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The ecological validity of laboratory cycling: Does body size explain the difference between laboratory- and field-based cycling performance?

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Abstract

Previous researchers have identified significant differences between laboratory and road cycling performances. To establish the ecological validity of laboratory time-trial cycling performances, the causes of such differences should be understood. Hence, the purpose of the present study was to quantify differences between laboratory- and road-based time-trial cycling and to establish to what extent body size [mass (m) and height (h)] may help to explain such differences. Twenty-three male competitive, but non-elite, cyclists completed two 25 mile time-trials, one in the laboratory using an air-braked ergometer (Kingcycle) and the other outdoors on a local road course over relatively flat terrain. Although laboratory speed was a reasonably strong predictor of road speed ($R^2 = 69.3\%$), a significant 4% difference ($P < 0.001$) in cycling speed was identified (laboratory vs. road speed: 40.4 ± 3.02 vs. 38.7 ± 3.55 $\text{km} \cdot \text{h}^{-1}$; mean ± s). When linear regression was used to predict these differences (Diff) in cycling speeds, the following equation was obtained: $\text{Diff} (\text{km} \cdot \text{h}^{-1}) = 24.9 - 0.0969 \cdot m - 10.7 \cdot h$, $R^2 = 52.1\%$ and the standard deviation of residuals about the fitted regression line = 1.428 ($\text{km} \cdot \text{h}^{-1}$). The difference between road and laboratory cycling speeds ($\text{km} \cdot \text{h}^{-1}$) was found to be minimal for small individuals (mass = 65 kg and height = 1.738 m) but larger riders would appear to benefit from the fixed resistance in the laboratory compared with the progressively increasing drag due to increased body size that would be experienced in the field. This difference was found to be proportional to the cyclists' body surface area that we speculate might be associated with the cyclists' frontal surface area.

Keywords: *Body mass, height, body surface area, allometric and linear regression models*

Introduction

Laboratory-based research in the applied sports sciences is conducted based on the assumption of ecological validity. More specifically, recommendations are made to the athletic population based upon the findings of laboratory studies (e.g. Convertino, Armstrong, & Coyle, 1996). For example, regarding the energetic cost of running, the validity of transferring information gained in the laboratory to the outdoor environment was addressed by Jones and Doust (1996), leading to the adoption of a 1% gradient for motorised treadmill running. In cycle sport, several authors have identified significant differences between laboratory-based and field-based time-trial performances (e.g. Palmer, Dennis, Noakes, & Hawley, 1996; Smith, Davison, Balmer, & Bird, 2001). In a recent review, Faria, Parker and Faria (2005, p. 308) identified the "examination of the relationship between laboratory cycling test results and competition performance" as one of ten key areas that require further research. Indeed, Saunders, Dugas, Tucker, Lambert and Noakes (2005) have recently highlighted the importance of this relationship, suggesting that previous guidelines for rehydration, being based upon laboratory research, cannot be extrapolated to exercise in the field.

Using the Kingcycle air-braked cycle ergometer during laboratory testing, Smith *et al.* (2001) identified a $2.4 \text{ km} \cdot \text{h}^{-1}$ difference between road and laboratory 40 km time-trial performances, with participants being ∼5.5% slower in the field. However, despite this speed difference, there was no difference in average power output between the separate race environments (measured using an SRM powermeter in both the field and laboratory, $P = 0.34$). This discrepancy would appear to suggest

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that the laboratory protocol does not accurately replicate "real-world" performance – that is, where riders in the laboratory are able to cover a greater distance for the same average energy expenditure.

It has long been recognized that many physiological capacities vary with differences in body mass (Åstrand & Rodahl, 1986; Nevill, Ramsbottom, & Williams, 1992). Although "weight-supported", the importance of body mass in cycling has recently been recognized for both level-ground and uphill cycling, leading to mass exponents of 0.32 and 0.91 respectively (Nevill, Jobson, Palmer, & Olds, 2005; Swain, 1994; A. M. Nevill *et al.*, unpublished observation). However, it remains unclear whether body mass has such an important impact during laboratory cycling performance.

