Title: An analysis of variability in power output during indoor and outdoor cycling time-trials

Submission type: Original Investigation

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Running Head:

Indoor *v.s.* outdoor cycling performance

Abstract

Purpose:

Regulation of power output during cycling encompasses the integration of internal and external demands to maximise performance. However, relatively little is known about variation in power output in response to the external demands of outdoor cycling. We compared mean power output and the magnitude of power output variability and structure during a 20-min time-trial performed indoors and outdoors.

Methods:

Twenty male competitive cyclists ($\dot{V}O_{2peak}$ 60.4 ± 7.1 $mL \cdot kg^{-1} \cdot min^{-1}$) performed two randomised maximal 20-min time-trial tests i) outdoors at a cycle-specific racing circuit or ii) indoors on a laboratory-based electromagnetically braked training ergometer, 7 days apart. Power output was sampled at 1 Hz and collected on the same bike equipped with a portable power meter in both tests.

Results:

Twenty-min time-trial performance indoor (280 ± 44 W) was not different from outdoor (284 ± 41 W) ($P = 0.256$), showing a strong correlation ($r = 0.94$; $P < 0.001$). Within-person SD was greater outdoors (69 ± 21 W) compared to indoors (33 ± 10 W) ($P < 0.001$). Increased variability was observed across all frequencies in data from outdoor cycling compared to indoors ($P < 0.001$) except for the very slowest frequency bin (<0.0033 Hz, $P = 0.930$).

Conclusions:

Our findings indicate a greater magnitude of variability in power output during cycling outdoors. This suggests that constraints imposed by the external environment lead to moderate and high frequency fluctuations in power output. Therefore, indoor testing protocols should be designed to reflect the external demands of cycling outdoors.

Key words: Frequency, Fluctuations, Pacing, Performance, Structure

Introduction:

Pacing refers to an athlete’s distribution of work or energy across an event (de Koning et al. 1999; Abbiss and Laursen 2008). Athletes vary their physical output (i.e. mechanical power output) to accommodate physiological or psychological constraints, for strategic racing purposes, or due to changing environmental factors (St Clair Gibson et al. 2006; Abbiss and Laursen 2008). Accommodation of these varying internal and external demands directly affect performance (Foster et al. 1994) with the adopted pacing strategy representing a behavioural expression of continuous decision making (Smits et al. 2014). When examined at increased resolution, these fluctuations may illustrate complex intrinsic control strategies to modulate work rate (Tucker et al. 2006) and reflect multiple levels of regulation to achieve homeostatic control during a task (Lambert et al. 2005; St Clair Gibson et al. 2006; St Clair Gibson et al. 2018). Given the additional external demands associated with performance cycling outdoors, it is interesting that mean power data is comparable indoors and outdoors over shorter duration 6-s sprints (Gardner et al. 2007), 4-min time-trials (Bouillod et al. 2017) and longer duration 40-km time-trials despite a ~ 6% reduction in performance time outdoors (Smith et al. 2001).

Relatively little is known about variation in power output in response to more immediate external demands of pacing during outdoor cycling such as, short strategic sprints, reductions in speed to facilitate manoeuvring and/or changes in gradient, or attentional fluctuations whilst scanning for potential hazards. Outdoor cycling performance time can be optimized by adopting a strategy that varies power output by 5-10% (Swain, 1997), increasing power during uphill or windy sections and reducing during downhill or less-windy sections (Swain 1997; Atkinson and Brunskill 2000; Abbiss and Laursen 2008). However, the less predictable attentional demands of the outdoor environment which remain in constant flux and require continual updates, conscious or otherwise, may also impact performance (St Clair Gibson et al. 2018). Variation in power output has been described in professional level time-trials conducted outdoors (Abbiss et al. 2010), and low frequency fluctuations in power output have been observed during indoor flat and simulated hilly conditions (Terblanche et al. 1999; Tucker et al. 2006).

However, the magnitude of power variability between different environmental conditions and the differences in physiological and mechanical demands and associated effects on cycling performance have not been well described.

