Sprint performance-duration relationships are set by the fractional duration of external force application

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ABSTRACT

We hypothesized that the maximum mechanical power outputs that can be maintained during all-out sprint cycling efforts lasting from a few seconds to several minutes can be accurately estimated from a single exponential time constant \( k_{\text{cycle}} \) and two measurements on individual cyclists: the peak 3 s power output \( P_{\text{mech max}} \) and the maximum mechanical power output that can be supported aerobically \( P_{\text{aer}} \). Tests were conducted on seven subjects, four males and three females, on a stationary cycle ergometer at a pedal frequency of 100 rpm. Peak mechanical power output \( P_{\text{mech max}} \) was the highest mean power output attained during a 3 s burst; the maximum power output supported aerobically \( P_{\text{aer}} \) was determined from rates of oxygen uptake measured during a progressive, discontinuous cycling test to failure. Individual power output-duration relationships were determined from 13 to16 all-out constant load sprints lasting from 5 to 350 s. In accordance with the above hypothesis, the power outputs measured during all-out sprinting efforts were estimated to within an average of 34 W or 6.6 % from \( P_{\text{mech max}}, P_{\text{aer}}, \) and a single exponential constant \( k_{\text{cycle}} = 0.026 \text{ s}^{-1} \) across a 6-fold range of power outputs and a 70-fold range of sprint trial durations \( (R^2 = 0.96 \text{ vs. identity, n} = 105; \text{range: 180 to 1136 W}) \). Duration-dependent decrements in sprint cycling power outputs were two times greater than those previously identified for sprint running speed \( k_{\text{run}} = 0.013 \text{ s}^{-1} \). When related to the respective times of pedal and ground force application rather than total sprint time, decrements in sprint cycling and running performance followed the same time course \( (k = 0.054 \text{ s}^{-1}) \). We conclude that the duration-dependent decrements in performance are set by the fractional duration of the relevant muscular contractions.
KEYWORDS: locomotion, cycling, running, anaerobic, aerobic, skeletal muscle, fatigue

Running head: Energetics of sprint locomotion
INTRODUCTION

The mechanical performance of skeletal muscle becomes progressively impaired during intense periods of contractile activity. The functional losses that are characteristic of skeletal muscle (5) can be observed at numerous levels of musculoskeletal organization. For example, the maximum speeds animals can attain during all-out locomotor efforts fall exponentially as the duration of the effort increases (18, 19, 25). Similarly, the force and power outputs of individual muscles and fibers drop off markedly with repeated stimulation (13, 14, 43). Although the mechanisms responsible are not well understood, performance is progressively compromised whenever skeletal muscle relies heavily on non-oxidative pathways of ATP resynthesis to fuel sequential contractions.

From a qualitative standpoint, the duration-dependent decrements in the mechanical performance of the musculoskeletal system during locomotion are generally more consistent than those observed in the various muscle and muscle fiber preparations. Peak locomotor performances, evaluated in terms of either the speed attained or mechanical power delivered to an external medium such as an ergometer, occur during efforts of 3 seconds or less (27, 37, 45). As the duration of an all-out effort is extended from seconds to minutes, performance declines in an exponential fashion. The characteristic negative exponential relationship between locomotor performance and effort duration was noted for both equine and human runners in the early work of A.V. Hill (18), and has been noted by Hill (19) and others (7, 10, 23, 47) subsequently for other modes of human locomotion such as swimming, cycling and skating.

While the performance-duration relationship is qualitatively consistent for different modes of human locomotion, the quantitative relationships between burst and
sustainable locomotor performances are not. For example, the maximum sprinting speeds human runners can attain for a burst of a few seconds are roughly twice as fast as the maximum speeds they can support aerobically (4, 46). In contrast, trained cyclists can achieve mechanical power outputs during short sprints that exceed the power outputs they can support aerobically by four-fold or more (27, 37, 47). The marked difference in the relative intensities that can be supported implies that the metabolic demands of sprinting may differ appreciably between these modes.

Our previous results may offer a general explanation for the decrements in sprinting performance that occur in relation to event duration. We recently found that the large absolute differences in sprint performance-duration relationships of sprint and endurance athletes are essentially invariant when expressed in the terms of our anaerobic reserve model. Specifically, when we expressed the performance curves of these athletes in relation to the difference between their mechanical maximums for speed and the metabolic maximums that they could support aerobically (i.e. the anaerobic speed reserve), we found that they all conformed to the same relationship (4, 46). These results suggest that the performance of the musculoskeletal system may undergo duration-dependent performance decrements dictated by the relative reliance on anaerobic metabolism to provide mechanical function.