The aims of the present study were to identify whether differences exist between laboratory- and road-based time-trial (TT) cycling and, if so, to what extent body size (mass and height) may help to explain these differences.

Methods

Participants

Twenty-three male cyclists were recruited from local cycling clubs to participate in this study (participant characteristics are presented in Table I). All cyclists had previous experience of laboratory-based testing and competitive road time-trials. This study was approved by the university's ethics committee. Before participation, the cyclists were fully informed of the nature and risks of the study, before providing written consent. Participants were competitive but non-elite cyclists with a mean ($\pm s$) road 25-mile (40.23 km) time-trial best of 62.7 ± 5.0 min.

Test schedule

Each participant completed three experimental sessions: (1) a preliminary test to determine their physical characteristics; (2) a 25-mile cycling time-trial in the laboratory; and (3) a competitive 25-mile road time-trial. Each session was completed in a random order separated by no more than 7 days during the months of May, June and July.

Table I. Physical characteristics of the participants ($n = 23$; mean $\pm s$).

Age (years)	41.3 ± 10.9
Body mass (kg)	78.0 ± 9.4
Height (m)	1.777 ± 0.071
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	4.29 ± 0.55
Maximal aerobic power (W)	336 ± 45.9

Preliminary testing

On arrival at the laboratory, an anthropometric assessment of each cyclist was undertaken. Measurements were made by an ISAK-qualified practitioner in accordance with procedures recommended by the International Society for the Advancement of Kinanthropometry (ISAK, 2001). Body mass was recorded using a balance beam scale (SECA 700, UK) and height was recorded using a stadiometer (Holtain, UK).

The participants then completed a progressive, incremental exercise test to exhaustion on a Kingcycle air-braked cycle ergometer (Kingcycle Ltd, High Wycombe, UK) as described previously (Nevill *et al.*, 2005). Following standardized calibration procedures (Palmer *et al.*, 1996), the Kingcycle system allows cyclists to exercise on their own bike against a resistance comparable to that of riding on the road. The reliability of this system has been shown during 20-km, 40-km (Palmer *et al.*, 1996) and maximal-test protocols (Keen, Passfield, & Hale, 1991).

Experimental trials

Laboratory time-trials. All participants completed a 25-mile time-trial on the Kingcycle ergometer, calibrated before testing as described above. Immediately before the start of the time-trial, participants completed a 10-min warm-up at a self-selected intensity. On completion of the warm-up, participants were asked to cover the 25-mile distance as quickly as possible, during which the only information available to the cyclist was the percentage of race distance remaining. Temperature, relative humidity and barometric pressure were measured on site every 5 – 10 min.

Road time-trials. Participants competed in one of five competitive 25-mile time-trial events, each being carried out on a flat "out and back" course and according to the regulations of the Road Time Trials Council (RTTC, 2004). Data collection was organized so as to minimize the disturbance to the normal race routine. Temperature, relative humidity and barometric pressure were also measured on the roadside every 5 – 10 min. Following a warm-up of self-selected duration and intensity, all cyclists used geared road bicycles fitted with "aero" bars to complete the race distance as quickly as possible. No drafting was permitted. Temperature, relative humidity, wind speed and wind direction were recorded at a local weather station during each of the time-trial events.

Body mass measured on the three occasions was found to be significantly higher on the road time-trial (79 kg) than on either laboratory-based session

(78.0 and 78.4 kg for maximal test and time-trial sessions respectively) ($P < 0.01$). However, the correlations between all three body mass assessments was greater than 0.994 ($P < 0.001$).

Statistical methods

Box and Cox (1964), Nevill *et al.* (1992) and more recently Ingham, Whyte, Jones and Nevill (2002) recognized the need to record performance time as average speed (i.e. using the inverse transformation) to be more symmetric, normally distributed and more linearly related to other variables, such as maximal oxygen uptake ($\dot{V}O_{2max}$). For this reason, cycling performance times were converted to average time-trial speeds ($km \cdot h^{-1}$).

Agreement between laboratory- and field-based cycling speeds was assessed using a paired samples *t*-test, limits of agreement (Bland & Altman, 1986; Nevill & Atkinson, 1997) and regression analyses performed using the statistical software package MINITAB (1995).