Comparison of time-series mechanical power data at increased resolution can offer further insight into the effects of environmental constraints on centrally controlled regulation of exercise intensity and subsequent behavioural outcomes, to different environments. We hypothesized that cycling in the outdoor environment might change (at some organisational level) the pattern of the oscillations in power output across time (St Clair Gibson et al. 2018). This may, in turn, allow athletes to better understand the necessity of environmental specificity when translating indoor performance to the outdoors. Therefore, the aims of this study were to i) compare the mean power output across a 20-min cycling time-trial conducted indoors and outdoors, ii) compare the magnitude of variability across different frequency bandwidths, iii) and establish whether fluctuations of power output are structured or due to random noise.

Methods

Participants

Twenty male cyclists (mean ± SD; age 36 ± 9 years, stature 180 ± 5 cm; body mass 76 ± 8 kg; $\dot{V}O_{2peak}$ 60.4 ± 7.1 $mL \cdot kg^{-1} \cdot min^{-1}$) volunteered to participate in this study. Cyclist's performance level (PL) was categorised based on their relative $\dot{V}O_{2peak}$ according to de Pauw et al. (2013): 6 = PL2; 6 = PL3; 6 = PL4; 2 = PL5. All cyclists were active in regional/national racing time trials, road races or triathlons and were familiar with time-trial performance tests. Written informed consent was obtained from each participant before testing. All procedures conformed to standards set by the *Declaration of Helsinki* and ethical approval was granted by the institutional ethics committee.

Study design

Participants completed three separate testing sessions, which included two randomised 20-min time-trial tests with data collected consistently using the same portable power meter either i) outdoors at a cycle-specific racing circuit (Figure 1) or, ii) indoors on a laboratory-based electromagnetically braked training ergometer, 7 days apart. The third visit was an incremental ramp test to exhaustion for the purpose of establishing maximal aerobic capacity. The participants were asked to refrain from strenuous exercise for 48-h before each test, as well as alcohol and caffeine 24-h before testing, and to arrive fully hydrated.

Indoor vs. outdoor tests

All performance tests on the same bicycle (Dolan Preffisio, size 56, Dolan Bikes, Ormskirk, UK) fitted with a portable left crank-based power meter (STAGES, Stages Cycling, Boulder, CO, USA) and data collected via a Garmin head unit (Garmin Edge 510 GPS headunit, Garmin (Europe) Ltd., Southampton, UK). Participants completed a self-selected warm up at ~ 100 W for 10-min which included 2 x 20-s maximal efforts before resting for 5-min. Indoor tests were performed on an electronically-braked indoor trainer (Computrainer, RacerMate One, Racermate, Seattle, USA). Prior to each trial, the recommended zero off-set calibration was performed for the STAGES power meter according to the manufacturer's instructions. For indoor tests the Computrainer was calibrated according to the manufacturer’s instructions and a tyre roll-down test performed to maintain a standardized rolling resistance (~ 3.0 lbs) across all testing, tyre pressure was controlled at 100 pounds per square inch [psi]. A commercially available plastic riser was placed under the front wheel to level the bicycle and gradient set at 0%. Ambient temperature was controlled to approximate outdoor air temperatures (Table 1). Fan cooling was provided during indoor tests to approximate conductive air movements experienced outdoors and was positioned in front of the cyclist at an angle of 45 degrees and set to an air speed of 10.4 km/h (HVD24, Sealey Power Products, Bury St Edmunds, UK). It did not rain on any outdoor test day. Outdoor tests were conducted on a cycle-specific, traffic-free race circuit. The track measured 1.52 km in distance, 6 m wide, with ~ 4 m total elevation gain per lap and 7 shallow corners that allowed continuous pedalling (Figure 1). In total, participants completed between 7-10 laps. During both tests, participants were allowed to change gear to increase resistance during the test and cadence was freely chosen dependant on their preferred pacing strategy. Participants were instructed to pace their efforts to achieve the highest average power output across the 20-min effort. Blood samples were collected 1-min pre and 1-min post-test from the earlobe via capillary puncture and analysed subsequently using an automated blood lactate analyzer (Biosen C-Line, EKF Diagnostics, Cardiff, UK). Heart rate was recorded continuously throughout all trials by a Garmin heart rate monitor (HRM3-SS, Garmin (Europe) Ltd., Southampton, UK) that wirelessly transmitted to the Garmin headunit. Participants were also asked to rate their perceived levels of exertion using the RPE scale at the end of the 20-min test. Non-specific verbal encouragement was given each lap (~ 2-3-min intervals) and was approximately time-matched for indoor trials. Power output and heart rate data were recorded but concealed from the participant. During the test, a countdown clock from 20-min on a Garmin headunit attached to the handlebars of the bike was the only visible external cue.

