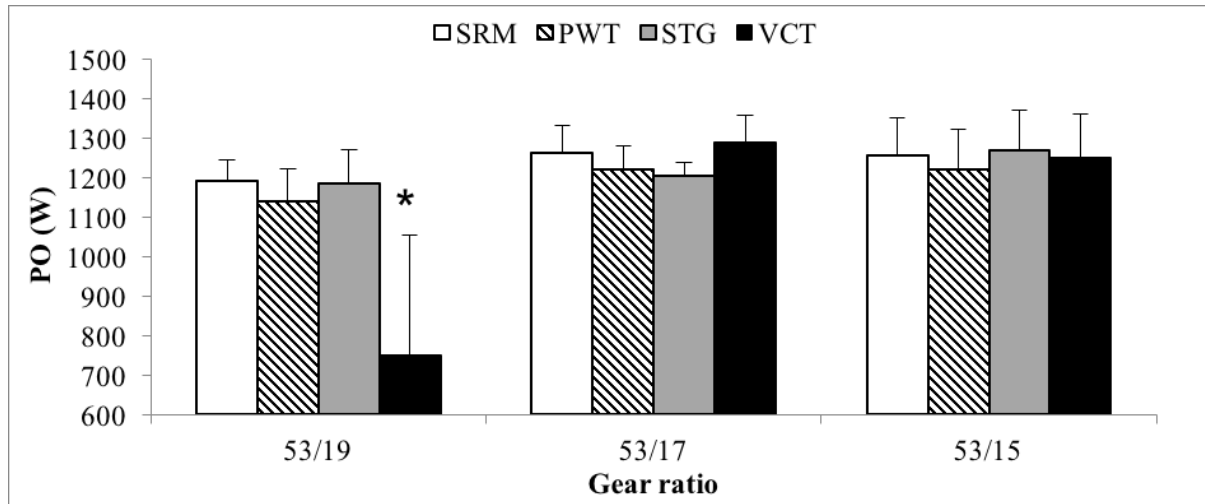


Figure 2. SRM, PWT, STG and VCT 5-sec PO during sprint test with low, middle and high gear ratios. *significant difference between VCT and SRM ($p < 0.05$).

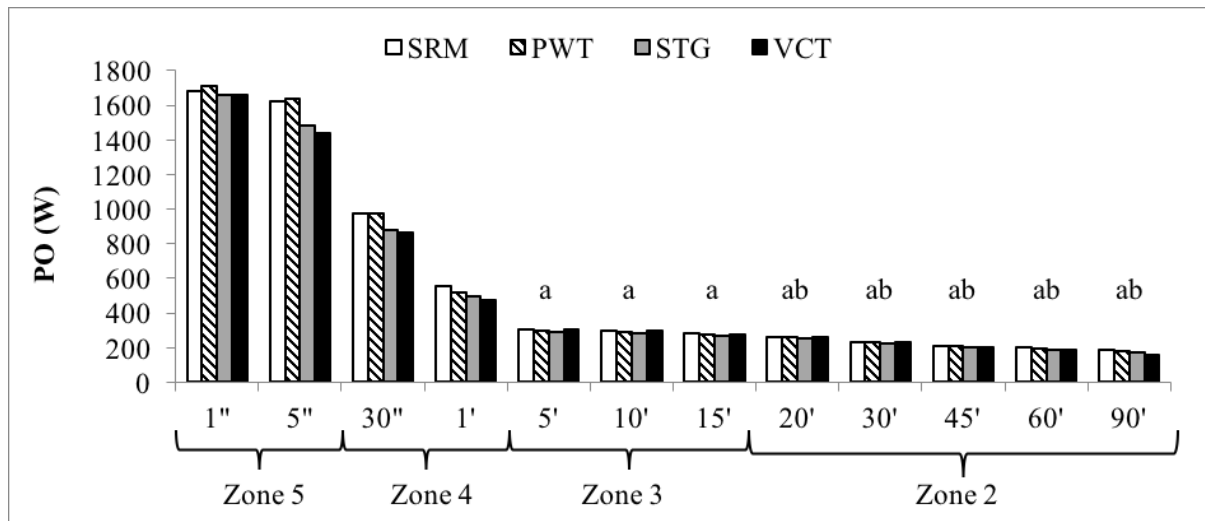


Figure 3. Record Power Profile according to the power meters and exercise intensity zones.

a significant differences between sTG and SRM ($p < 0.05$)

b significant difference between VCT and SRM ($p < 0.05$)

