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

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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 [V̇O₂(net) = V̇O₂ – resting V̇O₂] to body mass (M₇) and combined mass (M₆ = M₇ + bicycle) during uphill treadmill bicycling. It was hypothesized that V̇O₂(net) (l/min) would scale proportionally with M₆ [i.e., V̇O₂(net) ∝ M₆ⁿ] and less than proportionally with M₇ [i.e., V̇O₂(net) ∝ M₇ᵐ]. Twenty-five competitive cyclists (73.9 ± 8.8 and 85.0 ± 9.0 (SD) kg for M₇ and M₆, 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 V̇O₂ was measured. Multiple log-linear regression procedures were applied to the pooled V̇O₂(net) data to determine the exponents for M₆ and M₇ 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 M₆ (0.99, 95% confidence interval = 0.80–1.18) and M₇ (0.89, 95% confidence interval = 0.72–1.07) did not differ significantly from each other or 1.0. It was hypothesized that V̇O₂(net) for a given ṡ is provided by

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

where

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

and

\[ R_R = g \times M_C \times (\mu_D + \mu_R \times v) \times (\cos \theta) \]

where M₇ is the combined mass of the cyclist with bike and gear (kg), g is the constant of gravitational acceleration (9.81 m/s²), \( \theta \) is the inclination of the road surface (degrees), v is the air velocity relative to the bicycle and rider (m/s; \( \dot{s} \) on a treadmill), and \( \mu_D \) and \( \mu_R \) are the coefficients of static and dynamic friction (both dimensionless), respectively. If it is further assumed that the magnitude of \( R_R \) is negligible, by substituting Eq. 5 into Eq. 4 the metabolic power required to overcome gravitational resistance is given as

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

Thus, for a given \( \theta \) and \( \dot{s} \), the submaximal steady-state metabolic power required for steep uphill or inclined treadmill bicycling should be directly proportional to M₇ (i.e., \( \dot{W}_S \propto M_7^{\mu_D} \)).

Interestingly, research involving the energetic demands of uphill bicycling have mostly been limited to issues of pedal cadence and body position (26, 27). The relationship between submaximal V̇O₂ and M₇ during uphill bicycling has never been addressed experimentally.

The related issue of V̇O₂ demand during uphill bicycling as a function of body mass (M₇) was evaluated by Swain (25) using allometric scaling procedures. Swain concluded that the V̇O₂ cost of uphill bicycling was proportional to M₇ raised to the 0.79 power (i.e., \( \dot{W}_S \propto M_7^{0.79} \)). Because the 0.79 exponent was <1.0, heavier cyclists tended to expend less energy than smaller cyclists relative to M₇ when uphill bicycling at the same \( \theta \) and \( \dot{s} \). Swain further speculated that the differential expense of energy for graded treadmill bicycling and the 0.79 M₇ exponent was the result of the cyclists’ bicycles being relatively lighter for the heavier cyclists (i.e., as a percentage of M₇). The potential influence of \( R_R \) on the derived M₇ 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 submaxi-
mal $\dot{V}O_2$ and $M_C$ and $M_B$ during uphill bicycling. The
theoretical dependence of $\dot{V}O_2$ on $M_C$ ($\dot{V}O_2 \propto M_C^{1.00}$),
however, has never been verified experimentally,
whereas Swain’s (25) 0.79 exponent for $M_B$ has never
been explained theoretically or experimentally. Thus
the present study was designed to evaluate both of
these issues by measuring submaximal $\dot{V}O_2$ for trained
cyclists during uphill treadmill bicycling. These data
were then evaluated using log-linear multiple regres-
sion 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 Hu-
man Performance Laboratory at the University of Massa-
chusetts (Amherst, MA). Subjects refrained from strenuous
activity on the day before each visit and abstained from
caffeine ingestion for $\approx 3$ h before arriving at the laboratory.

Testing of peak $\dot{V}O_2$. 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 $\dot{V}O_2$ 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 $\dot{V}O_2$ ($\dot{V}O_{2\text{peak}}$) test began
immediately thereafter by increasing power output by 30 W
at 1-min intervals during pedaling 90 rpm until volitional ex-
hauation. Each subject’s $\dot{V}O_{2\text{peak}}$ was defined as an average of
the highest two or three values within 2.0 ml·kg$^{-1}$·min$^{-1}$ of
each other. The $\dot{V}O_{2\text{peak}}$ values were considered valid if at least
two of the three following criteria were satisfied: 1) a leveling
of $\dot{V}O_2$, 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 $\geq 1.1$.

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 deter-
mimed 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 measure-
ments.

