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Scaling of 2-Mile Run Times by Body Weight and Fat-Free Weight in College-Age Men

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ABSTRACT

The purpose of this study was to examine the validity of no body weight (BW) adjustment on 2-mile run time (TMRT) for college-age men. Allometric scaling can be used to find the value for α such that TMRT $\cdot$ BW$^{-\alpha}$ is a valid scaling for TMRT based on the relationship between TMRT and BW. Subjects, 59 male military academy cadets 18 to 25 years of age, had BW, fat-free weight (FFW) estimated from skinfolds, and TMRT assessed. Allometric scaling yielded the values of α for BW and FFW: 0.40 ± 0.086 and 0.31 ± 0.128, respectively, indicating that for college-age men, the use of TMRT as the index of aerobic fitness without adjustment for BW or FFW may penalize those who are heavier due to higher FFW, not just higher percent body fat.

Key Words: body dimensions, allometry, dimensional analysis

Introduction

Distance runs have been widely used to assess aerobic fitness or maximal oxygen uptake ($\dot{V}O_2$max), particularly for field testing situations in which direct assessment of $\dot{V}O_2$max is not feasible. This is based on the high correlation between $\dot{V}O_2$max expressed per unit of body weight (BW) in ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ and the time to run certain fixed distances such as 2 miles (7), or 3,200 meters (10).

The evaluation of $\dot{V}O_2$max in ml $O_2 \cdot kg^{-1} \cdot min^{-1}$, however, may penalize heavier subjects because maximal oxygen uptake, expressed in ml $O_2 \cdot min^{-1}$, has been shown to vary disproportionately to body weight. Several investigations (1, 2, 3, 9) have suggested that $\dot{V}O_2$max should be expressed in ml $O_2 \cdot kg^{-0.7} \cdot min^{-1}$ so that the influence of body weight is properly partialed out between subjects.

The same can be applied to adjunctive measures of aerobic fitness, that is, run times, since they correlate rather highly with $\dot{V}O_2$max expressed in ml $O_2 \cdot kg^{-1} \cdot min^{-1}$. The U.S. Army has used the 2-mile run time (TMRT), or the fastest one can run 2 miles, as the key index of aerobic fitness. Currently no consideration is given to body weight in the evaluation of TMRT. In other words, a large man or woman is held to the same standards as a light man or woman. However, despite the fact that TMRT is highly correlated with $\dot{V}O_2$max, the relationship is not one in which TMRT is equivalent to aerobic fitness. Although Mello et al. (7) demonstrated that, for college-age men, TMRT was indeed highly predictive of $\dot{V}O_2$max, in ml $\cdot kg^{-1} \cdot min^{-1}$ ($r = 0.91$) aerobic fitness has been more accurately classified as being of the form ml $\cdot kg^{-0.7} \cdot min^{-1}$ (1, 2, 3, 9). Therefore, dimensional analysis would indicate that TMRT would be proportional to BW$^1 \cdot$ BW$^{-0.7}$, or BW$^{0.3}$. We therefore hypothesized that TMRT adjusted for BW$^{0.3}$ would yield an index of run time free of the penalty imposed by BW.

Such scaling considerations have important implications particularly for the military services, where large-scale fitness testing is necessary and the resulting scores on this test, which are norm-referenced, play an important role in decisions about promotions or elimination from the service.

The purpose of this investigation was to use an allometric scaling technique (AS) to properly scale TMRT first by BW for college-age men. AS can be used to find the exponent, α, such that TMRT $\cdot$ BW$^{-\alpha}$ is a statistically proper scaling of TMRT given the true relationship between TMRT and BW (11). Since heavier men may be so because of higher percent body fat, we also used AS to properly scale TMRT by fat-free weight (FFW). That is, we investigated whether the present convention of evaluating aerobic fitness via TMRT penalized heavy men and, if so, would it penalize only those men who are heavier due to higher percent body fat?

Subjects

Selection of an appropriate sample of subjects is critical to the proper use of AS. Tanner (8) and Winter (11) emphasize that the distribution of the sample should be both normal and highly representative of the population under consideration. Subjects for this investigation were 59 male service academy cadets. As shown in Table 1, subject characteristics were fairly heterogeneous and, as

Table 1

Subject Descriptive Characteristics (n = 59)

	Age (yrs)	Body weight (kg)	% Fat	TMRT (min)
Mean	20.1	82.6	11.9	12.9
SD	1.43	12.1	5.3	1.37

verified by the Statistica for Windows™ software package's Kolgomorov-Smirnov test, were also normal ($p > 0.1$ for every variable).

We felt that these subjects were particularly appropriate for this investigation because all were apparently highly motivated to do their best on the TMRT. As each was to receive a letter grade for his performance which would have a significant impact on class standing and even postgraduation assignment, the cadets were motivated not only to perform their absolute best but to be highly prepared for the test. This gave us a sample of subjects who, although they varied in size and fitness level, were more likely nearer their aerobic potential than a typical sample of college-age men. This was essential if the results of the AS were to have interpretable value.

