# High-speed running performance: a new approach to assessment and prediction

**Matthew W. Bundle,[1] Reed W. Hoyt,[2] and Peter G. Weyand[2,3,4]**
[1]*Flight Laboratory, Division of Biological Sciences, University of Montana, Missoula, Montana 59812;*
[2]*United States Army Research Institute for Environmental Medicine, Biophysics, and Biomedical Modeling Division, Natick, 01760;* [3]*Concord Field Station, Harvard University, Museum of Comparative Zoology, Bedford, Massachussetts 01730; and* [4]*Department of Kinesiology, Locomotion Laboratory, Rice University, Houston, Texas 77005*

**Bundle, Matthew W., Reed W. Hoyt, and Peter G. Weyand.** High-speed running performance: a new approach to assessment and prediction. *J Appl Physiol* 95: 1955–1962, 2003; 10.1152/japplphysiol.00921.2002.—We hypothesized that all-out running speeds for efforts lasting from a few seconds to several minutes could be accurately predicted from two measurements: the maximum respective speeds supported by the anaerobic and aerobic powers of the runner. To evaluate our hypothesis, we recruited seven competitive runners of different event specialties and tested them during treadmill and overground running on level surfaces. The maximum speed supported by anaerobic power was determined from the fastest speed that subjects could attain for a burst of eight steps (~3 s or less). The maximum speed supported by aerobic power, or the velocity at maximal oxygen uptake, was determined from a progressive, discontinuous treadmill test to failure. All-out running speeds for trials of 3–240 s were measured during 10–13 constant-speed treadmill runs to failure and 4 track runs at specified distances. Measured values of the maximum speeds supported by anaerobic and aerobic power, in conjunction with an exponential constant, allowed us to predict the speeds of all-out treadmill trials to within an average of 2.5% ($R^2 = 0.94$; $n = 84$) and track trials to within 3.4% ($R^2 = 0.86$; $n = 28$). An algorithm using this exponent and only two of the all-out treadmill runs to predict the remaining treadmill trials was nearly as accurate (average = 3.7%; $R^2 = 0.93$; $n = 77$). We conclude that our technique *1*) provides accurate predictions of high-speed running performance in trained runners and *2*) offers a performance assessment alternative to existing tests of anaerobic power and capacity.

locomotion; anaerobic power; aerobic power; exercise testing

---

HUMAN RUNNERS CAN ATTAIN SPEEDS for a few seconds that are two to three times greater than those they can maintain for several hours. In relation to the duration of all-out running, these speed decrements are not uniform. Speed decreases markedly with increases in the duration of shorter efforts (i.e., <180 s) but only modestly with the same relative increases in the duration of longer ones (11, 12). Accordingly, top sprinters attain race speeds nearly twice as fast as those

achieved by the best milers, but mile runners race only moderately faster than marathon runners do. The negative exponential relationship between all-out speed and run duration is generally attributed to differences in the metabolic power available from anaerobic vs. aerobic sources in relation to time (8, 9, 22, 24). Specifically, peak rates of anaerobic energy release, which fuel brief maximal efforts, decline rapidly as the duration of the trial increases (15, 21). In contrast, the peak rates of aerobic energy release during prolonged efforts vary relatively little with event duration. For example, well-trained athletes can maintain >80% of their maximum aerobic power for events from 10 to 120 min (5–7).

The quantitative relationship between maximal aerobic power and endurance performance has been well established for more than two decades (5, 6). Consequently, standardized laboratory tests of aerobic energy release have been established for some time. Assessments of the maximum running speeds supported by aerobic power, or the velocity at maximal oxygen uptake, are known to provide accurate predictions of performance across a wide range of endurance events (7). For short-duration events, an equivalent relationship between metabolic power and performance is not available. Thus equivalently accurate performance predictions for these events cannot be made from direct measurements on individuals (23). Establishing a relationship has been hindered by the inability to directly measure the anaerobic energy released in the body during high-intensity efforts. Although extensive experimental efforts (2, 10, 13, 14, 17, 18, 23) have been made to develop suitable techniques for the assessment anaerobic energy release and high-intensity exercise performance, success has been limited. At present, a satisfactory standardized assessment technique remains to be established, and performance predictions from direct measurements on individuals have limited accuracy (23).

We approached the problem of predicting high-speed running performance with the idea that these perfor-

---

mances, like those for endurance efforts, might conform to a general relationship. We defined the difference between a runner's maximum burst speed and maximum aerobic speed as an anaerobic speed reserve. We anticipated that the exponential decrements in all-out speed in relation to run duration would be the same for different runners in relation to their anaerobic speed reserves. If correct, the postulated relationship would allow high-speed running performance to be accurately predicted from two variables that can be directly measured on individual runners: the maximum burst speed and the maximum aerobic speed of the runner.

We undertook this study to test two hypotheses. First, we hypothesized that we could accurately predict all-out running speeds for efforts of any duration from a few seconds to several minutes (3–240 s) from two direct measurements: the maximum respective speeds supported by the anaerobic and aerobic power of the runner. Second, we hypothesized that we could develop a brief assessment technique that would accurately predict high-speed running performance in either the laboratory or the field.