Incremental ramp test

The incremental ramp test was programmed by the indoor cycle trainer software, starting at 150 W and increasing by 1 watt every 2-s (30 $W \cdot min^{-1}$), until volitional exhaustion. Breath-by-breath gas exchanges were recorded to assess oxygen consumption ($\dot{V}O_2$) (Oxycon Pro, Erich Jaeger GmbH, Hoechberg, Germany).

Data processing

Power output data was sampled at 1 Hz and variability examined in several ways. First, the distribution of power output for both conditions was calculated by creating a histogram ranging from 0-750 W in 10 W bins for each person. The proportion of 1 s samples in each 10 W bin of the histogram was calculated for each participant and then averaged (mean) over the cohort. Next, the within-person standard deviation of power output was calculated for both conditions. Third, to better understand the variability of power output at different frequencies, we i) tested the within-person standard deviation for data filtered (4^{th} order Butterworth filter) from very slow frequencies (below 0.0033 Hz, 1 cycle each 300 s) to higher frequencies (0.5 Hz, 1 cycle each 2 s), in bins of 0.033Hz; and ii) visualised the frequency domain using Fast Fourier Transform which was extracted for each participant and then averaged (mean) over the cohort. Finally, detrended fluctuation analysis (DFA) was applied to the time series to better understand the underlying structure of the variability. We interpreted an $\alpha = .05$ resulting from the DFA analysis as random noise. In contrast, values of $0 < \alpha < 0.5$ and $.05 < \alpha < 1.0$ both indicates persistent long-range correlations in the fluctuation of power output (Peng et al. 1995).

Statistical Analysis

A Paired Student's *t*-test was used to examine paired data for performance between conditions. A two-way analysis of variance (ANOVA) for repeated measures was used to test for within-group effects across time and condition (indoors *vs.* outdoors). If sphericity was violated, a Greenhouse-Geisser correction was applied. When a significant difference was found for a main effect (condition or time), *post-hoc* pair-wise comparisons were made, incorporating a Holm Bonferroni adjustment. All statistical analyses were performed using SPSS (IBM SPSS statistics 22 Inc, USA). Data are presented as mean ± SD ($n = 20$). Significance was set at $P < 0.05$.

Results

Time trial performance indoor vs. outdoor

Mean 20-min power output during a time-trial conducted indoors (280 ± 44 W) was not different from outdoors (284 ± 41 W) ($t_{(19)}$ = 1.170; P = 0.256), showing strong correlation (r = 0.94; P < 0.001) with a typical error of ± 10 W (Figure 2A). Cycling cadence was higher indoors compared to outdoors (In: 97 ± 8, Out: 90 ± 7 rev·min^{-1}) ($t_{(19)}$ = -3.749; P = 0.001). Physiological measures of average heart rate (In: 172 ± 12, Out: 171 ± 10 beats.min^{-1}) ($t_{(19)}$ = -0.810; P = 0.428) and end test lactate [La] (In: 9.9 ± 2.7, Out: 10.3 ± 2.7 mmol.L^{-1}) ($t_{(19)}$ = -0.394; P = 0.698) were not different. RPE was lower outdoors compared to indoors (In: 19.4 ± 0.9, Out: 18.2 ± 0.8) ($t_{(19)}$ = -6.902; P > 0.05).