Here, we used the relatively greater intensities attained during sprint cycling to test this idea in two ways. First, we hypothesized that with increments in the duration of all-out efforts, the power outputs of different cyclists would decrease in the same relative manner from their mechanical maximum for 3 s to the metabolic maximum they could support aerobically. Second, we hypothesized that duration-dependent decrements in
performance would follow the same time course for different modes of sprint locomotion, in the same manner that the decrements of individual specialists do (4, 46). Accordingly, we predicted that the exponential time constant describing the duration-dependent decrements in sprint cycling power outputs would be identical to that previously identified for sprint running speed.
METHODS

Experimental Design

Testing our two hypotheses required adapting the anaerobic reserve model we originally developed for running (4) to the following form for cycling:

\[ P(t) = P_{\text{aer}} + (P_{\text{mech max}} - P_{\text{aer}}) \cdot e^{(-k_{\text{cycle}} \cdot t)} \]  

(1)

where \( P(t) \) is the power output maintained for a trial of duration \( t \), \( P_{\text{mech max}} \) is the maximum power output for a trial of 3 seconds, \( P_{\text{aer}} \) is the maximum mechanical power output that can be supported by aerobic metabolism, the quantity \( P_{\text{mech max}} - P_{\text{aer}} \) is the anaerobic reserve, \( e \) is the base of the natural logarithm, and \( k_{\text{cycle}} \) is the exponent that describes the decrements in power output occurring with increments in the duration of all-out cycling efforts. We expect that a single value of the exponent \( k_{\text{cycle}} \) will describe duration-dependent decrements in power output of any cyclist regardless of their mechanical and aerobic maxima.

The quantitative basis for the equations and relationships in our model are provided in greater detail elsewhere (46). \( P_{\text{mech max}} \) and \( P_{\text{aer}} \) are empirically determined quantities that are representative of the body’s functional limits for burst and endurance performance. However, when exercising at these specific intensities the body does not exclusively rely on the pathways of either anaerobic or aerobic ATP resynthesis.

We evaluated our 1st hypothesis that our anaerobic reserve model would accurately estimate sprint cycling power outputs for efforts of 3 to 300 s regardless of the ability of the performer by: 1) obtaining measurements of the respective maximum mechanical power outputs that could be attained for 3 s and supported aerobically by
each cyclist, 2) establishing the individual power output-duration curve for each cyclist, and 3) evaluating the agreement between the power outputs measured during the sprint cycling trials and those estimated by our anaerobic reserve model (eq. 1).

We evaluated our 2nd hypothesis that performance decrements from the mechanical maximum to the aerobic maximum would follow the same time course for sprint cycling and sprint running by assessing whether the mean values for $k_{cycle}$ and $k_{run}$ are equal. The value for $k_{cycle}$ was the mean of the individual values determined from an iterative best-fit procedure using eq. 1 and the measured $P_{mech\ max}$ and $P_{aer}$ of the individual cyclist (Kaleidagraph 3.51, Synergy Software). The value for $k_{run}$ was previously determined for 7 subjects during all-out sprint running over a similar range of trial durations ($k = 0.013 \pm 0.001$; ref 4). The respective means were compared with an unpaired student’s t-test.

We recruited both male and female subjects to maximize the range of values obtained for $P_{mech\ max}$, $P_{aer}$, and power outputs during sprint cycling trials. We conducted all cycling tests at a pedal frequency of 100 revolutions per minute. Although marginally greater peak power output values are obtained at frequencies greater than 100 rpm, this strategy allowed power output differences to be a direct function of force, rather than a more complicated function of force and velocity.

Subjects and Protocol

Seven subjects, 4 males and 3 females (mean age = 26 ± 2.7 years, se) of varying fitness levels from recreational cyclists to trained, competitive cyclists volunteered and provided
written, informed consent in accordance with the guidelines of the local institutional review board. Body masses and aerobic power maxima appear in Table 1.

