Scaling of submaximal oxygen uptake with body mass and combined mass during uphill treadmill bicycling

Heil, Daniel P. Scaling of submaximal oxygen uptake with body mass and combined mass during uphill treadmill bicycling, J. Appl. Physiol. 85(4): 1376–1383, 1998.—This study examined the scaling relationships of net O2 uptake ([VO2net] = VO2 – resting VO2) to body mass (MB) and combined mass (MC = MB + bicycle) during uphill treadmill bicycling. It was hypothesized that VO2net(l/min) would scale proportionally with MB[i.e., VO2net ∝ MB0.99] and less than proportionally with MB[i.e., VO2net ∝ MB0.89]. Twenty-five competitive cyclists [73.9 ± 8.8 and 85.0 ± 9.0 (SD) kg for MB and MC, respectively] rode their bicycles on a treadmill at 3.46 m/s and grades of 1.7, 3.5, 5.2, and 7.0% while VO2 was measured. Multiple log-linear regression procedures were applied to the pooled VO2net data to determine the exponents for MB and MC after statistically controlling for differences in treadmill grade and dynamic friction. The regression models were highly significant (R2 = 0.95, P < 0.001). Exponents for MB (0.99, 95% confidence interval = 0.80–1.18) and MC (0.89, 95% confidence interval = 0.72–1.07) did not differ significantly from each other or 1.0. It was concluded that the VO2 cost of uphill bicycling was less than the VO2 cost of treadmill bicycling at a level grade, RD is the dominant resistive force (7). In contrast, during bicycling up steep hills on an inclined treadmill, RG is the dominant resistive force and RD can be considered negligible (7). Thus, for uphill or inclined treadmill bicycling, it follows that Rnet = RG + RR and WS for a given s is provided by (from Eq. 3)

\[ \dot{W}_S = k (R_G + R_R) \times \dot{s} \]  

where (7)

\[ R_G = M \times g \times (\sin \theta) \]  

and (16)

\[ R_R = g \times M \times (\mu_O + \mu_R \times v) \times (\cos \theta) \]  

where MC is the combined mass of the cyclist with bike and gear (kg), g is the constant of gravitational acceleration (9.81 m/s²), θ is the inclination of the road surface (degrees), v is the air velocity relative to the bicycle and rider (m/s; v = s on a treadmill), and μO and μR are the coefficients of static and dynamic friction (both dimensionless), respectively. If it is further assumed that the magnitude of RR is negligible, by substituting Eq. 5 into Eq. 4 the metabolic power required to overcome gravitational resistance is given as

\[ \dot{W}_S = k [M \times g \times (\sin \theta)] \times \dot{s} \]  

Thus, for a given θ and s, the submaximal steady-state metabolic power required for steep uphill or inclined treadmill bicycling should be directly proportional to MC (i.e., WS ∝ MC = MB0.89).

Interestingly, research involving the energetic demands of uphill bicycling have mostly been limited to issues of pedal cadence and body position (26, 27). Thus the relationship between submaximal VO2 and MC during uphill bicycling has never been addressed experimentally.

The related issue of VO2 demand during uphill bicycling as a function of body mass (MB) was evaluated by Swain (25) using allometric scaling procedures. Swain concluded that the VO2 cost of uphill bicycling was proportional to MB raised to the 0.79 power (i.e., VO2 ∝ MB0.79). Because the 0.79 exponent was <1.0, heavier cyclists tended to expend less energy than smaller cyclists relative to MB when uphill bicycling at the same θ and s. Swain further speculated that the differential expense of energy for graded treadmill bicycling and the 0.79 MB exponent was the result of the cyclists' bicycles being relatively lighter for the heavier cyclists (i.e., as a percentage of MB). The potential influence of RB on the derived MB exponent,
however, was never addressed. Although the plausibility of Swain’s hypothesis seems reasonable, it has never been verified experimentally.

The above review outlines a theoretical framework for predicting the scaling relationship between submaximal \(V\ddot{O}2\) and \(M\ddot{C}\) during uphill bicycling. The theoretical dependence of \(V\ddot{O}2\) on \(M\ddot{C}\) \((V\ddot{O}2 \propto M^2)\), however, has never been explained experimentally, whereas Swain’s (25) 0.79 exponent for \(M\ddot{B}\) has never been explained theoretically or experimentally. Thus the present study was designed to evaluate both of these issues by measuring submaximal \(V\ddot{O}2\) for trained cyclists during uphill treadmill bicycling. These data were then evaluated using log-linear multiple regression techniques (19, 20) to define the appropriate scaling relationships.

**METHODS**

Subjects. Volunteer competitive cyclists from the local area read and signed an informed consent document, as well as a cycling history questionnaire, before any testing in the Human Performance Laboratory at the University of Massachusetts (Amherst, MA). Subjects refrained from strenuous activity on the day before each visit and abstained from caffeine ingestion for at least 3 h before arriving at the laboratory.