Variability in power output

The within-person standard deviation of power output was greater when cycling outdoors (mean: 69 ± 21 W) compared to indoors (mean: 33 ± 10 W) ($t_{(19)}$ = 7.239, P < 0.001), with no correlation (r = 0.13; P = 0.594) (Figure 2B). Histograms averaged across participants show that the increased variability of power output during outdoor cycling was due to a greater proportion of both lower and higher power outputs (Figure 3A). Increased variability in power output was observed across all frequencies in data from outdoor cycling compared to indoors, with main effects for frequency ($F_{(48,912)}$ = 134.548, P < 0.001) and cycling location ($F_{(1,19)}$ = 75.633, P < 0.001), and interaction ($F_{(48,912)}$ = 26.937, P < 0.001) (Figure 3B). *Post hoc* analysis revealed that variability was higher across all frequencies during outdoor cycling except for the very slowest frequency bin (<0.0033 Hz, 1 cycle per 300 s), where there was no difference between the two conditions (P = 0.930). Distinct peaks occurred at frequencies slower than 0.0033 Hz (>300 s per cycle), with two additional peaks for outdoor cycling at ~ 0.01 Hz (100 s per cycle) and ~ 0.08 Hz (12.5 s per cycle)(Figure 3C). To illustrate variability of power output across different frequencies, a low pass filter (<0.0055Hz, > 180 s per cycle), band pass filter (0.0055-.2 Hz, 5-180 s per cycle) and high pass filter (>0.2 Hz, < 5 s per cycle) was applied to a representative data set for one participant (Figure 4). An increase in variation of power output is evident in the unfiltered data, indicative of the increased within-person standard deviation (Figure 4A). The low pass filtered data shows slow variations in power output across the trial (Figure 4B). In contrast, the bandpass filter (5 – 180 s per cycle) reveals large variations of power output during the outdoor trial (Figure 4C) and the high pass filtered data illustrates greater variability (quicker than 0.2 Hz) in power output over the entire outdoor trial (Figure 4D).

Structure of power output fluctuations

Detrended fluctuation analysis resulted in an α of between $0.5 < \alpha < 1$, indicating an underlying structure in the fluctuations of power output rather than random noise for both indoor (mean: 0.85 ± 0.22) and outdoor conditions (mean: 0.85 ± 0.12)($P = 0.894$).

Discussion

We examined how power output varied across different frequencies when trained cyclists performed a 20-min cycling time-trial under laboratory-based indoor and field-based outdoor conditions. Mean power output was not different between conditions but there was greater variability in power output outdoors. Analysis of different frequency bandwidths revealed the presence of slow oscillations in power output both indoors and outdoors, suggestive of an underlying global physiological control strategy. Greater variability in power output during cycling outdoors beyond these slow oscillations appeared to reflect the cyclical nature of the outdoor circuit. However, increased variability in power output at higher frequencies when cycling outdoors suggest that modifications in mechanical work rate occur that are not replicated during an indoor task.

There was no difference in mean power output (~ 1% difference) between 20-min time-trials performed on an outdoor cycling circuit or an indoor electronically-braked trainer. Indeed, outdoor and indoor measures were strongly correlated. These findings are in agreement with previous studies that have reported comparable mean power output for shorter 4-min time-trials (~3% difference) (Bouillod et al. 2017) and longer 40 km time trials (~3% difference) (Smith et al. 2001) (> 1% difference) (Jobson et al. 2008), performed indoors and outdoors. However, despite the relative consistencies in power output, a notable increase in the variability of power output during cycling performed outdoors was only recognizable with an increased level of resolution. Within-person standard deviation was increased more than two-fold outdoors (69 ± 21 W) relative to indoors (33 ± 10 W). The lack of correlation and spread of standard deviations across the outdoor condition (Figure 2B) suggest that no relationship exists with the variability observed during an indoor performance test. Therefore, from a practical perspective, coaches and athletes should be aware that some individuals might adopt greater variation in their pedaling when outdoors, which would not be evident during indoor testing. In general, greater variability in outdoor cycling was achieved via a greater spread in power intensities utilised during cycling outdoors. To further describe the variability in power output, we examined the within-person standard deviation across low, moderate and high frequency bands. We observed that power output was more variable across all frequencies outdoors relative to indoors, except for very slow frequencies.

Slow variations (< 5 cycles per min, 0.003 Hz) in power output were consistent to both indoor and outdoor performance tasks, possibly indicative of a change in pacing strategy. Such slow variations have been previously demonstrated where an equivalent dominant frequency band was described for ~ 2.5 km cycles during a 20 km indoor performance time trial (Tucker et al. 2006). These oscillations were also evident during indoor cycling using a modified cycle ergometer that was able to simulate a hilly route (Terblanche et al. 1999). Similar to the current study, these slow fluctuations described by Terblanche et al. were independent of the nature of the course profile. Such control mechanisms have been proposed to reflect self-regulation whereby intrinsic biological control processes within the central nervous system respond to changing afferent information from the exercising muscles (St Clair Gibson et al. 2006; Tucker et al. 2006). Similar global fluctuations have also been reported across a range of other biological systems, such as in heartbeat dynamics (Ivanov et al. 1999) and during changes in gait stride during walking (Hausdorff 2005).