Testing was generally completed in 5 laboratory sessions. All tests were conducted on a stationary cycle (SRM Indoor trainer; Königskamp, Germany) equipped with a strain-gauge based ergometer (Powercontrol IV, SRM). The ergometer has a large, aluminum flywheel to which rotational resistance is offered by an external magnetic brake aligned along the flywheel’s outer rim. Brake position and resistance can be adjusted via cable and a lever mounted on the handlebars. Power output and cadence were continuously displayed on a PC monitor during all tests. The primary record of this data was recorded to the ergometer computer with a sampling frequency of 10 Hz and was downloaded to a PC following each trial. The zero torque output and slope settings of the ergometer were checked prior to each testing session.

The first testing session consisted of a progressive, discontinuous test to determine the maximum rate of oxygen uptake ($\dot{V}_{\text{aer max}}$). During the next three sessions, subjects completed a total of 13-16 all-out sprint cycling bouts of varying power outputs and durations to establish their individual power output-trial duration curves. Four to 6 all-out cycling bouts were generally completed per test session in accordance with subject performance and verbal feedback regarding recovery. The last session consisted of 6-8 all-out burst efforts of $\geq 3$ s. During all trials subjects were restrained in the saddle with use of a seat belt that did not hinder leg movement.
Measurements

Metabolic rate during cycling (\( E_{\text{metab}} \)). Rates of metabolic energy expenditure were determined from the rates of oxygen uptake measured with a computerized metabolic system (TrueMax 2400, Parvo Medics; Sandy, Utah). Each subject completed a progressive, discontinuous, power-output incremented cycling test that consisted of 5-min bouts of cycling at 100 rpm interspersed with rest periods of approximately 3 to 5 minutes. Initial power outputs generally ranged from 70 to 150 Watts, depending on the estimated fitness level of the subject. Power outputs for subsequent bouts were increased by 20-40 W until a power output was reached at which the subject could not maintain the required 100 rpm pedal frequency for the full 5 minutes while putting forth a maximal effort. Expired air was directed via a one-way breathing valve and corrugated tubing through a pneumotach into a mixing chamber. Aliquots were drawn from the mixing chamber and analyzed for O\(_2\) and CO\(_2\) fractions using paramagnetic and infrared analyzers, respectively. Rates of oxygen uptake at each power output were averaged over the 4\(^{\text{th}}\) and 5\(^{\text{th}}\) minutes of each bout.

Mechanical and Metabolic Maximums

Peak power output at 100 rpm (\( P_{\text{mech max}} \)). Peak power outputs were determined from the highest power output that subjects were able to maintain for 3 seconds at a pedal cadence of 100 revolutions per minute while strapped into the saddle. This value was determined from a series of all-out trials of \( \geq 3 \) s at varying resistances. Subjects were allowed to cycle for 4 unloaded revolutions to accelerate the flywheel before the load was applied with simultaneous verbal cue. The greatest power output attained for 3 s at 100 ± 5 rpm
for any of the trials was considered the peak mechanical power output of the subject
(P_{mech max}). The corresponding metabolic rate (E_{an max}) was estimated from linear
extrapolation of the submaximal power output and oxygen uptake relationship of each
individual. The validity of this extrapolation is not known.

Maximal aerobic power (E_{aer max}). Maximal aerobic power was determined from the
progressive, discontinuous cycling test previously described. The greatest E_{aer} value
measured during any 15 s interval during the progressive test was considered E_{aer max}.
The maximum mechanical power that could be supported aerobically (P_{aer}), a calculated
value, was computed from a linear extrapolation of each individual’s oxygen uptake-
power output relationship to the measured value of E_{aer max}. In general, 6 sub-maximal
bouts were completed before subjects reached E_{aer max}. A minimum of 5 steady-state
values no greater than 90% of E_{aer max} was used to formulate each subject’s oxygen
uptake-power output relationship.

Sprint cycling trials
Sprinting trials were initiated by the subject performing 4 unloaded pedal revolutions
before the prescribed resistance was applied to the ergometer’s flywheel. Subjects were
instructed to maintain a pedal frequency of 100 rpm throughout the trial using a
metronome and/or visual feedback from the PC monitor. When the cadence fell below
that prescribed, subjects were exhorted to restore the cadence to 100 rpm. If they were
unable to do so within 2 seconds, the trial was halted. Each subject completed a
minimum of 13 all-out trials. Flywheel resistance and power outputs for individual trials were chosen to obtain all-out trial durations throughout the desired target range of 5 to 300 s. Subjects were instructed to take as much time as necessary for a full recovery between sprint trials, but were required to take a minimum of ten minutes.