## METHODS

### Experimental Design

Testing our first hypothesis required *1*) obtaining measurements of the maximum speeds supported by the anaerobic and aerobic power of individual runners, *2*) establishing individual speed-duration curves for each athlete, and *3*) evaluating the agreement between the measured and predicted speeds for the all-out running trials completed. The quantitative expression of our hypothesis that the speed-duration curves of different runners would conform to a general relationship took the following form

$$\text{Spd}(t) = \text{Spd}_{aer} + (\text{Spd}_{an} - \text{Spd}_{aer}) \cdot e^{(-k \cdot t)} \qquad (1)$$

where $t$ is the duration of the all-out run, $\text{Spd}(t)$ is that speed maintained for a run of duration $t$, $\text{Spd}_{an}$ is the maximum speed supported by anaerobic power, $\text{Spd}_{aer}$ is the maximum speed supported by aerobic power, $e$ is the base of the natural logarithm, and $k$ is the exponent that describes the decrements in speed that occur with increments in run duration. We called the term $\text{Spd}_{an} - \text{Spd}_{aer}$ the runner's anaerobic speed reserve. The exponent $k$ used for predictive purposes was 0.013. This was the average value of the individual best fits on data previously acquired from 17 subjects. None of these 17 subjects participated in the present study.

Testing our second hypothesis required *1*) assessing whether high-speed running performances could be predicted from as few as two performance trials and *2*) obtaining running performance data in the field to supplement that obtained in the laboratory. The speeds and durations of any two all-out trials, *Eq. 1*, and algebra could be used to create a system of equations, which, when solved, would predict the speed-duration curve from 3 to 240 s for individual runners.

### Subjects and Protocol

Seven trained collegiate and postcollegiate runners, who were actively training or had recently finished their competitive season, volunteered and provided written, informed consent in accordance with the guidelines of Harvard Uni-

versity. Three subjects, average age 20 ± 1.5 yr (mean ± SE), specialized in races of 800 m or less and had 400-m personal records of <50 s, whereas the four remaining subjects, with an average age of 26.5 ± 3 yr, were long-distance specialists with an average 5,000-m personal best of 15 min 43 s. Estimated anaerobic ($\dot{E}_{an\,max}$) and measured aerobic ($\dot{E}_{aer\,max}$) maximums and corresponding running speeds ($\text{Spd}_{an}$ and $\text{Spd}_{aer}$, respectively) appear in Table 1.

Testing was generally completed in six sessions, with four sessions taking place in the laboratory and two sessions on the track. During laboratory sessions, subjects completed two progressive, discontinuous treadmill tests for respective determinations of the maximum speed supported by their anaerobic power and aerobic power. They also completed 10–13 all-out treadmill runs of varying speeds and durations to establish their individual speed-duration curves. Four to six all-out runs were completed during individual sessions. During the two track sessions, subjects completed four all-out runs at specified distances and a series of dash trials to determine their maximum overground sprinting speed. All running took place on level surfaces.

### Measurements

*Metabolic cost of running.* The energy cost of running at speeds below the minimum eliciting maximal aerobic power ($\dot{E}_{aer\,max}$) was determined from steady-state rates of oxygen uptake in accordance with Consolazio et al. (4). Each subject underwent a progressive, speed-incremented, discontinuous treadmill test that consisted of 5-min bouts of constant-speed running interspersed with 3- to 6-min rest periods. The initial speed was 2.5 m/s. Speeds for subsequent bouts were increased by 0.3–0.5 m/s until a speed was reached at which the subject could not complete the 5-min bout despite a maximal effort. During *minutes 4* and *5* of each bout, expired air was collected in Douglas bags. Aliquots from each bag were subsequently analyzed for oxygen (Beckman LB $O_2$ analyzer, and Ametek S-3A oxygen analyzer) and carbon dioxide (Ametek CD-3A $CO_2$) fractions after calibration with a gas of known $O_2$ and $CO_2$ concentrations. Minute volumes were determined by using a Parkinson-Cowan dry gas meter with simultaneous temperature determination with a digital TC thermometer (Wescor TH-65 TC thermometer). Rates of oxygen uptake, STPD, were determined in accordance with Consolazio et al. (4). The metabolic rates required at running speeds above the minimum speed eliciting $\dot{E}_{aer\,max}$ were estimated by a linear extrapolation of each individual's oxygen uptake-speed relationship to the speed of the all-out run (17, 25).

Table 1. *Metabolic power and speed maximums*

| Subject No. | $\dot{E}_{aer\,max}$, ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ | $\text{Spd}_{aer}$, m/s | $\dot{E}_{an\,max}$, ml $O_2$ eq $\cdot kg^{-1} \cdot min^{-1}$ | $\text{Spd}_{an}$, m/s |
|---|---|---|---|---|
| *1* | 57.6 | 4.9 | 101.1 | 9.0 |
| *2* | 67.5 | 5.5 | 102.1 | 7.9 |
| *3* | 68.0 | 5.7 | 100.7 | 8.1 |
| *4* | 53.4 | 4.9 | 107.5 | 10.4 |
| *5* | 64.2 | 5.3 | 104.1 | 8.0 |
| *6* | 61.8 | 5.2 | 115.3 | 10.0 |
| *7* | 59.6 | 5.4 | 87.7 | 7.7 |

$\dot{E}_{aer\,max}$, maximum estimate of aerobic power; $\text{Spd}_{aer}$, maximum aerobic speed; $\dot{E}_{an\,max}$, maximum estimate of anaerobic power; $\text{Spd}_{an}$, maximum anaerobic speed.

*Metabolic Maximums*

*Maximal anaerobic power.* $\dot{E}_{an\,max}$ was estimated from the highest speed that subjects were able to maintain for eight steps without backward drift on the treadmill (26). These maximum speeds were determined from a series of brief runs administered intermittently at progressive speeds until the subject could no longer match the speed of the belt for eight steps. The fastest speed for which eight steps were completed with no backward drift on the tread was considered the maximum speed supported by anaerobic power. The corresponding metabolic power was estimated from a linear extrapolation of the relationship between speed and metabolic rate at lower running speeds for the individual runner (17, 25). The validity of the estimates obtained by using this extrapolation technique is unknown (19).