Notable peaks in variability at ~ 100 s per cycle (0.013 Hz) and 20 s per cycle (0.093 Hz) were identified for the outdoor condition only. The fluctuations of power output in this frequency band are indicative of the cyclical nature of the outdoor 1.52 km circuit. A representative dataset illustrates the temporal nature of the time-trial outdoors with data filtered over the range ~ 5-180 s (Figure 4C). Variation in power output as a result of changes in elevation would prompt a greater application of power (Swain 1997), whereas corners in the cycle circuit would encourage a reduction in power, possibly explaining these observed micro-adjustments. These apparent pacing strategies, adopted consciously or subconsciously, support our understanding that modulating effort is important to distribute pace/power output effectively across the test duration over variable terrain (Swain 1997; Atkinson and Brunskill 2000; Abbiss and Laursen 2008). Atmospheric conditions such as wind direction that favored different parts of the circuit likely contributed as well. Regardless of the differences in pacing adopted by the athletes both approaches were equivalent in achieving a comparable maximal mean power output in their respective environments. However, when examining this variation outdoors at higher frequencies the differing mechanical demands evident in the application of power output suggest that these performances are not equivalent.

Greater variability in power output was observed at higher frequencies (< 5 s per cycle, 0.2 Hz) when riding outdoors (Figure 3D). These stochastic modifications in external force over brief periods did not however reflect changes in the circuit (Figure 4D). These high-frequency adjustments appear to be driven by environmental constraints such as variations in road surface, micro-environmental changes in air movement, or may reflect the increased cognitive demand associated with attending to balance via steering control inputs and rider lean (Cain et al. 2016). Muscle coordination has been shown to be dependent on the distribution of power and terrain profile in outdoor cycling (Blake and Wakeling 2012), suggesting that neuromuscular demands may be altered. Whereas, psychological stressors associated with attentional scanning strategies for planning and safety may also have impacted the intrinsic feedforward complexity in the regulation of power. Indeed, the visual exploration of environmental challenges in a relatively more unpredictable setting outdoors may have increased the attentional effort, something that would be reduced during an indoor task (Lacaille et al. 2004). In contrast, reallocation of attention towards novel stimuli outdoors, whilst increasing the cognitive demand, has been shown to reduce the sensation of effort during repetitive tasks, such as cycling (Bigliassi et al. 2017), which is supported by a reduction in RPE noted in our study outdoors. The relation between the cognitive demands of cycling and central control strategies warrants further investigation. Interestingly, measures of heart rate (HR) and indices of muscle bioenergetics (end-test B[La]) were similar across both indoor and outdoor tests suggesting that despite larger variability in power output this did not appear to increase the metabolic demands of exercise performance. This was unexpected; however, further research should interrogate time-series changes in heart rate and neuromuscular control during indoor and outdoor cycling, to explore the physiological significance of such variation in mechanical power.

Detrended fluctuation analysis indicated that the subtle changes in power output across both indoor and outdoor trials were not due to random noise. Rather, we found evidence of underlying self-similar patterns across different timescales, consistent with previous studies (Tucker et al. 2006). The findings were similar for both indoor and outdoor conditions, indicating that these patterns likely correspond to more global neuromuscular, physiological and psychological control mechanisms independent of the environment. Higher resolution testing using direct neuromuscular and physiological testing is required to better explain the nature of these patterns and underlying causes.

Practical applications

Our findings shed light on the characteristics of power output variation in two different environments. To prepare specifically for most cycling competitions, indoor testing protocols should reflect the external demands of cycling outdoors. An understanding of the design of indoor exercise protocols, which elicit equivalent mechanical responses, may drive adaptations that are more specific. However, careful consideration is needed to accurately simulate the variation in power output observed among competitive cyclists during outdoor training. This could be achieved by simulating (via ergometery control) realistic changes in power output to reflect varying demands, such as terrain and environment, or by designing interventions to increase cognitive engagement or distraction during the test. However, it is currently unclear how best to replicate these subtle, intrinsic variations in power. Future research should investigate ways to achieve this.

Conclusion

Our study demonstrates that measures of mean power output are similar during performance tests when cycling indoors and outdoors. However, outdoor cycling leads to moderate and high frequency variations in power output. This variation of power output in different frequency bands may reflect an altered neuromuscular demand during cycling time-trials conducted outdoors. Therefore, our findings should be considered when seeking to replicate the demands of outdoor competition using indoor training methods.