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 $\times$ 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
width. 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 mat-
tresses 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 ratio), 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 $\pm 0.5°$ 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 $R_n$ (7, 16)

$$R_{net} = (R_G + R_n) = [g \times M_C \times (\sin \theta) + g \times M_C \times (\cos \theta)]$$ (8)

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

$$\mu_D = \left[ R_{net} - g \times M_C \times (\sin \theta) - g \times M_C \times (\cos \theta) \times \mu_S \right] \times \left[ g \times M_C \times (\cos \theta) \times v \right]^{-1}$$ (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, Châtillon, 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 ($M_{LL}$) were also determined for use as potential covariates in the statistical analyses. Percent body fat was estimated from hydrostatic measures of body density ($\beta$) 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 $M_{LL}$ (kg) was computed as follows: $M_{LL} = 2(pTV_T + pTV_L + p2V_F)$, where the subscripts $T$, $L$, and $F$ refer to estimated segment densities ($\beta$, 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 gas volumes) were interfaced to the computer via an analog-to-digital board. The computer system compiled O$_2$ information at 50- 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 rest-$V\dot{O}_2$ 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).

F test grade was assessed using a two-factor repeated-measures ANOVA procedures. 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 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 $M_{cC}$. Measures of treadmill speed (P = 0.95) and pedaling cadence (P = 0.88) did not differ across the four test grades. Pedal cadence averaged 59.9 ± 1.6 rpm, while 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$_{xx}$ = 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$_2$(net)) on log($M_b$) (Fig. 1) and log($M_{cC}$) (Fig. 2) did not differ significantly across
the four test grades (P > 0.344) (13). This indicated that the log[VO₂(net)] data for all four test grades could be pooled for the final regression analyses.

The resulting coefficients from the pooled regression of VO₂(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 VO₂(net). The results in Table 1 suggest that, after controlling for differences in treadmill grade and µD, VO₂(net) increased positively with an increase in MB raised to the 0.89 power (95% confidence interval = 0.72–1.07; R² = 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 VO₂(net) on MC (Table 2), which found that VO₂(net) increased in proportion to MC raised to the 0.99 power (95% confidence interval = 0.80–1.18; R² = 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 VO₂(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., VO₂ ∝ MC¹⁰⁰). Indeed, results from the present study indicate that VO₂(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 VO₂(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...
Table 1. Final log-linear regression model relating $V_{O2^{(net)}}$ to differences in $M_B$ 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>
</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>
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</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>
<td>0.130</td>
<td>0.0936, 0.1672</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$M_B$, kg</td>
<td>0.895</td>
<td>0.7219, 1.0681</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.947</td>
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<td></td>
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<tr>
<td>Model $P$ value</td>
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Model coefficients ($\beta$), 95% confidence intervals (CIs) for $\beta$, and $P$ values are provided for dependent variables; $n = 97$. $V_{O2^{(net)}}$, 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).

Table 2. Final log-linear regression model relating $V_{O2^{(net)}}$ 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>
</tr>
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<tr>
<td>$C_1$</td>
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<td>0.1540, 0.1984</td>
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</tr>
<tr>
<td>$C_2$</td>
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<td>$C_3$</td>
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<td>0.0906, 0.1639</td>
<td>&lt;0.001</td>
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<tr>
<td>$M_C$, kg</td>
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<tr>
<td>$R^2$</td>
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<tr>
<td>Model $P$ value</td>
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$M_C$, 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 gait from a trot to a gallop. This analysis revealed that the quadrupeds, with a fourfold range in M_B (0.01–100 kg), consumed nearly a constant 5 J · stride^{-1} · 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 at any given speed was directly proportional to 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 M_B, for heavier cyclists should decrease the M_B exponent below 1.0 for combined mass. To investigate this issue in the present study, the extra mass (M_{EM}) of the bicycle, cleats, and helmet worn by each cyclist was calculated as follows: M_{EM} = M_C - M_B. With use of the same statistical procedures described earlier and M_{EM} as the dependent variable (no covariates), M_{EM} in the present group of cyclists scaled with the 0.11 power of M_B (M_{EM} \propto M_B^{0.11}, R^2 = 0.22). Because M_B is composed entirely of M_B and M_{EM} and VO_{2net} \propto M_C^{1.0}, the derived M_C exponent (Table 2) should be equivalent to the sum of the exponents for M_{EM} (0.11) and M_B (0.89). For example, using the M_B exponent of 0.89 for VO_{2net} in Table 1, one can compute M_B^{0.89} \times M_B^{0.11} \times M_C^{1.0}, which is close to the M_C exponent of 0.99 for VO_{2net} (Table 2). Thus the M_B exponent was lower than the respective M_C exponent because of the exclusion of the M_{EM} component of mass as a contributor to the energy demand for the M_B regression model. This verifies that Swain’s suggestion regarding the influence of bike mass (i.e., M_{EM}) on lowering the M_B exponent was indeed correct.