Results

The results of both the road and laboratory cycling time-trials are presented in Table II. The paired sample *t*-test identified a significant bias, with the mean road-based speed being 1.7 $km \cdot h^{-1}$ slower than the laboratory-based time-trial speed ($t_{22} = 4.04$, $P < 0.001$). The standard deviation of differences was ± 1.97 $km \cdot h^{-1}$ providing 95% limits of agreement of ± 3.85 $km \cdot h^{-1}$. Evidence of heteroscedastic differences or errors (error variation increase with greater cycling speeds) suggested that the differences or errors should be reported as a ratio or a percentage (see Nevill & Atkinson, 1997). When expressed as a percentage, the mean road-based time-trial speed was 4.2% slower than the laboratory time-trial, with the standard deviation of differences (CV = coefficient of variation) being */÷5.1%, and the 95% limits of agreement being */÷10.3%.

The relationship between each participant's road and laboratory 25-mile TT times was described by the following regression equation:

$$\text{road speed } (km \cdot h^{-1}) = 10.1 + 0.708 \cdot \text{laboratory speed } (km \cdot h^{-1})$$

with $R^2 = 69.3\%$ and the standard deviation of residuals about the regression line $s = 1.7$ ($km \cdot h^{-1}$).

Table II. Road- and laboratory-based 25-mile cycling time-trial data (mean ± *s*).

Trial	N	Time (min)	Speed ($km \cdot h^{-1}$)
Road	23	62.7 ± 4.98	38.7 ± 3.02
Laboratory	23	60.2 ± 5.55	40.4 ± 3.55
Difference	0	2.50 ± 3.13***	1.70 ± 1.97***

****P*<0.001.

We have previously reported the importance of body mass when describing road time-trial cycling speeds using a range of key physiological variables (e.g. $\dot{V}O_{2max}$, maximal aerobic power and power at the ventilatory threshold) (Nevill *et al.*, 2005; A. M. Nevill *et al.*, unpublished observation). For all three variables, body mass was a significant negative determinant of road-based cycling speed, assessed using allometric modelling described previously (Nevill *et al.*, 2005). However, using the same proportional allometric model to predict laboratory-based cycling performance, body mass was found to make no substantial contribution to the model ($P = 0.6$):

$$\text{laboratory speed } (km \cdot h^{-1}) = 14.58 \cdot (\dot{V}O_{2max})^{0.48} \cdot (m)^{0.07}$$

with ($k_1 = 0.48$, standard error of the estimate [SEE] = 0.12; $k_2 = 0.07$ SEE = 0.13), $R^2 = 51.9\%$, the standard deviation of residuals about the fitted regression line $s = 0.065$ and the error ratio of $s = 1.067$ or 6.7%, having taken antilogs.

Similarly, when maximal aerobic power (MAP) was used as a predictor variable instead of $\dot{V}O_{2max}$, body mass made no significant contribution to the model ($P = 0.8$):

$$\text{laboratory speed } (km \cdot h^{-1}) = 1.37 \cdot (\text{MAP})^{0.60} \cdot (m)^{-0.02}$$

with ($k_1 = 0.60$, SEE = 0.07; $k_2 = -0.02$, SEE = 0.08), $R^2 = 80.7\%$, the standard deviation of residuals about the fitted regression line $s = 0.041$ and the error ratio of $s = 1.042$ or 4.2%, having taken antilogs.

To assess the contribution that body mass makes to road-based time-trial cycling performance, multiple regression was used to predict road-based cycling speed, using laboratory-based cycling speed and body mass (*m*) as the predictor variables. The resulting regression model was as follows:

$$\text{road speed } (km \cdot h^{-1}) = 13.8 + 0.821 \text{ laboratory speed} - 0.106 \cdot m$$

with $R^2 = 78.3\%$ and the standard deviation of residuals about the fitted regression line $s = 1.47$ ($km \cdot h^{-1}$). Both the laboratory speed (0.821; SEE = 0.097) and body mass slope parameters (−0.106; SEE = 0.037) were significant ($P < 0.01$).