Testing of peak \(V\ddot{O}2\). On the first laboratory visit, each subject completed a continuous, incremental cycle ergometry test to exhaustion (model 829E cycle ergometer, Monark Bodyguard Fitness, Varberg, Sweden). Before each test, the ergometer was calibrated according to procedures outlined by the manufacturer. In addition, seat height and handlebar position were set according to each subject’s preference. Resting \(V\ddot{O}2\) was measured first with subjects sitting quietly on the ergometer (no pedaling) over a 5-min period. This was followed by a standardized warmup of 3 min at 80 W while pedaling 80 rpm, 3 min at 150 W and 80 rpm, and finally 3 min at 180 W and 90 rpm. The peak \(V\ddot{O}2\) \((V\ddot{O}2_{peak})\) test began immediately thereafter by increasing power output by 30 W at 1-min intervals during pedaling 90 rpm until volitional exhaustion. Each subject’s \(V\ddot{O}2_{peak}\) was defined as an average of the highest two or three values within 2.0 ml·kg\(^{-1}\)·min\(^{-1}\) of each other. The \(V\ddot{O}2_{peak}\) values were considered valid if at least two of the three following criteria were satisfied: 1) a leveling of \(V\ddot{O}2\), despite an increase in power output, 2) a maximal heart rate > 10 beats below each subject’s age-predicted maximal heart rate (220 – age in years), and 3) a respiratory exchange ratio ≥ 1.1.

Graded treadmill bicycling. On the second laboratory visit, body height (m), as well as separate mass measures for the body, the bike, and the cyclists’ extra gear for riding (i.e., helmet and cycling cleats), was obtained. Mass was determined using a standard beam scale to the nearest 0.1 kg. Bicycles were stripped of extraneous equipment such as tire pumps, spare tubes, and water bottles before mass measurements.

On the basis of observations during pilot testing and reports by other researchers (26), a separate laboratory visit for practice riding on the treadmill was not necessary. Thus subjects practiced and warmed up before testing by riding their own bicycles on the laboratory treadmill (Trackmaster TM500-E, JAS Fitness Systems). The treadmill’s surface measured 2.3 m long × 1.8 m wide, with speed and incline ranges of 1–11 m/s and 0–12.7°, respectively. The practice session also served to acquaint each subject with the specific treadmill speed and grades to be tested. Practice and testing on the treadmill were limited to the left side of the treadmill, where a handrail was installed down the entire length of the treadmill. The amount of practice time on the treadmill, which varied between 10 and 25 min, depended on how quickly each subject became comfortable with the task of treadmill bicycling. As an added safety measure, two mattresses were placed directly behind the treadmill to cushion the subject in the event of a fall.

Before treadmill practice and testing, all bicycle tires were inflated to the manufacturers’ suggested pressure (i.e., 69–83 N/cm\(^2\)). The four treadmill bicycling conditions corresponded to treadmill grades of 1.7% (1°), 3.5% (2°), 5.2% (3°), and 7.0% (4°), all at a treadmill speed of 3.46 m/s. Pilot testing indicated that these combinations of speed and grade would elicit a wide range of steady-state energetic demands in moderately trained cyclists. Subjects began their test session with a 2- to 3-min warmup on the treadmill at a speed of 3.46 m/s and grade of 1.7%, which was followed immediately with an adjustment of the grade to match the first condition being tested. The four grades were tested successively, with 6 min of riding at each grade, the order of which was counterbalanced across subjects. Subjects received verbal feedback during all treadmill bicycling and were encouraged to maintain a steady position on the treadmill that was centered lengthwise but within reach of the handrail. Subjects were also required to maintain the same gripping position (i.e., hands on the brake hoods of handlebars) on their handlebars during all four conditions to minimize changes in body position relative to the bicycle.

Because the subjects’ bicycles were equipped with various gear combinations, it was not feasible for all subjects to use the same gearing without major equipment modifications to many of the bicycles. Alternatively, the subjects used the gearing available on their own bicycles to achieve similar gear ratios and thus similar pedal cadences. The gear ratios actually used were 1.75 (42/24), 1.62 (42/26), 1.70 (39/23), and 1.63 (39/24).

Pedal cadence and treadmill speed were measured twice near the end of each condition; grade was measured at the beginning of each condition. Cadence was determined by timing 10 pedal revolutions; a digital hand tachometer (Biddle Instruments, Blue Bell, PA) was used to measure treadmill speed. Treadmill grade was measured within ± 0.5° using an inclinometer on a flat surface adjacent to the treadmill belt.