Interestingly, the estimated M_{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 M_{LL} data suggests two reasons for its exclusion from the regression models. First, the M_B and M_C regression models already had 95% of the total variance explained with the inclusion of M_B, M_D, and treadmill grade as dependent variables (Tables 1 and 2). Second, even if M_{LL} could have entered the models as a significant covariate, it would not have changed the M_B or M_C mass coefficients. By use of the same log-linear regression statistical procedures described earlier, it can be shown that M_{LL} for the group of cyclists studied scaled with M_B raised to the 1.01 power (i.e., M_{LL} \propto M_B^{1.01}; R^2 = 0.80). Thus M_{LL} increased proportionally with M_B and, therefore, represented a constant fraction of M_B, which is consistent with the literature (9). This means that individual differences in M_{LL} values were already being accounted for by the presence of M_B in the M_B and 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 M_C [i.e., VO_{2net} \propto W_{net} \propto 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 M_B less than proportionally [i.e., VO_{2net} \propto 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., M_{EM} \propto 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 M_B or 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 VO_{2net} \propto M_C for a constant grade and velocity on steep uphill climbs (influence of R_D assumed constant, R_D assumed negligible). It follows, therefore, that a decrease in M_C should

<table>
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<th>Decrease in M_B, kg</th>
<th>50.0</th>
<th>60.0</th>
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<tr>
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<td>0.71</td>
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<td>1.43</td>
<td>1.25</td>
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</tr>
<tr>
<td>-1.5</td>
<td>3.00</td>
<td>2.50</td>
<td>2.14</td>
<td>1.88</td>
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<tr>
<td>-2.0</td>
<td>4.00</td>
<td>3.33</td>
<td>2.86</td>
<td>2.50</td>
<td>2.22</td>
<td>2.00</td>
</tr>
<tr>
<td>-2.5</td>
<td>5.00</td>
<td>4.17</td>
<td>3.57</td>
<td>3.13</td>
<td>2.78</td>
<td>2.50</td>
</tr>
<tr>
<td>-3.0</td>
<td>6.00</td>
<td>5.00</td>
<td>4.29</td>
<td>3.75</td>
<td>3.33</td>
<td>3.00</td>
</tr>
</tbody>
</table>

| \(\text{Contribution of rolling resistance to } VO_{2\text{net}}\) | \(\text{assumed constant, whereas energy required to overcome aerodynamic drag is assumed negligible.}\) |
cause a proportional decrease in $\dot{V}_O_2^{\text{net}}$ for any given grade and velocity. By use of the coefficients from Table 2 and insertion of the mean value for $\mu_s$ (0.00206), a generalized description of the contribution of $M_c$ to $V_O_2^{\text{net}}$ at a 7% grade is given by

$$\dot{V}_O_2^{\text{net}}(l/min) = 0.036 \times M_C$$

where 0.036 is a constant [$\text{antilog}(−1.514 + 0.412) + 0.00206^{0.127}$] from Table 2 for 3.46 m/s and 7% grade. For example, two cyclists with $M_C$ of 50 kg ($M_b = 42 \text{ kg}, M_{EM} = 8.0 \text{ kg}$) and 100 kg ($M_b = 91 \text{ kg}, M_{EM} = 9.0 \text{ kg}$) will have $V_O_2^{\text{net}}$ of 1.80 and 3.60 l/min, respectively (Eq. A1). Thus $V_O_2^{\text{net}}$ 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 $V_O_2^{\text{net}}$ values are 36.00 ml·kg$^{-1}$·min$^{-1}$, indicating that neither cyclist appears to have an energetic advantage. However, 91% of the heavier cyclist's $V_O_2^{\text{net}}$ goes toward moving $M_b$, whereas only 9% of $V_O_2^{\text{net}}$ is used to move $M_{EM}$ uphill. In contrast, 84% of the lighter cyclist's $V_O_2^{\text{net}}$ is utilized to move $M_b$ and 16% is used to move $M_{EM}$ 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 more steeply and have an energetic advantage. How could the heavier cyclist's $V_O_2^{\text{net}}$ be decreased 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 $V_O_2^{\text{net}}$. 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 independent of gender.

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

$$s_{max} = \dot{W}_{S(max)} \times (kR_G)^{-1}$$

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

$$\dot{W}_{S(max)} \propto (kR_G)^{-1} \times M_b^{0.67} \times (M_b^{1.00})^{-1} = M_b^{-0.33}$$

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 $−\frac{2}{3}$ 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 $M_b^{0.89}$

$$\dot{W}_{S(max)} \propto (kR_G)^{-1} \times M_b^{0.67} \times (M_b^{0.89})^{-1} = M_b^{-0.23}$$

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 $−\frac{2}{3}$ 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 $−\frac{2}{3}$ 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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