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Acknowledgements

We are very grateful to the cyclists who participated in this study for their efforts and commitment.

The STAGES portable crank-based power meter used in this study across all testing was provided by (STAGES, Stages Cycling, Boulder, CO, USA). The results of the current study do not constitute endorsement of the product by the authors or the journal.

Table 1. Ambient conditions for performance tests performed indoors and outdoors.

	Indoor time-trial	**Outdoor time-trial**
Temperature (ºC)	17 ± 1	11 ± 3
Humidity (%)	33 ± 8	54 ± 15
Barometric Pressure (hPA)	1014 ± 15	1016 ± 9
Wind speed (km.h^{-1})		13.4 ± 5
Fan speed (km.h^{-1})	10.4 ± 0	

Figure legends

Figure 1. Outdoor cycle circuit 1.52 km (A) circuit design (B) elevation profile equating to > 5 m gain per lap.

Figure 2. Scatterplot of (A) mean and (B) standard deviation (SD) of power output during 20 minutes of outdoor and indoor cycling.

Figure 3. Power output data recorded during a 20-min time-trial shown for all 20 participants. (A) frequency histogram of mean power output data; (B) mean within-person standard deviation expressed as a function of frequency; (C) discrete Fourier transform of the mean power output of all participants. Indoor cycling represented by a dashed line and outdoor cycling by a solid black line. * $P < 0.05$.

Figure 4. Representative data filtered (n = 1) (A) raw data for outdoor and indoor cycling during a 20-min time trial (B) low pass filter (> 180 s cycles) (C) moderate pass filter (5-180 s cycles) (D) high pass filter (< 5s cycles).