Estimating \(\mu_D\). The \(\mu_D\) was determined for each subject at each grade for use as a covariate in the regression analyses. The \(R_{net}\) to treadmill bicycling was computed as the sum of \(R_G\) and \(R_s\) (7, 16).

\[
R_{net} = (R_G + R_s) = [g \times M_C \times (\sin \theta) + g \times M_C \times (\cos \theta) \times (\mu_S + \mu_D \times v)]
\]

(8)

The value of \(\mu_S\) can be assumed constant at ~0.0025 (16). Rearranging Eq. 8 to solve for \(\mu_D\) gives

\[
\mu_D = \frac{R_{net} - g \times M_C \times (\sin \theta) - g \times M_C \times (\cos \theta) \times \mu_S}{g \times M_C \times (\cos \theta) \times v^{-1}}
\]

(9)

where \(R_{net}\) is the only unknown, since \(M_C, \theta,\) and \(v\) were measured (v = s for treadmill bicycling), and \(g\) and \(\mu_S\) are constants.

Values for \(R_{net}\) were measured directly as the towing force required to maintain a stationary position on the treadmill.
After the metabolic testing described above, the head tube of each subject's bicycle was attached via a lightweight cable to a hand-held digital dynamometer (model DFIS 100, range 0.5–500 N, Chatillon, Greensboro, NC) that was zeroed before each measurement. Subjects maintained a balanced position on the moving belt of the treadmill for 5–10 s while the researcher held and visually read the digital display on the dynamometer. The most stable dynamometer reading was recorded within 0.5 N.

Anthropometry. Percent body fat and lower limb mass (MLL) were also determined for use as potential covariates in the statistical analyses. Percent body fat was estimated from hydrostatic measures of body density (8) and the formula derived by Brozek et al. (4). Lower limb volume for each subject was also estimated using a geometric modeling technique validated by Sady et al. (23) and Freedson et al. (10). All lower limb anthropometric measures were taken on the right side of the body by the same investigator using standard anthropometers (lengths and breadths) and cloth tape measures (circumferences) according to the procedures outlined by Lohman et al. (18). Total MLL (kg) was computed as follows: 

\[ M_{LL} = 2(pV_T + p_V_T + p_V_T), \]

where the subscripts T, L, and F refer to estimated segment densities (\( \rho \), g/cm\(^3\)) and segment volumes (V, liters) for the thigh, leg, and foot, respectively. Segment densities were estimated at 1.06, 1.08, and 1.10 g/cm\(^3\) for the thigh, leg, and foot, respectively (30).

VO\(_2\) instrumentation. Standard indirect calorimetry procedures were used to determine submaximal VO\(_2\) and VO\(_2\)peak. Expired gases were continuously sampled (250 Hz) from a 3-liter mixing chamber and analyzed for O\(_2\) and CO\(_2\) concentrations via a computer-based system (286 Leading Edge computer using VO2Plus Software from Exeter Research, Brentwood, NH) interfaced with Ametek O\(_2\) (model S-3AI) and CO\(_2\) (model CD-3A) analyzers. The gas analyzers and Rayfield Equipment dry gas meter (for measuring inspired gases) were interfaced to the computer via an analog-to-digital board. The computer system compiled O\(_2\) information at 60- and 30-s intervals for the submaximal VO\(_2\) and VO\(_2\)peak protocols, respectively. The metabolic system analyzers were calibrated using standardized gases of verified O\(_2\) and CO\(_2\) concentrations before each test. Heart rate was monitored continuously during the VO\(_2\)peak test with a Vantage heart-rate monitor (Polar CIC).

Statistical analyses. All submaximal VO\(_2\) values were converted to VO\(_2\)net values by subtracting subjects' sitting resting VO\(_2\) from their respective submaximal VO\(_2\) values from the four conditions. Computed VO\(_2\)net > 0 l/min were then assumed to represent the energetic needs of the bicycling task above those required for sitting at rest. The internal consistency of reliability of replicate VO\(_2\)net measures across minutes 3–5 for resting VO\(_2\)net and across minutes 4–6 for each test grade was assessed using a two-factor repeated-measures intraclass correlation (\( r_{IC} \)) model, as described by Baumgartner (3). Mean VO\(_2\)net values were determined by averaging across the last 3 min of measurement. Measured values for treadmill speed, pedal cadence, and mean VO\(_2\)net were analyzed for differences across treadmill grades using single-factor repeated-measures ANOVA procedures. The above significance tests were performed at the 0.05 alpha level.

Standard log-linear regression analysis techniques (19, 20) were used to determine the dependence of VO\(_2\)net on M\(_C\) and M\(_B\). The log-linear model for VO\(_2\)net takes the following form

\[
\log(VO_{2\text{net}}) = \log(k) + b_1 \times (G) + b_2 \times \log(C) + b_3 \times \log(M) + \epsilon
\] 

where \( \log(k) \) is the y-intercept, \( b_1 \) is a dummy-coded slope term for a nominal scale variable (G), \( b_2 \) is a slope term for any continuous scale covariate (C), \( b_3 \) is the slope term for mass (M, kg), and \( \epsilon \) is an additive error term. Transformed out of the logarithmic scale, Eq. 10 becomes

\[
VO_{2\text{net}} = a \times C^{b_2} \times M^{b_3} \times \epsilon
\] 