Procedures

Subjects were weighed on a calibrated and properly zeroed scale (Health-O-Meter) and skinfold thicknesses were assessed on the chest, abdomen, and thigh. The mean of the three measurements was used. A Lange skinfold caliper was used for all assessments. FFW was estimated in accordance with the equation provided by Jackson (4).

Within 2 weeks all subjects had TMRT assessed in accordance with the requirements and standards prescribed by the U.S. Military Academy's Department of Physical Education Testing Protocol. In brief, they ran in groups of no more than 20 on a linear course (down and back) of an asphalt surface. TMRT, recorded to the nearest second, was the time it took the subject to run 2 miles as fast as possible. TMRT scores were then converted to minutes and 10ths of minutes.

The TMRT used for this investigation was required of each cadet as part of his physical education curriculum and, as such, meant that letter grades were assigned based on TMRT performance. Each subject gave written informed consent for the other data used in this investigation, specifically BW and FFW, which were obtained from skinfolds.

Statistical Analyses

Given a key variable y, a scaling variable x, and the function best describing their association, $y = bx^{\alpha}$, AS is a procedure of linear regression to solve for the value of α and its corresponding 95% confidence interval. In other words, AS determines the interval within which α can be used to properly scale y by x. In this case, y is TMRT and x is BW. For linear regression to be applied to this function, it must be of a linear form. Taking the log of both sides transforms this relationship into a linear one: $\log(y) = (a)\log(x) + \log(b)$.

In this investigation, linear regression was applied to the dependent variable, log(TMRT), and the independent variable, log(BW), for the first analysis; then to log(TMRT) and log(FFW) for the second. Interestingly, the distributions of log(BW), log(FFW), and log(TMRT) were not only normally distributed but were more so than their respective raw values (in accordance with the Statistica for Windows™ Kolmogorov-Smirnov test for normality). This was important as normality is an important assumption of linear regression. The coefficients of log(BW) and log(FFW) in the two separate regression equations (the "B" values in the Statistica for Windows™ regression procedure) were the correct values of α for proper scaling of these variables. The standard error of the B values corresponded to the 68% confidence interval of α. Therefore, double this value corresponded to the 95% confidence interval. At an alpha level of 0.05, the resulting intervals were the range of statistically correct values of α for the scaling of TMRT by BW or FFW.

Results

We first examined whether conventional scaling of TMRT tended to penalize heavier men. It might seem apparent that run times, by themselves, are adjusted for by body weight because the larger individual, who must carry more body weight, should have proportionately more "aerobic machinery" to do so. However, detailed examination reveals otherwise. TMRT versus BW revealed a relatively high correlation ($r = 0.55$) which indicated a penalty applied to heavier men. In other words, as weight increases across the sample, TMRT times increase. This is not surprising since heavier men are often fatter and tend to be slower. In fact, the Pearson product-moment correlation between BW and percent body fat, $r = 0.68$ ($p < 0.0001$), provided rationale for scaling by FFW. Similar analysis applied to FFW and TMRT revealed the same trend but of lesser magnitude ($r = 0.32$, $p = 0.02$). For a sample of subjects from a population that is highly motivated to achieve on this test, this suggests that men with larger FFW may not be capable of running the TMRT as fast as lighter men. We felt, then, that proper scaling of TMRT via AS was warranted.

AS revealed that the proper value of α for TMRT $\cdot$ $BW^{-\alpha}$ was 0.40 with a 95% confidence interval from 0.228 to 0.572. This suggests that, for comparisons between individuals that partial out the effect of BW, TMRT should be divided by $BW^{0.4}$. However, since heavier men may be so due to higher percent body fat, scaling by FFW should be considered. Failure to do so (using $\alpha = 0.4$) would penalize a lean lighter man versus a lean heavier man. AS applied to FFW indicated that $\text{TMRT} \cdot \text{FFW}^{-0.31}$ was the correct scaling, with a 95% confidence interval for α between 0.054 and 0.566.

An important issue regarding the use of AS in this case pertains to the choice of function to best describe the association between TMRT and BW or FFW. AS assumes the relationship is exponential; other published methods, such as that described by Katch (5), assume a linear relationship. We compared the fit of the data using AS with that using the Katch method by generating actual versus observed values for each function for both BW and FFW. The total error values (in min) were nearly identical: for AS and Katch, BW = 1.16 versus 1.15 and FFW = 1.31 versus 1.31, respectively, suggesting that AS modeling can indeed minimize the sums of squared deviations from TMRT and not just log(TMRT).

Discussion

These data indicate that conventional expression of TMRT for men of this population tends to penalize not only men who are heavier but also men who are so because of higher FFW. This might be rather unremarkable for a sample of college-age men who do not regularly run the TMRT, do not train for it, and are not highly motivated to achieve. After all, one could argue that heavier men run less, are heavier because of a lack of training, and are less motivated to give their best effort for a test in which their performance is mediocre at best. However, since these cadets were receiving letter grades on the TMRT that would have an impact on overall academic standing and postgraduation assignment, we were confident that they trained for and gave their best effort on the TMRT test.