Figure 1

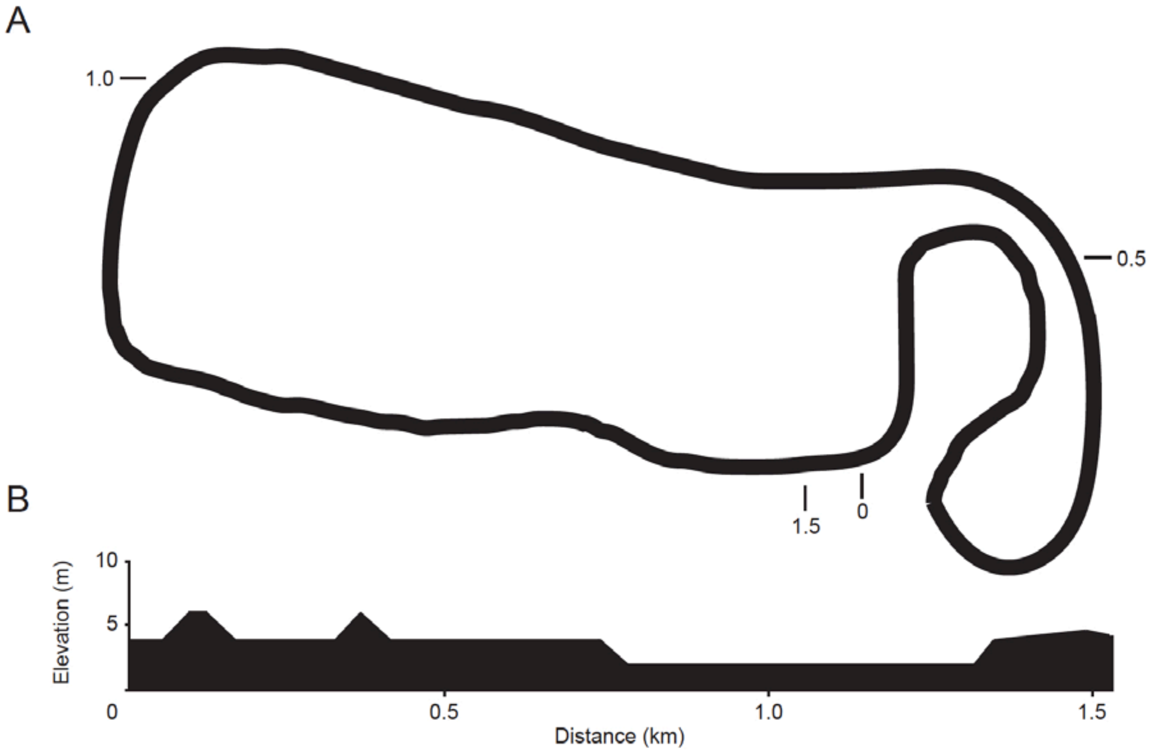


Figure 2

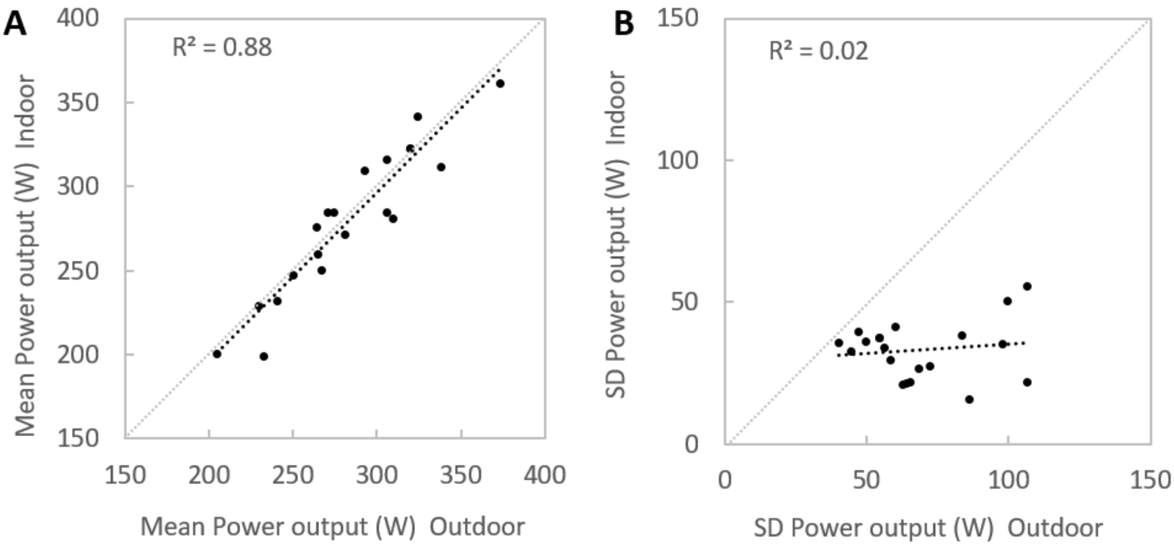

A
R² = 0.88
Mean Power output (W) Indoor
150
200
250
300
350
400
Mean Power output (W) Outdoor
150
200
250
300
350
400
B
R² = 0.02
SD Power output (W) Indoor
0
50
100
150
SD Power output (W) Outdoor
0
50
100
150