*Maximal aerobic power.* $\dot{E}_{aer\,max}$ was determined from the progressive, discontinuous treadmill test previously described. The maximum speed supported by aerobic power was calculated from the highest single minute value measured for $\dot{E}_{aer}$ and the linear relation between $\dot{E}_{aer}$ and speed for each individual. A minimum of six steady-state values <90% of $\dot{E}_{aer\,max}$ was used to formulate individual $\dot{E}_{aer}$-speed relationships for this purpose.

*All-out Treadmill Runs*

Treadmill trials were initiated by the subject lowering himself from the handrails onto the treadmill belt moving at the designated speed. Subjects were generally able to transfer their weight from the handrails to begin running without assistance in <2 s. They were instructed to maintain their position on the treadmill until they could no longer do so while putting forth a maximum effort. At the point of failure, they were to grab the handrails and straddle the treadmill as the belt was stopped. Throughout the testing, subjects wore a safety harness secured to the ceiling above the treadmill to prevent injury in the event of a fall. A minimum of 10 all-out trials were completed by each subject. Treadmill speeds for these trials were selected in attempt to elicit a range of all-out run durations from 3 to 240 s for each subject. The longest all-out trial was the final bout administered during the progressive discontinuous treadmill test.

*Rates of anaerobic energy release.* Average rates of anaerobic energy release for the all-out runs were calculated from the oxygen deficits incurred during the effort. The rate of oxygen taken up during the run was subtracted from the total oxygen demand. The latter was estimated from the linear extrapolation of each subject's $\dot{E}_{aer}$-speed relationship in accordance with previous descriptions (17, 25). Values for speed and average rates of both anaerobic and aerobic energy release in relation to run duration, and accompanying curve fits for one subject appear in Fig. 1.

*Rates of aerobic energy release.* Rates of oxygen uptake were determined from the Douglas bag method, as described in the preceding section. Expired air was collected in individual bags for 30 s for the first minute, and thereafter for 60 s or the interval for which the subject ran before stopping. Rates of oxygen uptake were averaged for the duration of each all-out running trial. Average rates were not determined for the longest trial.

*Overground Running Tests*

All measurements of overground running speeds were made at Harvard University's Albert H. Gordon 200-m indoor track. During the two track sessions, subjects performed all-out runs at 100, 200, 300, and 400 m and numerous
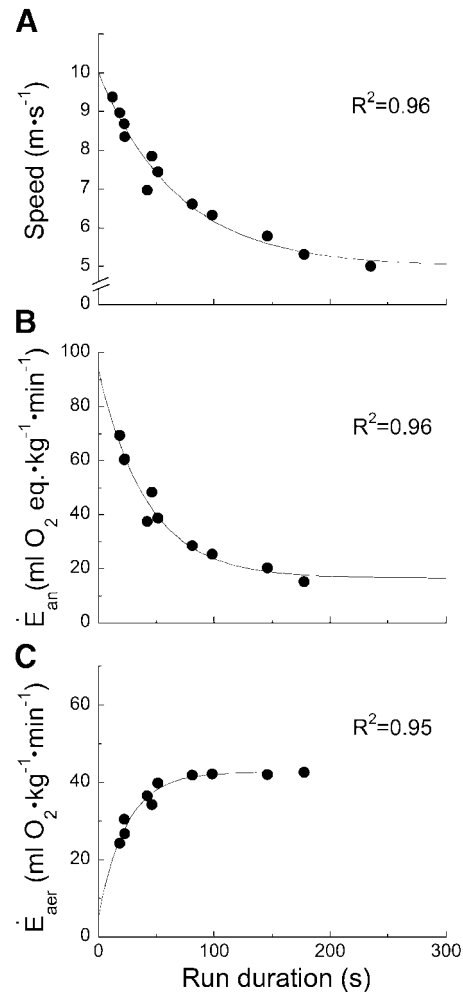


Fig. 1. Running speed (*A*) and estimated rates of anaerobic ($\dot{E}_{an}$; *B*) and aerobic ($\dot{E}_{aer}$; *C*) energy release as a function of the duration of all-out running trials for the fastest subject tested. Rates of anaerobic and aerobic energy release represent averages from the entire course of the run. Curves appearing for speed, $\dot{E}_{an}$, and $\dot{E}_{aer}$ were fit with equations of the following forms: $\mathrm{Spd}(t) = \mathrm{Spd}_{aer} + (\mathrm{Spd}_{an} - \mathrm{Spd}_{aer}) \cdot e^{-kt}$; $\dot{E}_{an}(t) = (\dot{E}_{an\text{-}}) \cdot e^{-kt}$; $\dot{E}_{aer}(t) = \dot{E}_{aer}(1 - e^{kt})$, where $\mathrm{Spd}(t)$ is the speed maintained for a run of duration $t$, $\mathrm{Spd}_{an}$ is the maximum speed supported by anaerobic power, $\mathrm{Spd}_{aer}$ is the maximum speed supported by aerobic power, $e$ is the base of the natural logarithm, and $k$ is the exponent that describes the decrements in speed that occur with increments in run duration.

top-speed sprint trials. The 100-, 200-, 300-, and 400-m trials were performed in random order, with the subjects taking as much rest as they felt necessary for full recovery between trials. Subjects generally performed three of the four specified trials in one session and the fourth specified trial plus the top speed track trials in the second session. Subjects crossed the starting line for each trial after accelerating up to the desired speed. All trials were hand timed with a stopwatch. The average velocities were determined by dividing trial distance by the timed duration.