Hence, linear regression was used to explore whether body mass (*m*) could help explain the observed difference (Diff) between road-based and laboratory-based cycling performances ($km \cdot h^{-1}$)

(Figure 1). The fitted regression equation was as follows:

$$\text{Diff }(\text{km}\cdot\text{h}^{-1}) = 8.70 - 0.133\cdot m$$

with $R^2 = 40.2\%$ and the standard deviation of residuals about the fitted regression line $s = 1.556$. Interestingly, when we fitted the same regression model but with body mass being centred about 65 kg (i.e. the rider mass equating to the total resistance offered by the Kingcycle system as reported by Palmer *et al.*, 1996), the resulting regression equation was as follows:

$$\text{Diff }(\text{km}\cdot\text{h}^{-1}) = 0.071 - 0.133\cdot(m - 65)$$

that is, the same slope parameter (0.133; SEE = 0.035) but the intercept was negligible (0.071; SEE = 0.56).

The ability to predict the difference between road and laboratory cycling speed was further enhanced by the inclusion of the cyclists' height (h). The resulting regression equation was as follows:

$$\text{Diff }(\text{km}\cdot\text{h}^{-1}) = 24.9 - 0.0969\cdot m - 10.7\cdot h \quad (1)$$

with $R^2 = 52.1\%$ and the standard deviation of residuals about the fitted regression line $s = 1.428$. Both the mass and height parameters were significant ($P < 0.05$). As reported earlier, since the differences in cycling speeds provided evidence of heteroscedastic errors (a characteristic that can be overcome with a log-transformation; see Nevill & Atkinson, 1997), the differences or errors would be better expressed as a ratio. When we explored the difference between log-transformed road and log-transformed laboratory cycling speeds (lnDiff), we found

$$\text{lnDiff} = 1.07 - 0.20\ \ln(m) - 0.45\ \ln(h)$$

with $R^2 = 49.6\%$, the standard deviation of residuals about the fitted regression line $s = 0.037$ and the error ratio of $s = 1.038$ or 3.8%, having taken antilogs. Note that the difference between two log-transformed numbers is the log of the ratio between the two numbers – that is, $\ln(X) - \log(Y) = \log(X/Y)$. Taking antilogs of the above log-linear regression model, we obtained the proportional "allometric" model to predict the ratio (road speed)/(laboratory speed) as $2.92\cdot m^{-0.2}\cdot h^{-0.45}$. Given that Dubois and Dubois's (1916) estimate of body surface area (BSA) is known to be proportional to $m^{0.425}\cdot h^{0.725}$, the allometric model to explain the ratio between road and laboratory cycling speeds is approximately $(\text{BSA})^{-0.5}$.

An average wind speed of 5.78 $\text{km}\cdot\text{h}^{-1}$ (range 0–16.7 $\text{km}\cdot\text{h}^{-1}$) was recorded for the five time-trial events, wind direction always being identified as a cross-wind with respect to the time-trial course. As anticipated, the contribution of wind speed (w) in the above regression equation was negative but not significant ($P = 0.922$). The assessment of environmental data (temperature, relative humidity and barometric pressure) identified a significant difference in barometric pressure between the laboratory and road-based time-trials (1021 vs. 1003 mbar; $P < 0.001$). However, when the environmental data were included in the regression equation to predict the difference between road and laboratory time-trial speeds, none of the environmental factors made a significant contribution ($P > 0.2$) having already controlled for mass and height.

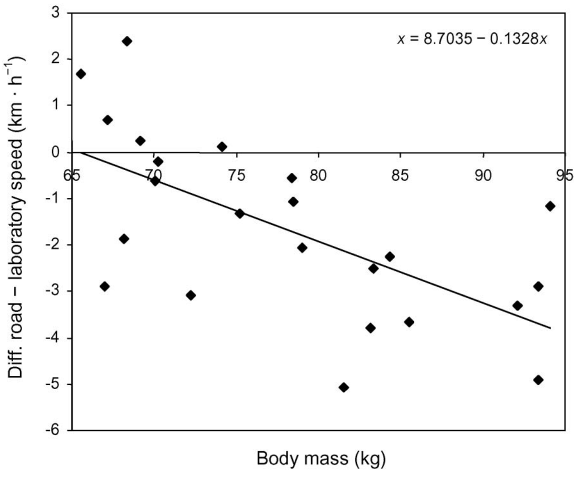

Figure 1. The differences between road and laboratory cycling speed ($\text{km}\cdot\text{h}^{-1}$) plotted against body mass (kg).