where \( a \) is a constant that varies with the value of the nominal scale variable, \( aC^{b_2} \) is the mass coefficient with units l/min \( -1 \cdot kg^{-b_3} \), \( \epsilon \) is a multiplicative error term, and \( b_3 \) is the mass exponent that describes the scaling relationship between VO\(_2\)net and mass \([i.e., \ VO_{2\text{net}} \propto M^{b_3}]\). Treadmill grade was modeled as a set of nominal scale variables \((C_1, C_2, C_3)\) with values of 0 or 1. The repeated measurements on individual subjects were also treated as a cluster of nominal scale variables, as outlined by Lee et al. (17). Possible continuous scale covariates in the regression analysis included years of endurance training experience, computed values for \( \mu_D \) and M\(_{LL} \), and percent body fat. If \( b_2 = 1 \), then changes in VO\(_2\)net were directly proportional to mass. If \( 0 < b_3 < 1 \), however, then the VO\(_2\)net associated with performing a specific uphill treadmill cycling task decreased with an increase in mass. The significance of all coefficients and possible interactions between covariates were verified with partial F tests (14) at the 0.15 alpha level, whereas the overall model significance was evaluated at the 0.05 alpha level. Normality of the log-linear model residuals was evaluated with the Shapiro-Wilk W test for normality (24).

RESULTS
The 25 subjects (23 men and 2 women) averaged 24.7 ± 5.7 (range 19–40) yr old, 1.80 ± 0.09 (range 1.57–1.96) m body height, 11.7 ± 4.5% (range 6–22%) body fat, 4.61 ± 0.79 (range 2.5–5.98) l/min VO\(_2\)peak, and 6.2 ± 3.4 (range 0.5–13) yr of endurance activity experience and were riding 262 ± 126 (range 100–523) km/wk at the time of testing. Mass measurements averaged 73.9 ± 8.8 (range 56.48–97.39) kg for M\(_B\), 10.1 ± 0.66 (range 8.86–11.00) kg for bike mass, 1.13 ± 0.19 (range 0.80–1.48) kg for all additional mass (helmet and cleats), and 85.0 ± 9.0 (range 66.93–108.86) kg for M\(_C\). Measures of treadmill speed (\( P = 0.95 \)) and pedal cadence (\( P = 0.88 \)) did not differ across the four test grades. Individual pedal cadences ranged from 57 to 63 rpm (this was a result of the slightly different gear ratios available on each subject's bicycle).

Data for three subjects on the steepest grade (7.0%) were dropped from all analyses, because the subjects could not maintain a steady-state VO\(_2\)net. With use of the remaining data (n = 97), all intraclass correlations for VO\(_2\)net during uphill bicycling were high (\( R_{IC} = 0.96–0.99 \)) with no significant differences between mean minute values over the 3 min of measurement (\( P > 0.255 \)). Therefore, mean VO\(_2\)net values were computed over the last 3 min of measurement for use in all ensuing analyses.

Mean VO\(_2\)net values for treadmill grades of 1.7% [1.10 ± 0.17 (SD) l/min], 3.5% (1.67 ± 0.22 l/min), 5.2% (2.26 ± 0.25 l/min), and 7.0% (2.88 ± 0.32 l/min) differed significantly from each other (\( P < 0.001 \)). Slopes for the regression of \( \log(VO_{2\text{net}}) \) on \( \log(M_{B}) \) (Fig. 1) and \( \log(M_{C}) \) (Fig. 2) did not differ significantly across
the four test grades (P > 0.344) (13). This indicated that the log(VO$_2$net) data for all four test grades could be pooled for the final regression analyses.

The resulting coefficients from the pooled regression of VO$_2$net on MB are provided in Table 1. The only consistently significant covariate across all regression analyses was µD, an increase of which was associated with a positive increase in VO$_2$net. The results in Table 1 suggest that, after controlling for differences in treadmill grade and µD, VO$_2$net increased positively with an increase in MB raised to the 0.89 power (95% confidence interval = 0.72–1.07; R$^2 = 0.95$, P < 0.001). The nominal scaled subject variables were not significant and thus were dropped from the final regression model (P > 0.08). The same analysis was performed for the regression of VO$_2$net on MC (Table 2), which found that VO$_2$net increased in proportion to MC raised to the 0.99 power (95% confidence interval = 0.80–1.18; R$^2 = 0.95$, P < 0.001). Neither the exponent for MB (0.89) nor that for MC (0.99) differed statistically from 1.0. Finally, neither regression model's residuals demonstrated a lack of normality (P > 0.20) (24).

**DISCUSSION**

The energetic demands of uphill bicycling have been modeled by a number of researchers (7, 16, 21), each utilizing some form of Eq. 1. The exact scaling relationship between VO$_2$net demand and MB or MC for uphill bicycling, however, has never been verified or explained experimentally. Thus the purpose of this study was to evaluate these issues using logarithmically based multiple regression analysis and allometric scaling procedures as analytic tools.