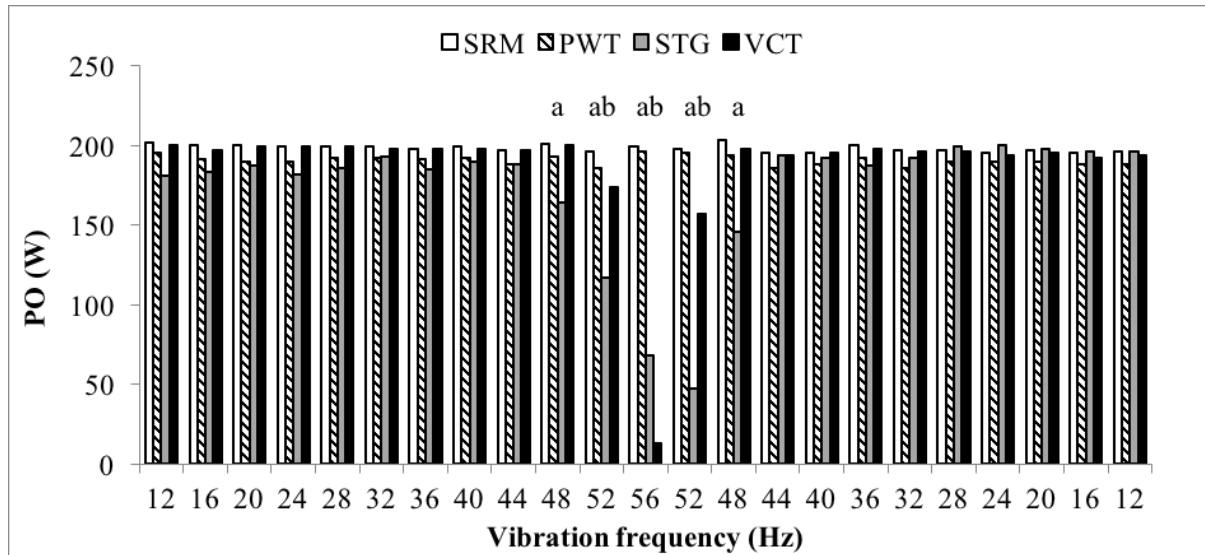


Figure 4. SRM, PWT, STG and VCT PO obtained during the vibration test.

a significant difference between STG and SRM ($p < 0.001$)

b significant difference between VCT and SRM ($p < 0.001$)

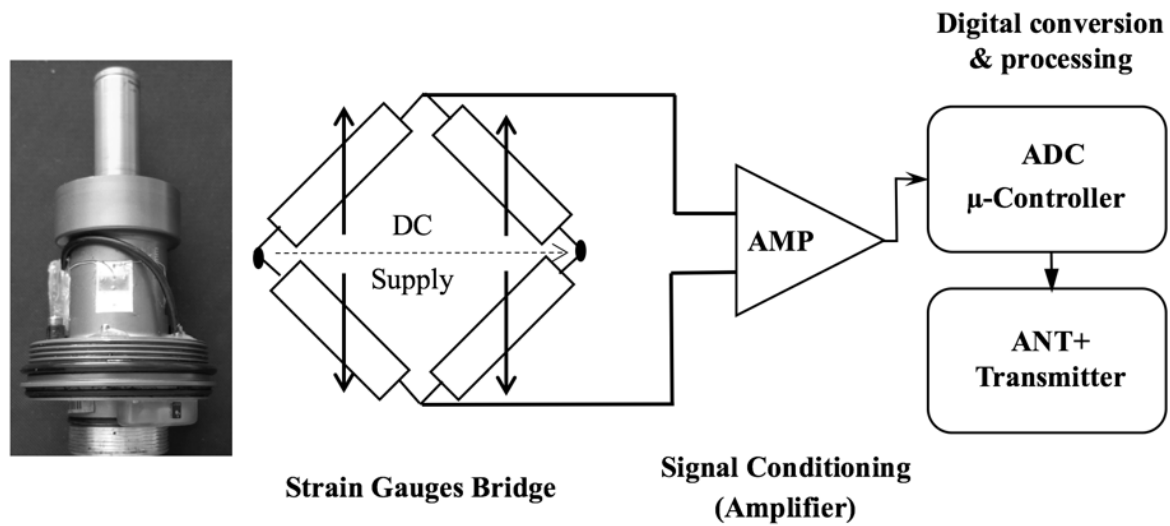


Figure 5. Powertap Operating Principle. Image of a Powertap rear hub (left). Measurement chain includes strain gauges’ bridge, amplification/filtering step (AMP), analog to digital conversion (ADC), data analysis in microcontroller and wireless transmission by ANT + protocol (2.4 GHz) (right).