*Maximum overground speed.* The maximum overground speed supported by anaerobic power was determined over the last 5 m of a 55-m straightaway to allow for full acceleration to the maximum sprinting speed before the timing zone. The time of voltage pulses corresponding to the interruption of infrared photocell beams positioned at 50- and 55-m marks on the track and at a height of 1.15 m were recorded at 5,000

Hz by a data-acquisition system (DIGIDATA 1200 16-bit, Axoscope 8.0, Axon Instruments). Run speeds were determined by dividing the time elapsing between beam interruptions by the 5-m distance separating the photocells. Subjects were instructed to take the time necessary for full recovery between trials. Sprint trials were repeated until the subject reported that he believed he had attained his fastest possible burst speed. The total number of sprint trials performed to establish the maximum for each individual ranged from five to seven. The fastest speed recorded was considered the maximum overground speed supported by anaerobic power and was used for subsequent analyses.

*Data Analysis*

*Hypothesis test 1: actual vs. predicted speeds (full testing protocol).* Measured speeds for the all-out treadmill and track runs were compared with the speeds predicted by *Eq. 1* by using a linear least-squares analysis. The proportion of variance accounted for by our model was determined from deviations of the predicted values from identity, rather than from the relationship providing the best fit.

*Hypothesis test 2: actual vs. predicted speeds (2-trial protocol).* A linear least-squares analysis assessing deviations from identity was also used to determine the proportion of variance in all-out running performance that could be accounted for by two brief all-out runs. These runs were the maximum burst treadmill speed and the speed of the all-out run that was closest to 60 s in duration for the subject in question. Given the relationship provided in *Eq. 1*, predicting $Spd_{an}$, $Spd_{aer}$, and the remainder of a runner's speed-duration curve can be calculated algebraically given duration ($t_1$, $t_2$) and speed ($Spd_1$, $Spd_2$) measurements of two all-out trials of different durations and a known value for $k$ (here 0.013 for durations in seconds and speeds in m/s), in accordance with the procedure provided in the APPENDIX.

**RESULTS**

*Metabolic Maximums*

*Anaerobic power.* The mean value for $\dot{E}_{an\,max}$ was $102.6 \pm 3.1$ ml $O_2$ eq·kg$^{-1}$·min$^{-1}$ (range = 87.7–115.2 ml $O_2$ eq·kg$^{-1}$·min$^{-1}$). The mean maximum speed supported by anaerobic power was $8.7 \pm 0.4$ m/s (range = 7.7–10.4 m/s; Fig. 2).

*Aerobic power.* The group $\dot{E}_{aer\,max}$ was $61.7 \pm 2.0$ ml $O_2$·kg$^{-1}$·min$^{-1}$ (range = 53.4–68.0 ml $O_2$·kg$^{-1}$·min$^{-1}$), and the maximum speed supported by aerobic power was $5.3 \pm 0.1$ m/s (range = 4.9–5.7 m/s). The maximum speed supported by aerobic power were $61 \pm 4\%$ of the maximum speed supported by anaerobic power (Fig. 2). Conversely, the maximum $Spd_{an}$ were $1.7 \pm 0.1$ times faster than the respective maximum speeds supported by aerobic power.

*$Spd_{an\,res}$.* The mean $Spd_{an\,res}$ was $3.5 \pm 0.6$ m/s (range = 2.3–5.6 m/s; Fig. 2).

*Speed as a Function of Run Duration*

*All-out running speeds: treadmill vs. track.* The average speeds subjects maintained for all-out track runs of 100, 200, 300, and 400 m closely matched their all-out treadmill runs of the same duration (Fig. 3A). The linear least-squares regression analysis of track and interpolated treadmill speeds was not far removed
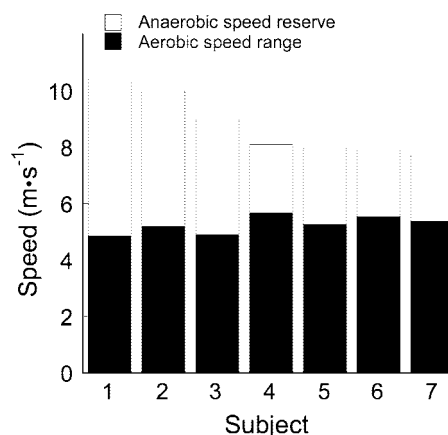


Fig. 2. Maximum respective velocities supported by anaerobic (full bar height) and aerobic (height of the darkened lower portion) power for each of the 7 subjects. The difference between these 2 variables (the anaerobic speed reserve), which is illustrated by the white upper portion of each bar, determines the magnitude of decrements in speed that occur with increments in the duration of all-out running for each runner.

from identity ($R^2 = 0.86$; Fig. 4). When the data from the one subject who reported muscle soreness during his track trials were excluded, the $R^2$ value for the trials completed by the remaining six subjects was 0.91.

*Maximum sprint speeds: treadmill vs. track.* Maximum sprint speeds from the overground sprint test agreed well with the maximum eight-step speeds measured on the treadmill (Fig. 3A). The lone exception was the subject who complained of muscle soreness in the aftermath of the high-speed treadmill sessions. For the other six subjects, maximum track and treadmill sprint speeds agreed to within an average of $0.22 \pm 0.08$ m/s (range = 0.00–0.60 m/s). In the case of the one subject who reported soreness, maximum overground and treadmill speeds differed by seven times more than 0.22 m/s mean difference for the other six subjects (1.51 m/s; see outlying closed circle in Fig. 4). Of the remaining six subjects, three had maximum overground sprint speeds exceeding their maximum eight-step treadmill speeds, one had identical values for both, and two had maximum overground sprint speeds that were slightly less than their treadmill maximums.