These results further suggest that larger men (in terms of FFW) are not simply large-scale models of smaller men specifically regarding run performance, despite the theory of geometric similarity which suggests that running speed is independent of size (1). Not stated in this theory, however, is the fact that running speed in endurance events is dependent on the maximum rate of oxygen consumption which, in turn, is proportional to $\text{BW}^{0.7}$. Therefore the results of this investigation may in fact support the more correct version of this theory of similarity. The exponents determined for this investigation are also very similar to that predicted from the aforementioned empirical data ($\alpha = 0.3$) regarding the relationship between TMRT and $\dot{V}O_2\text{max}$, expressed in $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ (7).

Men with higher FFW, even when highly motivated to train and achieve, are apparently at a disadvantage when competing against men with lower FFW in running races. This disadvantage, likely a combination of differences in cardiovascular and biomechanical function, is worthy of detailed further investigation. Also, the effects of motivation and training, not specifically controlled in this investigation, should be elucidated in future study.

Scaling by BW alone for this sample is probably not as appropriate as scaling by FFW, because the former would tend to reduce the penalty for excess body fat. This would be advantageous for heavy lean men as compared to lean light men. Scaling by FFW can be impractical if large-scale testing is indicated and assessment of percent body fat is not possible.

One can argue that TMRT can legitimately be scaled by $\text{BW}^{0.31}$, the exponent for the scaling of FFW. In this way the problem associated with $\alpha = 0.40$ is mitigated, that is, the penalty for excess body fat is not reduced so much that light lean men would be at a disadvantage compared to heavy lean men. Use of this convention would grant an adjustment for BW, but only by the amount allowable to FFW. This is perhaps the fairest way to scale TMRT for large-scale field testing.

Table 2

Four Methods of Evaluating 2-Mile Run Times

Subj	TMRT (min)	BW (kg)	% Fat	TMRT *z*-score	TMRT · $\text{BW}^{-0.40}$ *z*-score	TMRT · $\text{FFW}^{-0.31}$ *z*-score	TMRT · $\text{BW}^{-0.31}$ *z*-score
A	14.5	109.8	14.5	−1.14	0.032	−0.312	−0.266
B	12.6	68.3	8.0	0.249	−0.537	−0.150	−0.344
C	12.3	101.8	15.4	0.468	1.438	1.020	1.232
D	11.8	65.8	5.8	0.834	0.043	0.456	0.258
E	11.7	94.6	5.5	0.907	1.635	1.556	1.500

Table 2 shows the relative effect (adjusted score of each individual's TMRT compared to all other subjects) of four evaluation methods: TMRT with no adjustment, $\text{TMRT} \cdot \text{BW}^{-0.40}$, $\text{TMRT} \cdot \text{FFW}^{-0.31}$, and $\text{TMRT} \cdot \text{BW}^{-0.31}$ on z scores for 5 subjects. As expected, for those with high BW, TMRT with no scaling is the worst method and $\text{TMRT} \cdot \text{BW}^{-0.40}$ is the best. $\text{TMRT} \cdot \text{BW}^{-0.40}$, however, penalizes more the lighter subjects with the same leanness as the heavier subjects. $\text{TMRT} \cdot \text{BW}^{-0.31}$ tends to reduce this penalty so that the effect of body fatness is partialed out. Particularly for subjects who are at the extreme level of BW, FFW, or TMRT, score differences between evaluation methods for the same TMRT are quite significant.

AS can be used to properly scale many variables dealing with physiological markers or human performance indices (e.g., $\dot{V}O_2\text{max}$, muscular strength). Use of common ratio methods, in other words assuming $\alpha = 0$ or 1, fails to partial out the effect of the scaling variable and may be no better than no scaling at all (5, 6). Investigators should be mindful that evaluation via simple ratio methods is not fundamentally wrong, as long as the results do not purport to partial out the effects of the scaling variable.

In summary, conventional assessment of TMRT, that is, no adjustment for BW or FFW, tends to penalize heavier college-age men. We suggest that if FFW can be determined, TMRT be scaled by $FFW^{0.31}$. For large-scale field testing of aerobic fitness via TMRT, run times can be scaled by $BW^{0.31}$ to avoid the potential penalty against lean light men compared to lean heavy men. These results suggest that larger scale testing involving men and women of different age groups should be done to examine the legitimacy of such scaling for Army-wide use. Furthermore, future investigation is needed to elucidate the effect of BW and/or FFW on competitive endurance running (events longer than 1 mile) with elite-level runners by gender. Such research may validate the practice of factoring in body size to determine race success.

Practical Applications

Allometric scaling revealed that failure to adjust TMRT for BW or FFW penalized heavier men. This was particularly noteworthy given that the subjects, 59 college-age military cadets, were motivated to train for and achieve on the TMRT because they were receiving letter grades for their efforts. These results suggest that, to ensure that college-age men are not penalized due to BW or FFW, TMRT can be divided by $BW^{0.40}$ or $FFW^{0.31}$. These findings have important implications for adjusting competitive run times by BW or FFW. Future research should be done on other running events with other populations to examine similar valid scaling.

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