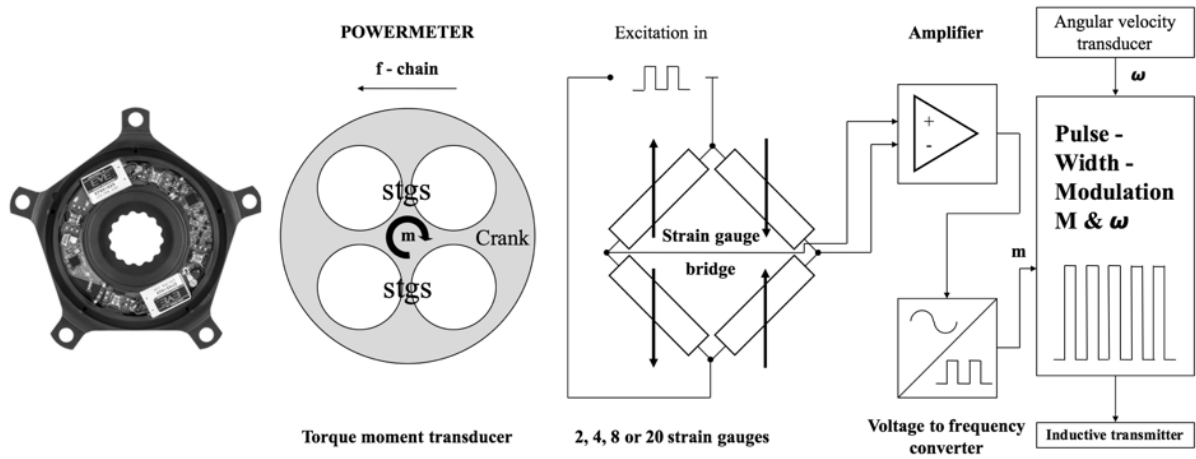


Figure 6. SRM Operating Principle. Image of a SRM crankset (left). Measurement chain includes strain gauges' bridge, amplification/filtering step (AP), Pulse Width Modulation step (PWM) and wireless transmission ANT + protocol (2.4 GHz) (right).

Table 1. Mean PO (W) and CV (%) for SRM, PWT, STG and VCT power meters at different velocities, pedalling cadences and positions during the sub-maximal incremental test.

Velocities (km.h ⁻¹)	Pedalling cadences (rpm)	Positions	Mean PO _{SRM}	Mean PO _{PWT}	Mean PO _{STG}	Mean PO _{VCT}	SRM CV	PWT CV	STG CV	VCT CV
			(W)				(%)			
19.5	60	Seated	149.7	153.7	151.7	155.7	2.5	1.6	3.6	0.4
19.5	60	Standing	154.0	154.7	143.3	153.3	4.5	1.3	5.6	5.6
19.5	80	Seated	152.7	155.0	155.3	157.0	2.5	0.6	1.6	2.9
19.5	80	Standing	154.3	157.0	136.3	154.0	5.4	3.2	5.0	4.9
19.5	100	Seated	149.7	153.0	143.7	155.7	4.9	2.3	6.9	3.5
19.5	100	Standing	155.7	159.3	130.0	157.0	4.1	1.0	9.4	2.9
21.0	60	Seated	195.7	198.3	195.0	197.3	1.1	5.1	1.0	2.0
21.0	60	Standing	198.3	202.7	190.0	196.3	1.0	3.3	2.8	1.5
21.0	80	Seated	196.7	201.0	196.3	200.7	0.8	4.8	2.9	2.1
21.0	80	Standing	200.3	204.0	185.7	200.3	0.8	4.9	0.3	1.8
21.0	100	Seated	196.3	200.0	188.3	201.7	0.6	4.0	2.6	2.1
21.0	100	Standing	201.3	206.7	173.7	201.3	1.6	3.3	3.2	1.7
22.5	60	Seated	252.7	250.0	253.7	254.3	2.9	4.2	3.6	4.4
22.5	60	Standing	253.7	253.0	241.3	254.3	2.0	4.8	1.9	1.3
22.5	80	Seated	251.3	252.0	246.7	256.7	2.4	3.5	2.8	1.8
22.5	80	Standing	256.7	258.7	236.3	254.0	1.6	2.2	2.8	1.0
22.5	100	Seated	252.7	251.7	245.0	257.0	2.5	5.3	4.7	2.7
22.5	100	Standing	260.7	262.0	230.3	258.3	2.2	1.1	2.4	0.2
24.0	60	Seated	303.3	301.7	303.3	308.7	2.1	1.9	2.0	3.1
24.0	60	Standing	305.3	303.7	291.3	303.0	0.7	0.5	0.5	2.0
24.0	80	Seated	302.3	299.3	293.0	304.7	1.6	3.0	0.7	1.9
24.0	80	Standing	307.7	308.7	288.3	302.7	1.7	2.8	3.7	4.0
24.0	100	Seated	304.7	306.0	289.7	309.0	1.7	2.1	1.4	3.7
24.0	100	Standing	314.7	317.7	278.0	307.3	0.7	1.4	3.4	3.3
25.5	60	Seated	344.3	338.0	335.7	342.0	1.0	2.1	0.6	1.5
25.5	60	Standing	346.0	342.0	330.0	342.3	0.3	1.0	2.9	1.9
25.5	80	Seated	344.7	345.7	331.3	348.7	1.9	3.1	2.5	3.4
25.5	80	Standing	351.7	349.7	324.3	341.7	0.7	0.9	2.2	3.3
25.5	100	Seated	342.3	347.3	324.0	348.0	1.0	2.0	3.6	2.3
25.5	100	Standing	355.7	361.7	313.7	348.7	1.0	0.9	2.1	2.1