*Hypothesis test 1: actual vs. predicted level running speeds (full protocol).* The all-out running speeds predicted by *Eq. 1* using the mean $k$ value of 0.013 and the measured individual values for the maximum respective treadmill speeds supported by the anaerobic and aerobic power of the subject appear in Fig. 5. Over a 2-fold range of running speeds and a 30-fold range (7–244 s) of run durations, actual and predicted speeds agreed to within an average of 2.5% for all of the 84 level treadmill runs completed ($R^2 = 0.94$).

*Hypothesis test 2: actual vs. predicted speeds (2-trial protocol).* Our algorithmic procedure for predicting the speed of the all-out trials from the speeds and durations of two all-out running trials (3 and ~60 s) predicted the remaining treadmill trials to within an av-
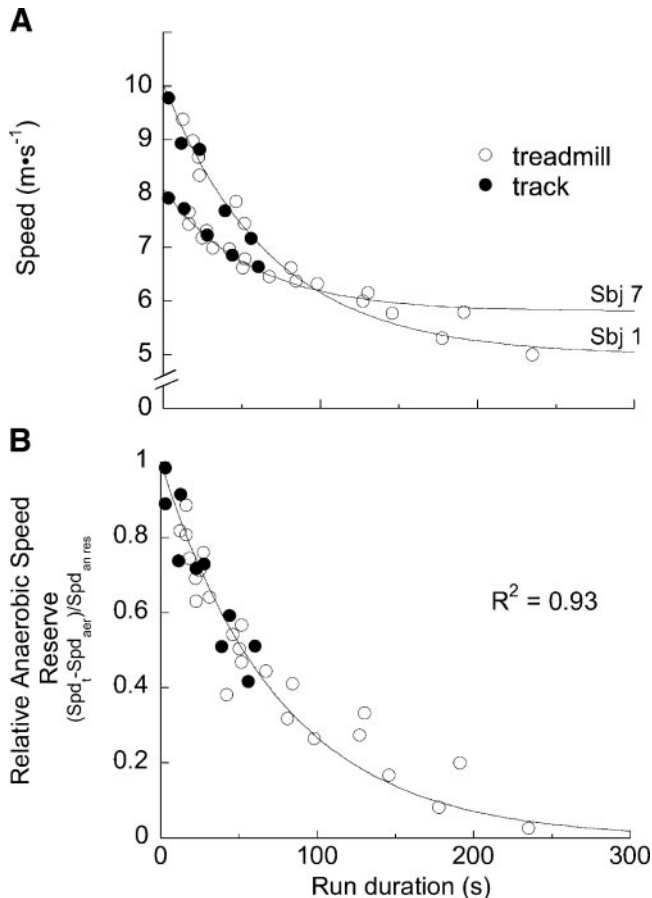
**A**

**B**

Fig. 3. All-out running treadmill and track speeds in relation to run duration for the subjects with the fastest and slowest maximum sprint speeds (*A*) and all-out treadmill and track velocities expressed relative to the anaerobic speed reserve of these subjects (*B*). Despite different absolute speeds at a given duration (*A*), when expressed in relation to the anaerobic speed reserve, these differences are essentially eliminated. The curve were fit with the following equations: for *A*, $Spd = Spd_{aer} + (Spd_{an} - Spd_{aer}) \cdot e^{-kt}$; for *B*, relative $Spd = e^{-kt}$.

erage of 3.7% ($R^2 = 0.93$; $n = 77$) and track trials to within an average of 3.3% ($R^2 = 0.89$; $n = 28$).

**DISCUSSION**

The results from the tests of both our first and second hypotheses were positive. First, we found that high-speed running performance can be accurately predicted from direct measurements of the maximum speeds supported by the anaerobic and aerobic power of individual runners. Across a 30-fold range of trial durations and a 2-fold range of all-out running speeds (Fig. 3*A*), the speeds predicted with these two measures matched the actual speeds to within an average of 2.5 and 3.4% for the treadmill and track trials, respectively. Second, we were able to develop an abbreviated, and therefore more practical, testing procedure that provided predictions of similar accuracy. The shorter two-trial procedure predicted the speeds of the treadmill and track trials to within averages of 3.7 and 3.3%, respectively. Because the abbreviated procedure requires only speed and duration measurements for
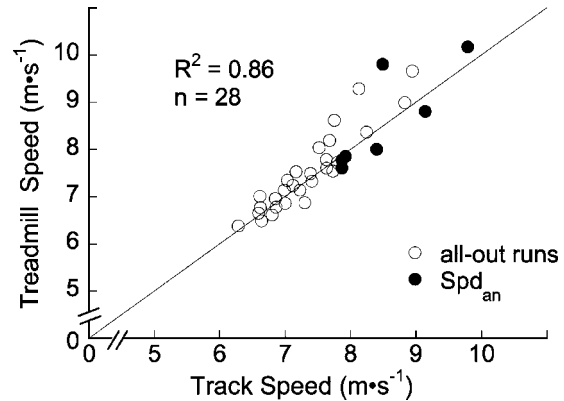


Fig. 4. Interpolated all-out treadmill running speeds vs. measured all-out track running speeds for the 7 subjects. Treadmill speeds were interpolated to compare runs of identical durations. Closed symbols represent the maximum speeds attained for runs of ≤3 s. Treadmill and track velocities were virtually identical for all but 1 subject. The closed circle well above the line of identity and 4 of the 5 open circles above the line of identity at speeds exceeding 7 m/s are those of the subject who reported considerable soreness throughout his track sessions.

two all-out runs, test administration requires only a timing device, two measured distances, and the equations reported in the APPENDIX. The ease of administration and the predictive accuracy that we report identify our technique as a promising alternative to the many tests currently used to assess high-speed running performance.