Rates of anaerobic energy release ($\dot{E}_{an}$). Estimated rates of anaerobic energy release, averaged over the duration of each sprint cycle bout, were determined from the oxygen deficits (ml O2 eq·kg⁻¹·min⁻¹) incurred during each all-out sprint trial in accordance with Medbø et al. (31). The oxygen taken up during the cycling trial was subtracted from the estimated total demand. The total oxygen demand of each trial was estimated using a linear extrapolation of the subject’s steady-state oxygen uptake–power output relationship to the power output of the sprint trial. The limitations of this technique have been discussed at great length (1, 2, 34). Although widely used, the validity of this technique is not known.

Rates of aerobic energy release ($\dot{E}_{aer}$). Rates of aerobic metabolism were determined from the rates of oxygen uptake using the Douglas bag technique in accordance with Consolazio et al. (8). Expired air was collected in individual bags for 60, 90 seconds or for a final bag interval determined by the duration of the subject’s performance on the particular trial. Aliquots from each bag were analyzed for O₂ and CO₂ fractions after the analyzers were calibrated with a gas of known O₂ and CO₂ concentrations. Minute volumes and expired air temperatures were determined using a 120 L Tissot wet spirometer with simultaneous temperature measurement. Rates of oxygen uptake,
corrected to STPD, were averaged for the duration of each all-out cycling trial. Values for $\dot{E}_{an}$, $\dot{E}_{aer}$, $\dot{E}_{tot}$ and P for all the sprint cycle trials completed by subject 5 appear in Figure 1. The curve-fit equations were the same as those previously described (46).

Run-Cycle Comparisons

The exponential value ($k_{cycle}$) best describing the power output-trial duration relationship for each subject was determined using an iterative best-fit procedure (KaleidaGraph, Version 3.6, Fig. 1D) given the measured values for $P_{mech \, max}$, $P_{aer}$ and eq. 1. The same procedure was previously employed to determine $k_{run}$ for 7 male runners from their maximum burst sprint speeds and running velocities at $\dot{V}_{O2 \, max}$ (4).

RESULTS

Mechanical and Metabolic Maximums

Peak Power Output ($P_{mech \, max}$). For male subjects the maximum mechanical power output attained for 3 s was 1127 ± 143 W (mean ± SE are reported throughout). The estimates for the corresponding metabolic power, $\dot{E}_{an \, max}$, that were obtained via linear extrapolation were 217.3 ± 27.2 ml O$_2$ eq·kg$^{-1}$·min$^{-1}$ (range = 193-256 ml O$_2$ eq·kg$^{-1}$·min$^{-1}$). For female subjects the maximum mechanical power output for 3 s was 639 ± 56 W with corresponding estimates for $\dot{E}_{an \, max}$ of 116.3 ± 11.5 ml O$_2$ eq·kg$^{-1}$·min$^{-1}$ (range = 103-123 ml O$_2$ eq·kg$^{-1}$·min$^{-1}$).
Aerobic power output (P_aer). The male mean for the maximum mechanical power output supported aerobically was 328 ± 39 W, and the corresponding mean $\dot{E}_{\text{aer max}}$ was 56.9 ± 3.1 ml O$_2$·kg$^{-1}$·min$^{-1}$. For females, the maximum mechanical power output that could be supported aerobically was 187 ± 32 W, and their mean $\dot{E}_{\text{aer max}}$ was 39.0 ± 1.7 ml O$_2$·kg$^{-1}$·min$^{-1}$.

Anaerobic Power Reserve (P_an res). The quantity $P_{\text{mech max}} - P_{\text{aer}}$, or the mean P_an res was 799 ± 149 W for males and 452 ± 78 W (Fig. 2) for females, respectively. On average, the maximum mechanical power outputs attained for 3 s were 3.5 ± 0.6 times higher than the maximum power outputs that could be supported by aerobic power (Fig. 2).

Power Output vs. Trial Duration

Although individual subjects differed considerably in absolute power outputs maintained during the sprint trials (Fig. 3A), when these power outputs were expressed as a fraction of the individual’s anaerobic power reserve $(P(t) - P_{\text{aer}})/P_{\text{an res}}$, the power output decrements of different subjects were essentially identical (Fig. 3B). The mean $k_{\text{cycle}}$ exponent of the 7 individual values providing the best fit to the measured power output-duration curves using eq. 1 was $0.026 ± 0.005$ s$^{-1}$ (range = 0.020-0.033).