Discussion

In support of previous findings (e.g. Balmer, Davison, & Bird, 2000; Coyle *et al.*, 1991), the regression analysis confirmed the capacity of laboratory-based tests to predict "real-world" cycling performance, with 69.3% of the variation in road time-trial speed being explained by laboratory time-trial speed. However, the applied sports scientist might expect a stronger relationship before accepting a test's ecological validity. Indeed, the limits of agreement suggest that a cycling time-trial performed on a Kingcycle ergometer does not accurately replicate a time-trial performed in the field, given there was a systematic difference between road and laboratory time-trial cycling speeds (4% faster in the laboratory than on the road; $P < 0.001$).

This difference, however, might simply be explained by the time-trial course profile. The Kingcycle "course" was entirely homogeneous, whereas the road courses used during the field trials, although relatively flat, exhibited some topographical variation. As such, road speed would be comparatively stochastic, with the reduction in speed on inclined sections not being entirely compensated by increases in speed on descents. A number of authors have identified the significant influence of variable topographical and environmental conditions on road speed while maintaining a given mean power (Atkinson & Brunskill, 2000; Swain, 1997; White, 1994). Incorporating equal sections of headwind and tailwind into a model of time-trial performance, Swain (1997) showed that these environmental conditions produce variations in the cyclist's speed that result in a slower finishing time than would be achieved on a course without wind. A similar situation has been described for time-trial courses of variable gradient – that is, where the slower uphill sections contribute more to overall time than the faster downhill sections (Atkinson & Brunskill, 2000; Swain, 1997).

The results of the present study suggest that wind speed had little influence on the difference between road- and laboratory-based cycling performance. This is unsurprising given that the relatively low wind speeds were never manifest as direct head/tail winds (Nevill *et al.*, 2005). Indeed, the use of aerodynamic equipment would appear to have eliminated the potentially negative impact of any crosswind (Kyle, 1991). In contrast, a lack of topographic data for each of the time-trial courses means that the impact of variable gradient on performance could not be fully examined. However, being "relatively" flat, it is unlikely that variation in course gradient would be sufficient to explain the difference in performance ($1.7 \text{ km} \cdot \text{h}^{-1}$) between the road and laboratory environments. Indeed, it is possible to use standard equations of motion for cycling (e.g. Martin, Milliken, Cobb, McFadden, & Coggan, 1998) to compare performances between a flat 40-km time-trial course and a course of variable profile (e.g. 36 km flat, 2 km uphill at 2% grade, 2 km downhill at 2% grade). Using standard rider parameters (i.e. body mass = 75 kg, effective frontal area = 0.40 m^2, drag coefficient = 0.5, coefficient of rolling resistance = 0.004, power = 240 W), a cyclist is able to maintain an average speed of $42.74 \text{ km} \cdot \text{h}^{-1}$ on a flat course compared with $42.44 \text{ km} \cdot \text{h}^{-1}$ on a variable course, a difference of just $0.3 \text{ km} \cdot \text{h}^{-1}$.

We have previously identified the important influence of body mass on cycling performance in the field (Nevill *et al.*, 2005; A. M. Nevill *et al.*, unpublished observation). Typically, extra mass is advantageous during flat time-trials, as power demand (found to scale proportional to $m^{0.32}$) is less than power supply (proportional to $m^{0.67}$). Conversely, during hill time-trials, power demand (found to scale proportional to $m^{0.9}$) is greater than power supply (proportional to $m^{0.67}$), benefiting the lighter rider (A. M. Nevill *et al.*, unpublished observation).

Berry, Woodard and Storsteen (1992) observed a small body mass effect during stationary cycling. At low work rates (< 132 W), increased effort was required for very large individuals (range 58–147 kg) due to the need to move heavier legs. However, possibly due to higher workloads (> 200 W) in the current study, this effect was not observed. Indeed, allometric modelling suggests that the inclusion of body mass as an independent predictor variable makes no contribution to the prediction (utilizing key physiological variables such as $\dot{V}O_{2\max}$ and maximal aerobic power) of laboratory cycling performance ($P > 0.05$). Therefore, the calibration (carried out before all tests) of this laboratory-based ergometer (Kingcycle) would appear to effectively unload participant body mass.