It was hypothesized that, for a given grade and speed, the energetic cost of overcoming gravitational resistance would be directly proportional to MC (i.e., VO$_2$ ~ M$_C^{1.00}$). Indeed, results from the present study indicate that VO$_2$net scaled with MC raised to the 0.99 power. Thus the results of this study support the premise by others (7, 21) that the VO$_2$net demand for overcoming gravitational resistance during uphill bicycling is directly proportional to the combined mass of the cyclist, the bicycle, and all other equipment being transported uphill. The effects of small changes in MC...
computed values of \( \mu_D \) as a covariate in the analysis, different approaches to the statistical analysis. In the 10% grade. These differences may be the result of

\[
V_\dot{O}_2(\text{net}) \text{ to differences in } M_B \text{ for uphill treadmill bicycling in trained cyclists}
\]

Table 1.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>( \beta )</th>
<th>95% CIs for ( \beta )</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-1.270</td>
<td>-1.560, -0.979</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Grade</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( C_1 )</td>
<td>0.176</td>
<td>0.1539, 0.1982</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0.308</td>
<td>0.2855, 0.3299</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>0.411</td>
<td>0.3879, 0.4340</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( \mu_D )</td>
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<td>0.0936, 0.1672</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( M_B, \text{kg} )</td>
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<td>0.7219, 1.0681</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model ( P ) value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model coefficients (\( \beta \)), 95% confidence intervals (CIs) for \( \beta \), and \( P \) values are provided for dependent variables; \( n = 97 \). \( V_\dot{O}_2(\text{net}) \), net \( O_2 \) uptake; \( M_B \), body mass; \( C_1, C_2, \) and \( C_3 \) are dummy-coded (0, 1) variables for treadmill grades of 3.5, 5.25, and 7.0%, respectively; \( \mu_D \), coefficient of dynamic friction (dimensionless).

on submaximal energy demand during uphill cycling and the theoretical relationships between \( M_C \) and \( M_B \) on uphill time-trial cycling performance are discussed in the APPENDIX.

The present study also found that \( V_\dot{O}_2(\text{net}) \) scaled with \( M_B \) to the 0.89 power. This value is higher, although not significantly, than the 0.79 \( M_B \) exponent reported by Swain (25) for \( V_\dot{O}_2 \) during uphill treadmill bicycling at a 10% grade. These differences may be the result of different approaches to the statistical analysis. In the present study, for example, it was necessary to use computed values of \( \mu_D \) as a covariate in the analysis, whereas Swain did not report the use of any covariates for deriving the 0.79 exponent. Values for \( \mu_D \) in the present study averaged 2.06E-03 ± 9.13E-04 (SD), which is much higher than 3.4E-05 reported for high-pressure sew-up racing tires on a smooth surface (16). These high \( \mu_D \) values are attributed to the treadmill surface, which was specifically designed with a high rolling friction so that in-line skating at steep grades was possible. When the regression model in Table 1 for \( V_\dot{O}_2(\text{net}) \) was recomputed without \( \mu_D \) as a covariate, the \( M_B \) exponent decreased from 0.89 to 0.75, which is similar to Swain’s reported value of 0.79. Therefore, Swain’s 0.79 \( M_B \) exponent may be due, in part, to a lack of statistical control over high \( \mu_D \) values as a covariate.

Initially, there was some doubt concerning the physiological significance of the 0.89 \( M_B \) exponent, since it did not actually differ statistically from 1.0. This issue was addressed by using various energetic equations of locomotion from the literature (1, 7, 12) to verify the experimental derivation of the 0.89 exponent. For example, an equation for the metabolic cost of walking with various-size loads carried on the back is given by (12)

\[
E = (M_B + M_{EM}) \times [2.3 + 0.32 (v - 2.5)^{0.65}] + G [0.2 + 0.07 (v - 2.5)]
\]

where \( E \) is the metabolic cost (kcal/h), \( M_{EM} \) is the external mass carried (kg), \( v \) is walking speed (km/h), and \( G \) is treadmill grade (%). Values of \( E \) were then computed for \( M_B \) between 50 and 100 kg for various combinations of speed and grade and assuming no external load (\( M_{EM} = 0 \)). With use of the log-linear regression procedures described earlier, the computed \( M_B \) exponent for \( \log(E) \) vs. \( \log(M_B) \) for every combination of speed and grade was exactly 1.0 (in this instance, \( M_B = M_C \) because \( M_{EM} = 0 \)). These results mirror the present study findings precisely for the combined mass of the cyclists and their equipment. To simulate the energy cost of locomotion with an external load, values of \( E \) were then recomputed for \( M_{EM} \) of 10 kg (which is similar to the nearly constant 10.1 kg of cyclists’ equipment). This time the \( M_B \) exponent decreased from 1.0 to 0.88 while the exponent for \( M_C \) (where \( M_C = M_B + 10 \) kg) remained at 1.0 for every combination of speed and grade. Again, these results appear to simulate the experimentally derived 0.89 and 1.0 exponents for \( M_B \) and \( M_C \), respectively, determined for uphill bicycling in the present study. Furthermore, the simulations described above can be replicated exactly (with and without external loads) using generalized equations predicting the metabolic cost of level and graded walking (1), level and graded running (1), and graded bicycling (7). Thus the scaling relationships described by the present study findings appear to be independent of speed and grade, the nature of the added mass (e.g., increased fat mass, bicycle equipment mass, backpack mass), and the mode of locomotion (bicycling, walking, running), so long as gravity is the primary external resistance. One should also note that the above equations were derived on adults similar in body size (e.g., adults were not evaluated together with children). Briefly, the consistency of the above simulations with the present experimental findings suggests that the \( M_C \) and \( M_B \) exponents reported in Tables 1 and 2 reflect predictable physiological consequences to the steady-state resistance of gravity and are not merely statistical artifacts.