*Hypothesis Test 1: Predictive Accuracy of the Full Assessment Technique*

The predictive accuracy of our technique was achieved in large part because each runner's speed decrements occur in direct proportion to the difference between the maximum speeds supported by anaerobic and aerobic powers (Fig. 3*B*). We termed this difference ($Spd_{an} - Spd_{aer}$) the anaerobic speed reserve of the runner. Although the magnitude of the speed decrements that occurred for different individuals varied
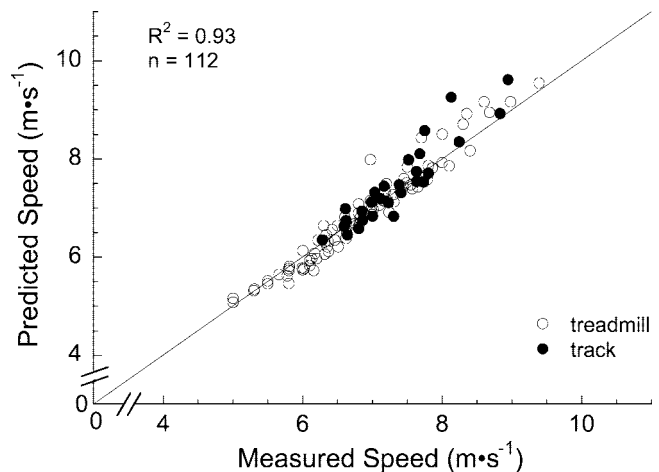


Fig. 5. Measured all-out treadmill and track running speeds for all of the trials completed vs. those predicted by *Eq. 1* from the measured $Spd_{an}$ and $Spd_{aer}$.

substantially (Fig. 3*A*), when expressed relative to the individual's anaerobic speed reserve, they were essentially invariant. Thus the duration for which any given fraction of the anaerobic speed reserve was maintained during an all-out effort did not vary between subjects. This result indicates that fractions of the anaerobic speed reserve provide an expression of relative exercise intensity for all-out bouts of 3–240 s. Given known values of Spd$_{an}$ and Spd$_{aer}$, *Eq. 1* can be used to calculate either the durations or speeds of all-out efforts in this range of durations.

### Hypothesis Test Two: Predictive Accuracy of the Abbreviated Assessment Technique

Use of the maximum 3-s treadmill test (Fig. 2) and a second all-out treadmill trial of roughly 60 s enabled us to predict the speeds of the remaining treadmill trials to within an average of 3.7%. Predictions of level treadmill running performance generated by using the speeds attained on the track for the maximum sprint and 400-m trials were less accurate but still reasonably good (Table 2). The less accurate predictions in the latter case did not result from systematic differences between treadmill and track speeds for all-out runs of the same duration. Generally, we found close agreement between treadmill and track speeds for runs of the same duration, including the maximum sprinting speed (Fig. 3*A* and Fig. 4). The one exception to the close overall agreement was a 1.6 m/s discrepancy in the maximum sprinting speed of the subject who reported considerable muscle soreness throughout his two track sessions (Fig. 4). By excluding this subject, accuracy of this prediction was improved from 4.1% ($R^2 = 0.86$) to 3.2% ($R^2 = 0.93$). These results indicate that our abbreviated two-trial procedure can provide accurate predictions of performance in both the laboratory and the field.

We recognize that the results presented here likely represent the upper limit of predictive accuracy our fitness assessment technique can provide. Because our primary objective was to investigate the predictive validity of our techniques, we tested well-trained, highly motivated athletes in the activity in which they specialized. At present, we do not know how well our technique will work for untrained subjects and for modes of exercise other than running.
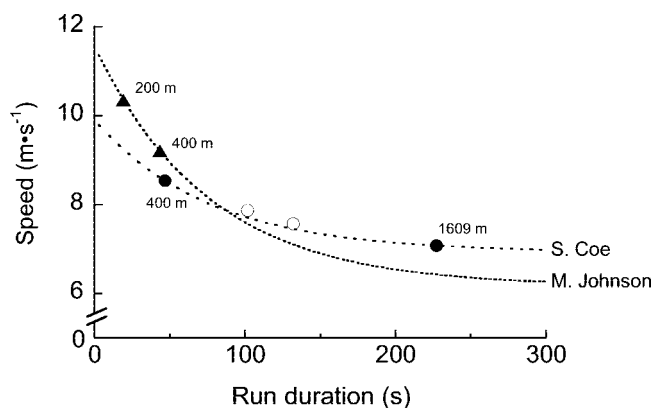


Fig. 6. Predicted speed duration curves for Michael Johnson and Sebastian Coe, based on 2 all-out runs. For Michael Johnson the 2 runs utilized were his gold-medal performances at 200 and 400 m (▲), in Atlanta, 1996. For Sebastian Coe, the runs utilized were his mile world-record run in August 1981 and his personal record for the 400 m (●). The speeds of the world record runs that Coe established at 1,000 and 800 m during the same 1981 season (○) were predicted by our 2-trial procedure to within 1.5 and 2.0%, respectively.