The 105 sprint trials completed spanned a 70-fold range (5-350 s) of durations and 6-fold range of mechanical power outputs (range: 180-1136 W). For these trials the power outputs measured matched those estimated from the individual $P_{\text{mech max}}$ and $P_{\text{aer}}$ values of each cyclist and the mean $k_{\text{cycle}}$ value of 0.026 s$^{-1}$ (eq. 1; Fig. 4) to within an average of 6.6% and 34 W per trial. Across the 6-fold range in mechanical power output,
our anaerobic reserve model accounted for 96% of the variance measured in all sprint trials, with a standard error of estimate (SEE) of 48.4 W. The predictions generated using the highest (0.033 s⁻¹) and lowest (0.020 s⁻¹) individual $k_{cycle}$ values agreed with those measured to within an average of 10.1 and 8.8%, respectively (SEE = 70.2 W and 58.7 W, respectively).

*Sprint Cycling vs. Running*

Mean values for $\dot{E}_{an}$, $\dot{E}_{aer}$, and $\dot{E}_{tot}$ in relation to trial duration for both cycling and running appear in Fig. 5A. In order to compare cyclists and runners of similar aerobic power, the means of the male cyclists only (n = 4) were compared to those of 7 similarly athletic male runners who were tested previously (cycle vs. run group $\dot{E}_{aer max}$ means = 56.9 ± 3.1 vs. 61.7 ± 2.0 ml O₂ ·kg⁻¹·min⁻¹). For sprint trials of all durations, estimated rates of $\dot{E}_{an}$, during sprint cycling were two times greater than those estimated during sprint running. Values of $\dot{E}_{an}$, were estimated as the difference between the linear extrapolation of each individual subject’s sub-maximal oxygen uptake-power output relationship and the measured values of oxygen uptake. Unlike $\dot{E}_{an}$, $\dot{E}_{aer}$ values were similar between the different modes across all trial durations. Accordingly, between mode differences in $\dot{E}_{tot}$, the sum of $\dot{E}_{an}$ plus $\dot{E}_{aer}$, depended on the duration of the all-out trial.

Sprinting performance, expressed in relation to the intensity of the maximum aerobic performance in the respective modes ($P(t)/P_{aer}$ and $Spd(t)/Spd_{aer}$), was also two times greater for sprint cycling than sprint running for the shortest trials of less than 10 s (Fig. 5B). For all-out efforts of longer durations, cycling values for $P(t)/P_{aer}$ were also...
greater than the corresponding running values for Spd(t)/Spd_{anaer}, with between mode differences being smaller for trials of progressively longer durations. For all trial durations of 100 s and longer, the relative performance values from the two modes were nearly identical.

_Sprint Cycling vs. Running: exponential time constants_

Expressed as a fraction of the respective anaerobic reserves for the two modes of locomotion, the decrements in sprinting performance in relation to trial duration were two times greater for sprint cycling than sprint running. Accordingly, the exponent providing the best-fit descriptions for the duration-dependent performance decrements in cycling was twice that previously identified for running ($k_{cycle} = 0.026 \pm 0.005$ and $k_{run} = 0.013 \pm 0.001$ s$^{-1}$; $p < 0.001$).
DISCUSSION

The results of our hypothesis tests were mixed: one positive, one negative. First, in accordance with expectation, we found that decrements in sprint cycling power outputs of different individuals, although different in absolute terms, were the same when expressed in relation to their anaerobic reserves for power. Second, in contrast to expectation, we found that the sprint performance-duration relationships of cycling and running did not follow the same time course: duration-dependent decrements in sprint cycling power output were two times greater than those in sprint running speed. Thus, the value of the exponent in our model that describes these decrements is mode-specific rather than universal (Fig 6A). Why is this so?

We postulated that the greater duration-dependent performance decrements in sprint cycling vs. running might somehow be related to the greater relative intensities attained for the shortest cycling bouts. Accordingly, we focused on the timing of the muscular contractions that ultimately determine performance in the respective modes: those periods during which the limbs apply force to either the pedal or the ground. During cycling, each limb applies force to the pedal during the down stroke portion of the revolution (duty factor = 0.50) regardless of pedal frequency (9, 33, 39). During running at the speeds tested (4), each limb applies force to the running surface for 0.24 ± 0.02 of the total stride time, with negligible variation between subjects or speeds (46). We did not include the muscular activity that can occur during the upstroke of the pedal revolution or the aerial phase of the running stride because the direct influence of this activity on performance appears to be negligible (9, 26, 45). When performance decrements in the two modes were expressed in relation to the durations for which the
muscles were activated to apply force to the environment (i.e. total trial time • duty factor), they were essentially identical (cycle = 0.052 ± 0.01; run = 0.054 ± 0.01; p = 0.85; Fig. 6B).