Regression analyses, however, did identify a significant contribution of body mass to the prediction of road time-trial speed. Providing laboratory speed as the only independent variable explained 69.3% of the variation in road speed, whereas the addition of body mass increased the explained variance to 78.3%. These results and those illustrated in Figure 1 show that body mass does become an important factor in explaining the difference between laboratory and road time-trial performance.

The slope parameter obtained when using linear regression to predict this difference identified a change in performance speed of $0.133 \text{ km} \cdot \text{h}^{-1}$ for every 1 kg of body mass. Furthermore, when body mass was centred about 65 kg (i.e. the rider mass equating to the total resistance offered by the Kingcycle system as reported by Palmer *et al.*, 1996), the slope parameter remained the same while the intercept became negligible. This supports the finding that the Kingcycle ergometer provides resistance equivalent to that experienced by a 65-kg cyclist when riding on the road. Thus, during a laboratory-based time-trial using a Kingcycle ergometer, a rider weighing 75 kg is able to sustain an average speed that is $1.3 \text{ km} \cdot \text{h}^{-1}$ faster than that of a rider of 65 kg body mass. The heavier rider experiences less resistance to motion (equivalent to a 65-kg rider) and is thus able to maintain a higher speed than a lighter rider.

Further inclusion of body size information (height) improved our explanation of the difference between road and laboratory time-trial performance. When multiple linear regression was used to predict these differences, mass and height were both significant negative predictors. Indeed, when we explored the difference in cycling speeds using allometric modelling, we obtained the following ratio between cycling speeds: ratio (laboratory/road) $= 2.92 \cdot m^{0.2} \cdot h^{0.45}$. It is well known that both height and mass have been used to predict body surface area (BSA), given by the equation BSA approximates to $m^{0.425} \cdot h^{0.725}$ (Dubois & Dubois, 1916). The ratio between laboratory and road cycling speeds is therefore crudely $(\text{BSA})^{0.5}$.

Therefore, we might speculate that the negative contributions of both height and body mass in the above regression equations are a crude approximation of body surface area that might also be proportional to the frontal surface area (known to be an important limiting factor to road cycling speed; Di Prampero, Cortilli, Mognoni, & Saibene, 1979).

These findings have important implications for the applied sports sciences, principally in identifying the discrepancy between laboratory- and field-based cycling performance. This investigation has identified the major role played by body size in explaining ~52% of the difference between road-based and laboratory-based cycling performance. For practical purposes, a simple rearrangement of equation (1) predicts road time-trial cycling speed as:

$$\text{road speed } (\text{km}\cdot\text{h}^{-1}) = \text{laboratory speed } (\text{km}\cdot\text{h}^{-1}) + 24.9 - 0.0969\cdot m - 10.7\cdot h \tag{2}$$

Although the Kingcycle ergometer appears to provide an unbiased estimate of road cycling speed for a 65-kg individual [the difference's intercept being negligible at 0.071 $(\text{km}\cdot\text{h}^{-1})$, SEE = 0.56; see Results], any variation about this mass will limit the ecological validity of research findings. Interestingly, based on the rearranged equation (2) above, there will be zero difference between road and laboratory cycling speed for a cyclist whose body mass is 65 kg and whose height 1.738 m. However, for a cyclist who is heavier or taller than these values, the difference widens/declines with increasing body size.

Further research is required to ascertain the ecological validity of alternative cycle ergometers. It is probable that other ergometers (e.g. Monark, SRM, Velotron) negate the variable impact of body mass observed when using the Kingcycle system, since they do not rely upon a wind-load simulator of fixed dimensions. Furthermore, despite the importance of body mass, a large proportion of the difference between laboratory and field time-trial performance remains to be explained. Variation in other factors such as pacing strategy, cadence, thermoregulation and motivation may explain further the observed differences between laboratory and field time-trial cycling performance on a flat course.

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