Although the simulations described above support the present study findings, the simulations appear to contradict reports in the literature (22, 28). Rogers et al. (22), for example, determined that an \( M_B \) exponent of 0.75 was more appropriate than 1.0 for comparing

Table 2. Final log-linear regression model relating \( V_\dot{O}_2(\text{net}) \) to differences in \( M_C \) for uphill treadmill bicycling in trained cyclists

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>( \beta )</th>
<th>95% CIs for ( \beta )</th>
<th>( P )</th>
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<td>Constant</td>
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<td>Grade</td>
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</tr>
<tr>
<td>( C_1 )</td>
<td>0.176</td>
<td>0.1540, 0.1984</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>0.308</td>
<td>0.2865, 0.3302</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>0.412</td>
<td>0.3884, 0.4346</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( \mu_D )</td>
<td>0.127</td>
<td>0.0906, 0.1639</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( M_C, \text{kg} )</td>
<td>0.989</td>
<td>0.7965, 1.1809</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>( R^2 )</td>
<td>0.947</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model ( P ) value</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( M_C \), combined mass; see Table 1 legend for definition of other abbreviations; \( n = 97 \).
the submaximal energetic cost of treadmill running between prepubertal children, circumpubertal children, and adults. The authors noted that the 0.75 exponent was probably a function (in part) of the children having a greater stride frequency than the adults. Similar observations were reported by Taylor et al. (28) for an interspecies comparison of submaximal energetic data on 62 avian and mammalian species. Taylor et al., however, followed up their observations with a computation of the energy required per stride per unit mass at the relative speed where a quadruped changes from a trot to a gallop. This analysis revealed that the quadrupeds, with a fourfold range in \( \text{M}_B \) (0.01–100 kg), consumed a nearly constant 5 J \cdot \text{str}^{-1} \cdot \text{kg}^{-1} \) when compared at a physiologically similar running speed (i.e., speed corresponding to gait transition). Thus, when compared by relative rates of limb movement, the submaximal energetic cost of treadmill running is not an appropriate analogy to the results of the present study.

Swain (25) suggested that the relatively lighter bicycle mass, as a percentage of \( \text{M}_B \), for heavier cyclists should decrease the \( \text{M}_B \) exponent below 1.0 for combined mass. To investigate this issue in the present study, the extra mass (\( \text{M}_{\text{EM}} \)) of the bicycle, cleats, and helmet worn by each cyclist was calculated as follows: \( \text{M}_{\text{EM}} = \text{M}_C - \text{M}_B \). With use of the same statistical procedures described earlier and \( \text{M}_{\text{EM}} \) as the dependent variable (no covariates), \( \text{M}_{\text{EM}} \) in the present group of cyclists scaled with the 0.11 power of \( \text{M}_B \) (\( \text{M}_{\text{EM}} \propto \text{M}_B^{0.11}, R^2 = 0.22 \)). Because \( \text{M}_C \) is composed entirely of \( \text{M}_B \) and \( \text{M}_{\text{EM}} \) and \( \text{VO}_{2\text{net}} \propto \text{M}_C^{1.0} \), the derived \( \text{M}_C \) exponent (Table 2) should be equivalent to the sum of the exponents for \( \text{M}_{\text{EM}} \) (0.11) and \( \text{M}_B \) (0.89). For example, using the \( \text{M}_B \) exponent of 0.89 for \( \text{VO}_{2\text{net}} \) in Table 1, one can compute \( \text{M}_B^{0.89} \times \text{M}_B^{0.11} \propto \text{M}_C^{1.0} \), which is close to the derived \( \text{M}_C \) exponent of 0.99 for \( \text{VO}_{2\text{net}} \) (Table 2). Thus the \( \text{M}_B \) exponent was lower than the respective \( \text{M}_C \) exponent because of the exclusion of the \( \text{M}_{\text{EM}} \) component of mass as a contributor to the energy demand for the \( \text{M}_B \) regression model. This verifies that Swain’s suggestion regarding the influence of bike mass (i.e., \( \text{M}_{\text{EM}} \)) on lowering the \( \text{M}_B \) exponent was indeed correct.