A direct relationship between performance and the contractile durations during which the limb muscles convert chemical energy into external power and force is compatible with the current understanding of skeletal muscle fatigue (13, 14, 43) and mechanistically more logical. Our findings indicate that the qualitative similarity long observed for different performance-duration relationships (3, 7, 10, 11, 18, 19, 23, 25, 35, 38, 40, 41) can be quantitatively explained by two factors: the anaerobic power or speed reserve available, and the proportion of the total sprint time that the muscles are activated to apply force to the environment.

In contrast to other investigations (7, 11, 16, 22, 23, 35, 40, 41) of performance capabilities for efforts of up to a few minutes, the performance outcomes provided by our model do not rely on quantitative estimates of the anaerobic energy released. Our anaerobic reserve model simply quantifies that portion of the power output or speed that is provided anaerobically. Thus, the common performance-duration relationship we report is completely independent of the uncertainties associated with estimates of the anaerobic energy released during exercise.

*How well does the Anaerobic Reserve Model apply to cycling?*

Because the all-out power outputs of different cyclists did fall in the same relative manner from their mechanical to their aerobic maxima as trial durations increased, the estimated power outputs from our model closely matched those that we measured (Fig.
4). Across a 70-fold range of trial durations and a 6-fold range of power outputs, our anaerobic reserve model estimated the actual power outputs of our subjects to within an average of ± 6.6% (R² = 0.96 vs. identity). Performance estimates were similarly accurate for individual subjects regardless of their mechanical and aerobic power maxima (R² range for individuals: 0.92-0.98; Fig. 3). The overall accuracy of the model for cycling was similar to that we previously reported for running (R² = 0.97; ref 46). These positive results for a second mode of locomotion suggest that our model will accurately describe the performance-duration relationship for other whole-body exercises with measurable mechanical and aerobic maxima.

Our test of the accuracy of our model for sprint cycling performance was not completely independent as was the case with our prior running tests. Here, in contrast to previous practice (4, 46), we derived the value of our exponential time constant (k_cycle) from the same subjects whose performances were subsequently estimated. Our primary interest here was the general validity of the model rather than the specific degree of predictive accuracy. Thus, we deemed a goodness of fit approach to be valid, and our data supported this premise. When we generated performance estimates using the highest and lowest individual k_cycle values (0.020 and 0.033, respectively) rather than the overall mean (0.026), the agreement of the performance estimates was virtually unaffected (R² = 0.90 and 0.95, respectively).

The similarly accurate performance estimations obtained for cycling and running indicate that the model’s general applicability is independent of the mechanical differences that exist between sprint locomotor modes. In contrast to running, cycling is a non-weight bearing exercise in which performance depends on the delivery of
mechanical power to the pedals (27, 28) rather than the rapid application of force to the
ground (26, 45). The external forces applied to the pedals during cycling (27, 28) are
roughly an order of magnitude less than those applied to the ground during sprint running
(45). Much lower external force outputs are consistent with the active muscles operating
at greater strains, greater relative shortening velocities (i.e. \( V/V_{\text{max}} \)) and lesser stresses
during cycling (19, 27, 36). Although these and accompanying differences in rates of
cross-bridge detachment and ATP hydrolysis (21, 30) might have affected the time
course of the sprint performance decrements examined in a variety of ways, they did not.
Regardless of the requirements for power and force in the different modes, decrements in
the proportion of the performance provided anaerobically were all but identically related
to the cumulative duration of the contractions involved (Fig. 6).

Metabolic power and sprint performance limits: general implications
Our cycle-run comparisons offer additional evidence that the reserves of chemical energy
within the active muscles have flexible release rates that meet the metabolic demands
generated by all-out sprint efforts; whatever those demands might be. Generally, the
rates of anaerobic energy release during all-out sprint efforts have been assumed to be
maximal (3, 7, 10, 12, 19, 25, 35, 38, 40, 41, 42). However, when hypoxic conditions are
created to reduce the aerobic contributions to all-out sprint efforts, rates of anaerobic
energy release compensate (6, 44) and considerably exceed the normoxic values that have
been traditionally regarded as maximums. Here, we found when expressed in relation to
the maximum cycling power outputs and running speeds supported aerobically, the
mechanical maximums for burst sprint performance were two times greater for cycling
than running. Additionally, we found that the estimated rates of anaerobic energy release were from 67 to 22% greater during sprint cycling vs. running for those trials that lasted from 3 to 60 s. Given that the extensor muscle mass recruited was not likely to be any greater during sprint cycling than sprint running (32), our results suggest that the rates of anaerobic energy release; within individual fibers, muscles and throughout the whole body, can vary considerably during all-out sprinting efforts, and do so in accordance with the metabolic demands incurred by the contractions involved in the activity.