Figure 3

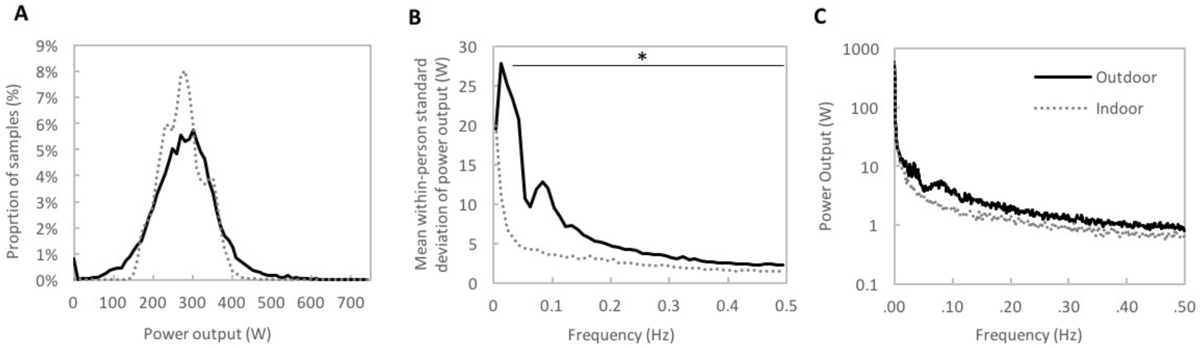
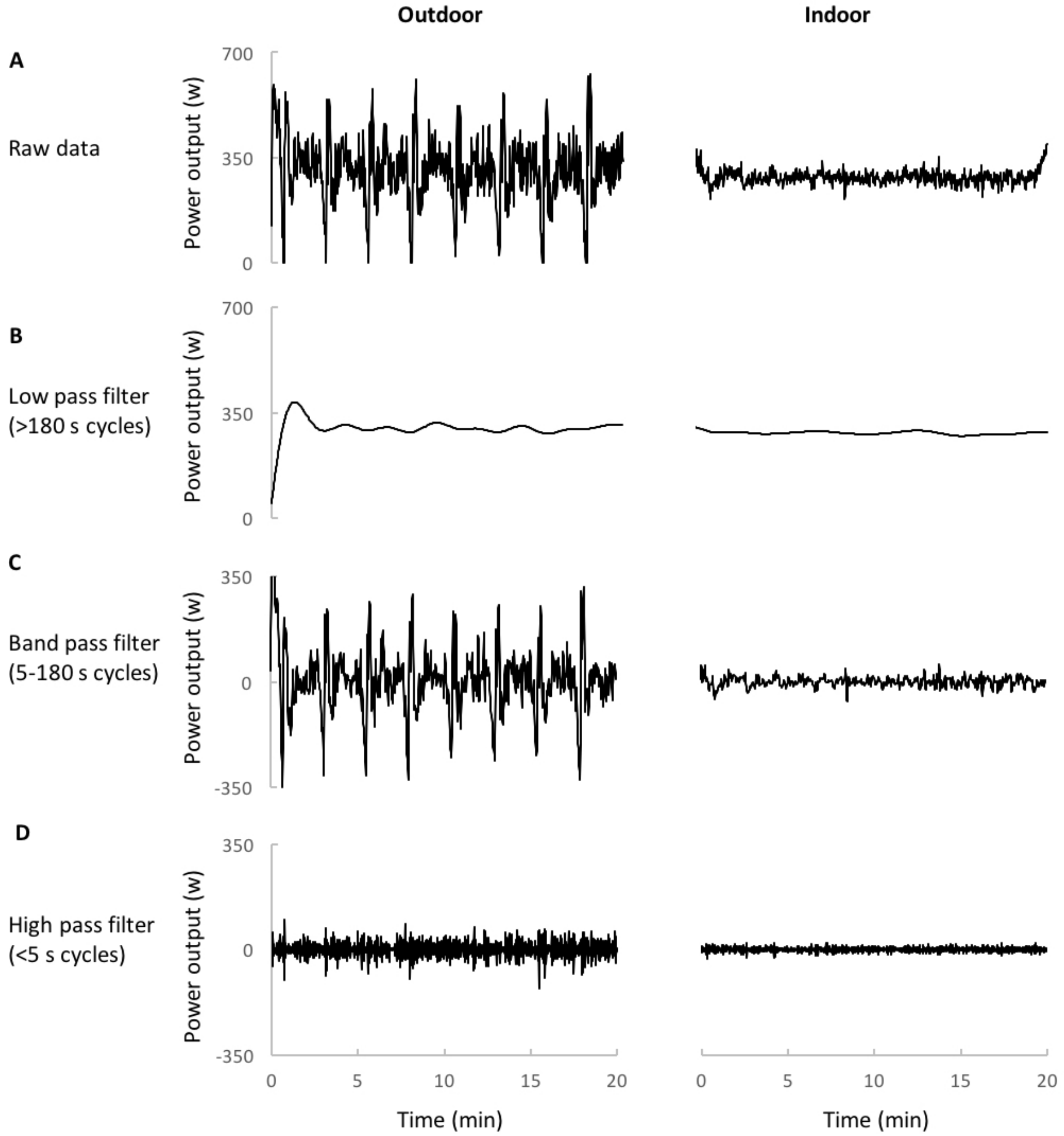

A
9%
8%
7%
6%
5%
4%
3%
2%
1%
0%
Proprtion of samples (%)
0
100
200
300
400
500
600
700
Power output (W)
B
30
25
20
15
10
5
0
Mean within-person standard deviation of power output (W)
*
0
0.1
0.2
0.3
0.4
0.5
Frequency (Hz)
C
1000
100
10
1
0.1
Power Output (W)
Outdoor
Indoor
.00
.10
.20
.30
.40
.50
Frequency (Hz)

Figure 4


Outdoor
Indoor
A
Raw data
B
Low pass filter
(>180 s cycles)
C
Band pass filter
(5-180 s cycles)
D
High pass filter
(<5 s cycles)
Power output (w)
700
350
0
-350
0
5
10
15
20
Time (min)