Interestingly, the estimated \( \text{M}_{\text{LL}} \) did not enter either regression model (Tables 1 and 2) as a significant covariate. Initially, this was unexpected, because segmental energy analyses (29) and physiological evaluations of pedaling efficiency (9, 11) have demonstrated how influential movement of the lower limb segments during pedaling can be on the total energy demand of a cycling task. A closer evaluation of the \( \text{M}_{\text{LL}} \) data suggests two reasons for its exclusion from the regression models. First, the \( \text{M}_B \) and \( \text{M}_C \) regression models already had 95% of the total variance explained with the inclusion of \( \text{M}_B \), \( \text{M}_D \), and treadmill grade as dependent variables (Tables 1 and 2). Second, even if \( \text{M}_{\text{LL}} \) could have entered the models as a significant covariate, it would not have changed the \( \text{M}_B \) or \( \text{M}_C \) mass coefficients. By use of the same log-linear regression statistical procedures described earlier, it can be shown that \( \text{M}_{\text{LL}} \) for the group of cyclists studied scaled with \( \text{M}_B \) raised to the 1.01 power (i.e., \( \text{M}_{\text{LL}} \propto \text{M}_B^{1.01}, R^2 = 0.80 \)). Thus \( \text{M}_{\text{LL}} \) increased proportionally with \( \text{M}_B \) and, therefore, represented a constant fraction of \( \text{M}_B \), which is consistent with the literature (9). This means that individual differences in \( \text{M}_{\text{LL}} \) values were already being accounted for by the presence of \( \text{M}_B \) in the \( \text{M}_B \) and \( \text{M}_C \) terms.

In summary, the results of this study support the premise by others (7, 21) that the submaximal energetic demand of uphill bicycling increases proportionally with \( \text{M}_C \) [i.e., \( \text{VO}_{2\text{net}} \propto \text{W}_\text{net} \propto \text{M}_C^{1.0} \)]. Furthermore, this scaling relationship will remain independent of road speed, road grade, and the type of mass being transported (biologic mass vs. equipment mass) so long as gravity is the dominant resistive force and the cyclists are at a steady state. In contrast, the same energetic demands scale with \( \text{M}_B \) less than proportionally [i.e., \( \text{VO}_{2\text{net}} \propto \text{M}_B^{0.89} \)], because the extra mass associated with bicycling equipment (bicycle, cleats, and helmet) is relatively lighter for heavier cyclists than for lighter cyclists (i.e., \( \text{M}_{\text{EM}} \propto \text{M}_B^{1.11} \)). These findings could be useful to researchers in constructing allometric models of endurance bicycling performance as a function of differences in \( \text{M}_B \) or \( \text{M}_C \).

APPENDIX

The results of this study can be used to predict the influence of mass on the submaximal energetics and performance of uphill time-trial cycling.

Submaximal energetics. From Table 2 it is given that \( \text{VO}_{2\text{net}} \propto \text{M}_C \) for a constant grade and velocity on steep uphill climbs (influence of \( \text{R}_B \) assumed constant, \( \text{R}_D \) assumed negligible). It follows, therefore, that a decrease in \( \text{M}_C \) should

| Table 3. Predicted percent decrease in \( \text{VO}_{2\text{net}} \) to overcome gravitational resistance when \( \text{M}_C \) of cyclist, bicycle, and cycling gear are decreased by 0.5–3.0 kg |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \text{M}_C, \text{kg} \) | 50.0 | 60.0 | 70.0 | 80.0 | 90.0 | 100.0 |
| 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.5 | 1.00 | 0.83 | 0.71 | 0.63 | 0.56 | 0.50 |
| -1.0 | 2.00 | 1.67 | 1.43 | 1.25 | 1.11 | 1.00 |
| -1.5 | 3.00 | 2.50 | 2.14 | 1.88 | 1.67 | 1.50 |
| -2.0 | 4.00 | 3.33 | 2.86 | 2.50 | 2.22 | 2.00 |
| -2.5 | 5.00 | 4.17 | 3.57 | 3.13 | 2.78 | 2.50 |
| -3.0 | 6.00 | 5.00 | 4.29 | 3.75 | 3.33 | 3.00 |

| Contribution of rolling resistance to \( \text{VO}_{2\text{net}} \) is assumed constant, whereas energy required to overcome aerodynamic drag is assumed negligible. |

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cause a proportional decrease in \( \dot{V}O_2\)(net) for any given grade and velocity. By use of the coefficients from Table 2 and insertion of the mean value for \( M_C \) (0.00206), a generalized description of the contribution of \( M_C \) to \( \dot{V}O_2\)(net) at a 7% grade is given by

\[
\dot{V}O_2\)(net) (l/min) = 0.036 \times M_C
\]