These results do not support the widely held view that performance-duration relationships can be explained by rates of ATP supply (3, 7, 10, 12, 19, 22, 23, 25, 35, 38, 40, 41, 42). Rather, a reliance on anaerobic metabolism somehow induces decrements in the mechanical performance of the musculoskeletal system as the cumulative duration of the contractile activity becomes more prolonged. The mechanism almost certainly involves the progressive inhibition of intracellular force production that occurs with intense sequential contractions (13, 14, 43), but may also include reductions in the muscle volumes available (15), and perhaps other factors.

The absence of a direct metabolic limitation is well supported by interventions that have enhanced sprinting performance by prolonging the timing of the muscular contractions involved. The peak power outputs measured during single leg cycling sprints were elevated by elliptical pedal orbits that increased the duty factor by prolonging the downward phase of the pedal stroke (29). Similarly, the racing speeds attained by competitive speed skaters were enhanced by the invention of the klapskate. The klapskate has a hinged blade that prolongs the period of blade-ice interaction during which propulsion occurs (20, 24). The prolonged periods of propulsion and greater duty
factors provided by the klapskates allowed skaters to increase the mechanical power they
deliver to the ice (24) thereby producing improvements in the record sprinting speeds
achieved.

_A general performance-duration relationship?_

Our findings raise the possibility that a general quantitative description of the
performance-duration relationship for the human musculoskeletal system may now be
possible for these non-steady state efforts. Given a dynamic activity engaging an
appreciable fraction of the body’s musculature with a known duty factor (d), we can
express duration-dependent performance decrements using our anaerobic reserve model
and a single exponential constant as:

\[
\text{Perf} (t) = \text{Perf}_{aer} + (\text{Perf}_{\text{mech max}} - \text{Perf}_{aer}) \cdot e^{-k_{\text{muscle}} \cdot t \cdot d}
\]  

Where Perf is expressed as an intensity and therefore with units of speed, power, etc, d is
expressed as a fraction and the exponential constant, \( k_{\text{muscle}} = 0.054 \text{ s}^{-1} \) quantifies
performance decrements in relation to the cumulative duration of the contractions
involved in the all-out effort.

Two aspects of our findings warrant further comment. First, the time course with
which non-oxidative pathways of ATP resynthesis impair musculoskeletal performance
__in vivo__ is quite rapid. When expressed in the non-dynamic terms of uninterrupted
contractile durations, 50% of the maximum mechanical function that can be provided
anaerobically is unavailable at an effort duration of 15 s. Second, in contrast to previous
suggestions prompted by the varied results obtained from muscle and fiber preparations outside the body, the fatigue process may not be beyond quantitative understanding (17). Under the *in vivo* conditions examined here, both the operative mechanisms and time course over which mechanical function of muscle is impaired appear to be extremely consistent.
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References


Figure Captions

Fig. 1. Estimated rates of anaerobic ($\dot{E}_{\text{an}}$; $A$), aerobic ($\dot{E}_{\text{aer}}$; $B$), and total ($\dot{E}_{\text{tot}}$; $C$) energy release and cycling mechanical power output ($D$) as a function of the duration of sprint cycling trials for subject 5.

Fig. 2. Maximum 3 s mechanical (full bar height, $P_{\text{mech max}}$) and aerobic (height of the dark lower portion, $P_{\text{aer}}$) power outputs for each of the 7 subjects (male: 1-4; female: 5-7). The difference between these respective power outputs (the anaerobic power reserve, $P_{\text{an res}}$) is illustrated by the white upper portion of each bar. Duration-dependent decrements in mechanical power outputs are determined by the respective anaerobic power reserves of each cyclist. Numeric values for the ratio of $P_{\text{mech max}}/P_{\text{aer}}$ appear within the bars of each subject.