### Practical Implications

Traditionally, tests of anaerobic power and capacity have been used to assess performance capabilities for brief, all-out exercise. The shortcomings of available techniques and ongoing lack of an acceptable standardized assessment technique have been described at length (10, 21, 23). Although considerable testing remains before the utility and value of our technique are fully known, the potential advantages could be numerous. The technique we present here may allow the administration and interpretation of performance tests for high-intensity exercise bouts to become brief and convenient as well as mode specific. For example, in conjunction with aerobic power as a copredictor, the proposed ~3-s all-out tests may extend the range of durations for which a meaningful physical work capacity (1) can be assessed to encompass efforts of <5 min in duration that have previously defied accurate quantification. Additionally, our results raise the possibility that the more lengthy and rigorous tests currently in use for estimating anaerobic capacity (17), critical power (18), and similar entities (3) may be unnecessary for assessing performance capabilities.

Although the conventional focus, and that throughout this paper, has been on predicting performance

Table 2. *Predictive accuracy of the two-trial testing procedure*

| Origin of the Values Used for Calculation | Predicted Trials | No. of Observations | $R^2$ | Average Error, % |
|---|---|---|---|---|
| Treadmill | Treadmill runs | 77 | 0.93 | 3.7 |
| Treadmill | Track runs | 28 | 0.89 | 3.3 |
| Track | Treadmill runs | 84 | 0.86 | 4.1 |
| Track | Track runs | 21 | 0.91 | 3.1 |
| Treadmill | Treadmill and track runs | 112 | 0.93 | 3.6 |

The 2 speeds used in the calculation were Spd$_{an}$ and the run closest to 60 s in duration completed by each subject. No. of trials varies in accordance with those particular trials used to formulate predicted values.

from measurements of metabolic power, the process can just as easily be reversed. Given measurements of all-out running speed for two or more trials that differ in duration, our model allows the maximum respective speeds supported by anaerobic and aerobic power to be determined algebraically by using the procedure that appears in the APPENDIX. This procedure can be used to predict not only the maximum speeds supported by both anaerobic and aerobic power but also the entirety of the speed-duration curve from 3 to 240 s and perhaps beyond. These predictions are of potential value to individuals who regularly engage in all-out running efforts of a few minutes or less but for whom frequent laboratory testing is impractical.

*Overview and Conclusions*

Our method provides an alternative to the many techniques that have been developed and implemented over the past half century (2, 13, 17, 18, 20) to assess performance capabilities during brief, all-out exercise. Two aspects of our approach made this possible. First, the relationship expressed in *Eq. 1* incorporates terms directly influenced by the metabolic power available from both the anaerobic and aerobic sources of chemical energy that together fuel these efforts. In contrast, existing tests of anaerobic power, anaerobic capacity, and aerobic power incorporate only one. Second, a single exponent appears to be sufficient to provide accurate descriptions of the relationship between the maximum speed provided by both sources of metabolic power in relation to the duration of the effort. Many previous investigators have noted the exponential nature of the decrements in anaerobic power and increments in aerobic power that occur as the duration of all-out running or other exercise becomes more prolonged (8, 9, 22, 24, 27). For parsimony, we used a brief quantitative description that includes only one exponent. This approach allows fitness testing for these efforts to be reduced to identifying the respective upper performance limits supported by the anaerobic and aerobic power of the individual. More conveniently, our algorithms allow these upper limits to be derived from performance data that can be obtained in a matter of minutes and from as few as two trials.

### APPENDIX

*Abbreviated Assessment Technique (2-Trial Protocol)*

Given the relationships provided by *Eq. 1*, predicting $\text{Spd}_{an}$, $\text{Spd}_{aer}$, and the remainder of a runner's speed-duration curve can be determined given duration ($t_1$, $t_2$) and speed ($\text{Spd}_1$, $\text{Spd}_2$) measurements of two all-out trials of different durations and the established $k$ value of 0.013 (for durations in seconds and speeds in m/s) as follows

$$\text{Spd}_1 = \text{Spd}_{aer} + (\text{Spd}_{an} - \text{Spd}_{aer}) \cdot e^{(-kt_1)} \quad (2)$$

$$\text{Spd}_2 = \text{Spd}_{aer} + (\text{Spd}_{an} - \text{Spd}_{aer}) \cdot e^{(-kt_2)} \quad (3)$$

Subtracting *Eq. 3* from *Eq. 2* gives

$$(\text{Spd}_1 - \text{Spd}_2) = (\text{Spd}_{an} - \text{Spd}_{aer}) \cdot [e^{(-kt_1)} - e^{(-kt_2)}] \quad (4)$$

because the term $\text{Spd}_{an} - \text{Spd}_{aer}$ is a constant that we have defined as the anaerobic speed reserve ($\text{Spd}_{an\ res}$), *Eq. 4* becomes

$$(\text{Spd}_1 - \text{Spd}_2) = \text{Spd}_{an\ res}[e^{(-kt_1)} - e^{(-kt_2)}] \quad (5)$$

which can be rearranged and solved as

$$\text{Spd}_{an\ res} = \frac{(\text{Spd}_1 - \text{Spd}_2)}{[e^{(-kt_1)} - e^{(-kt_2)}]} \quad (6)$$

$\text{Spd}_{asr}$ can then be substituted into *Eq. 2* to obtain

$$\text{Spd}_1 = \text{Spd}_{aer} + \text{Spd}_{an\ res} \cdot e^{(-kt_1)} \quad (7)$$

which can be rearranged to

$$\text{Spd}_{aer} = \text{Spd}_1 - \text{Spd}_{an\ res} \cdot e^{(-kt_1)} \quad (8)$$

Because the right-hand side of *Eq. 8* is composed of known quantities, we can calculate a value for $\text{Spd}_{aer}$, which then permits the calculation of $\text{Spd}_{an}$

$$\text{Spd}_{an} = \text{Spd}_{an\ res} + \text{Spd}_{aer} \quad (9)$$

With calculated values for $\text{Spd}_{an}$ and $\text{Spd}_{aer}$ for a particular subject and the known exponent, either the velocity or run duration can be estimated for any run within the duration window for which our model applies.