(A1)

where 0.036 is a constant \([\text{antilog}(-1.514 + 0.412) + 0.00206]^{-1}\) from Table 2 for 3.46 m/s and 7% grade. For example, two cyclists with \( M_C \) of 50 kg (\( M_E = 42 \) kg, \( M_E = 8.0 \) kg) and 100 kg (\( M_B = 91 \) kg, \( M_E = 9.0 \) kg) will have \( \dot{V}O_2\)(net) of 1.80 and 3.60 l/min, respectively (Eq. A1). Thus \( \dot{V}O_2\)(net) for a cyclist with \( M_C \) of 100 kg will be exactly twice that of a cyclist with \( M_C \) of 50 kg to overcome gravity at the same steady-state speed. When scaled by \( M_C \), these \( \dot{V}O_2\)(net) values are 36.00 ml\cdot kg^{-1} \cdot min^{-1}, indicating that neither cyclist appears to have an energetic disadvantage. However, 91% of the heavier cyclist’s \( \dot{V}O_2\)(net) goes toward moving \( M_B \), whereas only 9% of \( \dot{V}O_2\)(net) is used to move \( M_E \) uphill. In contrast, 84% of the lighter cyclist’s \( \dot{V}O_2\)(net) is utilized to move \( M_B \) and 16% is used to move \( M_E \) uphill. Thus, given a constant steep uphill speed and incline, the lighter cyclist will expend –7% (84% – 91%) less energy (relative to total energy) to move his own \( M_B \) but 7% (16% – 9%) more energy to move his cycling equipment uphill than to move the steeper inclines than the heavier cyclist.

Interestingly, if \( M_C \) is decreased by an absolute amount through a decrease in equipment mass or percent body fat (the source of mass is not important so long as the cyclist is in an energetic steady state), the smaller cyclist will actually gain an advantage (Table 3). By use of Eq. A1, the percent decrease in \( \dot{V}O_2\)(net) expected with absolute decreases in \( M_C \) between 0.5 and 3.0 kg are provided for \( M_C \) values between 50 and 100 kg (Table 3). For example, a 50-kg cyclist can decrease \( \dot{V}O_2\)(net) by 3.0% by decreasing \( M_C \) by 1.5 kg, but a 100-kg cyclist must decrease \( M_C \) by 3.0 kg to realize the same decrease in \( \dot{V}O_2\)(net). The percentages provided in Table 3 should apply as long as the cyclists are at the same speed and grade and at an energetic steady state (Eq. 7) and should not be dependent on gender.

Uphill time-trial cycling performance. The influence of mass on uphill time-trial cycling performance can also be evaluated theoretically by determining the mass exponent for the ratio of metabolic power \( W_S\)(max) to \( R_G \). Rearranging Eq. 2 to solve for \( s_{max} \) and substituting \( R_G \) for \( R_{net} \) gives

\[
s_{max} = W_S\)(max) \times (R_C)^{-1} \tag{A2}
\]

where \( s_{max} \) is the average speed maintained during an uphill time-trial race. If it is assumed that \( \dot{V}O_2\)peak and other measures of aerobic power (2, 13, 25) scale with \( M_B \) to the \( \frac{1}{3} \) power [i.e., \( W_S\)(max) \( \propto M_B^{0.67} \)] and that \( R_G \propto M_B \) (assuming \( M_E = M_C \) Eq. 5), it follows that

\[
\dot{W}_S\)(max) \propto (R_C)^{-1} \times M_B^{0.67} \times (M_B^{1.0})^{-1} = M_B^{-0.33} \tag{A3}
\]

Thus \( s_{max} \propto M_B^{-0.33} \), which means that the smaller cyclist should tend to decrease with an increase in \( M_B \) to the –\( \frac{1}{3} \) power. For uphill cycling, however, the present study indicates that \( R_G \propto M_B^{0.89} \) and not \( M_B^{1.00} \). Recalculating the \( s_{max} \) performance exponent with \( M_B^{0.89} \)

\[
\dot{W}_S\)(max) \propto (R_C)^{-1} \times M_B^{0.67} \times (M_B^{0.89})^{-1} = M_B^{-0.223}
\]

which still indicates that the smaller cyclist will tend to have a performance advantage when time-trial cycling on steep uphill courses. The difference between the theoretical \(-\frac{1}{3}\) exponent and the predicted –0.233 exponent is due to the need for cyclists of all sizes to carry a nearly constant mass of 10 kg uphill along with their own bodies. One might predict, therefore, that the –\( \frac{1}{3} \) exponent would more closely describe uphill running performance where the contribution of equipment mass to the total mass being transported is minimal. Again, the scaling relationships described above should be independent of gender.

Predicted and theoretical performance exponents for steep uphill cycling are consistent with anecdotal observations that lighter cyclists tend to win uphill time trials and stage races that end with a long steep climb. The –0.223 depends completely, however, on the present experimental finding that \( R_G \propto M_B^{0.89} \) and thus may vary somewhat between subject samples because of the ever-changing preferences for and availability of bicycle equipment.

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