Fig. 3. All-out mechanical power outputs in relation to cycling trial duration for 3 subjects with different absolute maxima for $P_{\text{mech max}}$ and $P_{\text{aer}}$ ($A$). Individual differences in absolute power outputs at any given duration were virtually eliminated when power outputs were expressed in relation to the anaerobic power reserve ($B$). The curves were fit with the following equations: for $A$, $P(t) = P_{\text{aer max}} + (P_{\text{an max}} - P_{\text{aer max}}) \cdot e^{-kt}$, for $B$, relative $P(t) = e^{-kt}$.

Fig. 4. Measured sprint cycling mechanical power outputs for all trials completed vs. those estimated using Eq. 1, the measured $P_{\text{mech max}}$ and $P_{\text{aer}}$, and the average value of $k = 0.026$ derived from the 7 subjects.
Fig. 5. Estimated rates of anaerobic ($\dot{E}_{\text{an}}$), aerobic ($\dot{E}_{\text{aer}}$), and total ($\dot{E}_{\text{tot}}$) energy release (panel A) and relative performance (panel B) as a function of the duration of all-out sprinting trials of male cyclists (n=4) and male runners (n=7). Respective cycle and run curves were formulated using group mean values for $\dot{E}_{\text{an max}}$ and $\dot{E}_{\text{aer max}}$. $\dot{E}_{\text{tot}}$ and relative performance curves were generated using values for $k_{\text{cycle}}$ and $k_{\text{run}}$ that were determined empirically during the respective modes of sprinting. Relative performances are expressed as power outputs and speeds divided by those supported by $\dot{E}_{\text{aer max}}$ in the respective modes (i.e. $P_{\text{mech max}}/P_{\text{aer max}}$ and $Spd_{\text{mech max}}/Spd_{\text{aer}}$).

Fig. 6. Cycling power outputs and running speeds, expressed as fractions of the respective anaerobic reserves vs. total sprint trial duration (A) and vs. the cumulative time of force application to the pedals and ground, respectively (B).
Table 1. Subject characteristics and aerobic maxima.

<table>
<thead>
<tr>
<th>Subject (No.)</th>
<th>Gender</th>
<th>Mass (kg)</th>
<th>( \dot{E}_{aer\ max} ) (ml O₂·kg⁻¹·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>79</td>
<td>54.2</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>77</td>
<td>54.2</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>82</td>
<td>59.3</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>82</td>
<td>59.8</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>63</td>
<td>37.7</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>70</td>
<td>40.9</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>74</td>
<td>38.3</td>
</tr>
</tbody>
</table>

Gender, mass, and maximum aerobic power of the subjects.
Figure 1

A

$R^2 = 0.98$

$\dot{E}_{an} \text{ (ml O}_2\text{ eq.kg}^{-1}\cdot\text{min}^{-1})$

B

$R^2 = 0.95$

$U_{an} \text{ (ml O}_2\text{ eq.kg}^{-1}\cdot\text{min}^{-1})$

C

$R^2 = 0.98$

$\dot{E}_{tot} \text{ (ml O}_2\text{ eq.kg}^{-1}\cdot\text{min}^{-1})$

D

$R^2 = 0.98$

Power Output (W)

Trial Duration (s)
Figure 2

- **Anaerobic power reserve**
- **Aerobic power range**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.4 M</td>
</tr>
<tr>
<td>2</td>
<td>3.0 M</td>
</tr>
<tr>
<td>3</td>
<td>3.1 M</td>
</tr>
<tr>
<td>4</td>
<td>3.4 M</td>
</tr>
<tr>
<td>5</td>
<td>3.5 F</td>
</tr>
<tr>
<td>6</td>
<td>4.3 F</td>
</tr>
<tr>
<td>7</td>
<td>2.7 F</td>
</tr>
</tbody>
</table>
Figure 3

A

Power (W)

Subj 1
Subj 4
Subj 6

B

Relative Anaerobic Power Reserve

\( \frac{P(0) - P_{\infty}} {P_{\infty}} \)

\( R^2 = 0.96 \)
Figure 4

$R^2 = 0.96$

$n = 105$
Figure 5

A. Metabolic Power (ml O_2 eq·kg^{-1}·min^{-1})

- E_{tot}
- E_{aer}
- E_{an}

B. Relative Performance (Perf / Perf at E_{aer,max})

- k_{cycle} = 0.026
- k_{run} = 0.013

Trial Duration (s)
Figure 6

A. Total Trial Time

B. Time of Force Application Only
   (total trial time · duty factor)