This two-trial procedure was used to determine the $\text{Spd}_{an}$, $\text{Spd}_{aer}$, and the speed-duration curves for Michael Johnson and Sebastian Coe from their record-breaking 1996 and 1981 seasons, respectively (Fig. 6). Specific trial durations and speeds used for Michael Johnson were his gold medal runs in the 200-m (19.32 s) and 400-m (43.44 s) races from the 1996 Atlanta Olympics, whereas those used for Sebastian Coe were his personal best at 400 m (46.87 s; London, 14 July, 1979), and his world record for the 1-mile run (227.33 s) in August of 1981.

### REFERENCES

1. **Åstrand PO and Rodahl K.** *Textbook of Work Physiology.* New York: McGraw-Hill, 1986.
2. **Bar-Or O.** The Wingate anaerobic test: an update on methodology, reliability and validity. *Sports Med* 4: 381–394, 1987.
3. **Blondel N, Berthoin S, Billat V, and Lensil G.** Relationship between run times to exhaustion at 90, 100, 120, and 140% of $\dot{V}_{O_2\ max}$ and velocity expressed relatively to critical velocity and maximal velocity. *Int J Sports Med* 22: 27–33, 2001.
4. **Consolazio CF, Johnson RE, and Pecora LJ.** *Physiological Measurements and Metabolic Functions in Man.* New York: McGraw-Hill, 1963.
5. **Costill DL.** Physiology of marathon running. *JAMA* 221: 1024–1029, 1972.
6. **Costill DL, Thomason H, and Roberts E.** Fractional utilization of the aerobic capacity during distance running. *Med Sci Sports Exerc* 5: 248–252, 1973.
7. **Daniels J and Daniels N.** Running economy in elite male and elite female runners. *Med Sci Sports Exerc* 24: 483–489, 1992.
8. **diPrampero PE, Capelli C, Pagliaro P, Antonutto G, Girardis M, Zamparo P, and Soule RG.** Energetics of best

performances in middle-distance running. *J Appl Physiol* 74: 2318–2324, 1993.

9. **Ettema JH.** Limits of human performance and energy-production. *Int Z Angew Physiol Einschl Arbeitsphysiol* 22: 45–54, 1966.

10. **Green S and Dawson BT.** Measurement of anaerobic capacity in humans: definitions, limitations, unsolved problems. *Sports Med* 15: 312–327, 1993.

11. **Hill AV.** The physiological basis of athletic records. *British Association for the Advancement of Science: Report of the 93rd meeting.* 1925, p. 156–173.

12. **Hill AV.** The dimensions of animals and their muscular dynamics. *Sci Prog* 150: 209–230, 1950.

13. **Maragaria R, Edwards HT, and Dill DB.** The possible mechanism of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. *Am J Physiol* 106: 689–715, 1933.

14. **Margaria R.** Measurement of muscular power (anaerobic) in man. *J Appl Physiol* 21: 1662–1664, 1966.

15. **Margaria R.** *Biomechanics and Energetics of Muscular Exercise*. Oxford, UK: Clarendon, 1976, p. 53–55.

16. **Margaria R, Cerretelli P, Aghemo P, and Sassi G.** Energy cost of running. *J Appl Physiol* 18: 371–377, 1963.

17. **Medbo JI, Mohn AC, Tabata I, Bahr R, Vaage O, and Sejersted OM.** Anaerobic capacity determined by maximal accumulated $O_2$ deficit. *J Appl Physiol* 64: 50–60, 1988.

18. **Monod H and Scherrer J.** The work capacity of a synergic muscle group. *Ergonomics* 8: 329–338, 1965.

19. **Olesen HL.** Accumulated oxygen deficit increases with the inclination of uphill running. *J Appl Physiol* 73: 1130–1134, 1992.

20. **Rusko H, Numela A, and Mero A.** Measurement of maximal and submaximal anaerobic power. *Int J Sports Med* 17, *Suppl* 2: S89–S90, 1996.

21. **Saltin B.** Anaerobic capacity: past, present, and prospective. In: *Proceedings from the 7th International Biochemistry of Exercise Conference*, edited by Taylor AW. Champaign, IL: Human Kinetics, 1990, vol. 7, p. 388–412.

22. **Savaglio S and Carbone V.** Scaling in athletic world records. *Nature* 16: 244, 2000.

23. **Vandewalle HG, Peres G, and Monod H.** Standard anaerobic exercise tests. *Sports Med* 4: 268–289, 1987.

24. **Ward-Smith JA.** Aerobic and anaerobic energy conversion during high-intensity running. *Med Sci Sports Exerc* 31: 1855–1860, 1999.

25. **Weyand PG, Lee CS, Martinez-Ruiz R, Bundle MW, Bellizzi MJ, and Wright S.** High-speed running performance is largely unaffected by hypoxic reductions in aerobic power. *J Appl Physiol* 86: 2059–2064, 1998.

26. **Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S.** Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991–1999, 2000.

27. **Wilkie DR.** Equations describing power input by humans as a function of duration of exercise. In: *Exercise Bioenergetics and Gas Exchange*, edited by Cerretelli P and Whipp BJ. Amsterdam, Holland: Elsevier, 1980, p. 75–80.