Effects of Submaximal Performances on Critical Speed and Power: Uses of an Arbitrary-Unit Method with Different Protocols

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Abstract: The effects of submaximal performances on critical speed ($S_{\text{Crit}}$) and critical power ($P_{\text{Crit}}$) were studied in 3 protocols: a constant-speed protocol (protocol 1), a constant-time protocol (protocol 2) and a constant-distance protocol (protocol 3). The effects of submaximal performances on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ were studied with the results of two theoretical maximal exercises multiplied by coefficients lower or equal to 1 (from 0.8 to 1 for protocol 1; from 0.95 to 1 for protocols 2 and 3): coefficient $C_1$ for the shortest exercises and $C_2$ for the longest exercises. Arbitrary units were used for exhaustion times ($t_{\text{lim}}$), speeds (or power-output in cycling) and distances (or work in cycling). The submaximal-performance effects on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ were computed from two ranges of $t_{\text{lim}}$ (1–4 and 1–7). These effects have been compared for a low-endurance athlete (exponent $= 0.8$ in the power-law model of Kennelly) and a high-endurance athlete (exponent $= 0.95$). Unexpectedly, the effects of submaximal performances on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ are lower in protocol 1. For the 3 protocols, the effects of submaximal performances on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ are low in many cases and are lower when the range of $t_{\text{lim}}$ is longer. The results of the present theoretical study confirm the possibility of the computation of $S_{\text{Crit}}$ and $P_{\text{Crit}}$ from several submaximal exercises performed in the same session.

Keywords: critical speed; critical power; performance reliability; modelling

1. Introduction

1.1. Empirical Model of Running and Cycling Performances

Several empirical and descriptive models of performance have been proposed: the power-law model by Kennelly [1], asymptotic hyperbolic models by Hill and Scherrer [2,3], and, more recently, the logarithmic model of Péronnet and Thibault [4] and the 3-parameter asymptotic models by Hopkins [5] and Morton [6]. These empirical models are often used to estimate (i) the improvement in performance (ii) the future performances and running speeds over given distances (iii) the endurance capability, i.e., “the ability to sustain a high fractional utilization of maximal oxygen uptake for a prolonged period of time” [4].

In 1954, Scherrer et al. proposed a linear relationship [3] between the exhaustion time ($t_{\text{lim}}$) of a local exercise (flexions or extensions of the elbow or the knee) performed at different constant power outputs ($P$) and the total amount of work performed at exhaustion ($W_{\text{lim}}$) for $t_{\text{lim}}$ ranging between 3 and 30 min:

$$W_{\text{lim}} = a + bt_{\text{lim}} = Pt_{\text{lim}}$$

Consequently, the relationship between $P$ and $t_{\text{lim}}$ is hyperbolic:

$$a = Pt_{\text{lim}} - bt_{\text{lim}} = (P - b) t_{\text{lim}}$$
where \( b \) is a critical power (\( P_{\text{Crit}} \)).

In 1966, Ettema applied the critical-power concept to world records in running, swimming, cycling, and skating exercises [7] and proposed a linear relationship between the distances (\( D_{\text{lim}} \)) and world records (\( t_{\text{lim}} \)) from 1500 to 10000 m:

\[
D_{\text{lim}} = a + b t_{\text{lim}}
\]

It was assumed that the energy cost of running was almost independent of speed (1 kcal.kg\(^{-1}\).km\(^{-1}\)) under 22 km.h\(^{-1}\) [8]. Consequently, \( D_{\text{lim}} \) and parameter “\( a \)” were equivalent to amounts of energy. Therefore, parameter “\( a \)” has been interpreted as equivalent to an energy store. Thereafter, parameter “\( a \)” was considered as an estimation of maximal Anaerobic Distance Capacity (ADC expressed in metres) for running exercises [7,9]. Slope \( b \) was considered as a critical velocity (\( S_{\text{Crit}} \)).

\[
D_{\text{lim}} = \text{ADC} + S_{\text{Crit}} t_{\text{lim}}
\]

In 1981, the linear \( W_{\text{lim}}-t_{\text{lim}} \) relationship was adapted to exercises on a stationary cycle ergometer and it was demonstrated that slope \( b \) of the \( W_{\text{lim}}-t_{\text{lim}} \) relationship was correlated with the ventilatory threshold [10]. Therefore, slope \( b \) was proposed as an index of general endurance (\( P_{\text{Crit}} \)). Thereafter, Whipp et al. [11] proposed another linear model with \( S_{\text{Crit}} \) (or \( P_{\text{Crit}} \)) and \( a \):

\[
S = S_{\text{Crit}} 1/t + a (1/t_{\text{lim}}) \text{ Running}
\]

\[
P = P_{\text{Crit}} 1/t + a (1/t_{\text{lim}}) \text{ Cycling}
\]

where \( S \) is running speed.

Actually, the hyperbolic model is often used as it is the simplest model that corresponds to a linear relationship between exhaustion time (\( t_{\text{lim}} \)) and distance (\( D_{\text{lim}} \)) in running and swimming or total work (\( W_{\text{lim}} \)) in cycling. For many exercise physiologists, \( S_{\text{Crit}} \) and \( P_{\text{Crit}} \) are considered as fatigue thresholds [12]. Moreover, the values of \( S_{\text{Crit}} \) and \( P_{\text{Crit}} \) become endurance indices when they are normalized to Maximal Aerobic Speed (\( S_{\text{Crit}} /\text{MAS} \)) or Maximal Aerobic Power (\( P_{\text{Crit}} /\text{MAP} \)). Parameter “\( a \)” is also called ADC (Anaerobic Distance Capacity) or ARC (Anaerobic Running Capacity) in running [7,9] and AWC (Anaerobic Work Capacity) in cycling [13,14].

However, the relationship between \( t_{\text{lim}} \) and \( D_{\text{lim}} \) is not perfectly linear as suggested by the power-law model by Kennelly:

\[
D_{\text{lim}} = k t_{\text{lim}}^g
\]

\[
S = D_{\text{lim}}/t_{\text{lim}} = (k t_{\text{lim}}^g)/t_{\text{lim}} = k t_{\text{lim}}^{g-1}
\]

where exponent \( g \) can be considered as an endurance index and parameter \( k \) is equal to the maximal speed corresponding to the unit of \( t_{\text{lim}} \) [15].

### 1.2. Variability of the Performances of Exhausting Exercises.

Three protocols are used for the estimation of the performances of exhausting exercises:

1. to run as long as possible at a constant speed or to cycle as long as possible at a constant power output. This constant-speed protocol is often called Time-to-Exhaustion;
2. to run as much distance (or to produce as much work on a cycle-ergometer) as they can within a given time period (constant-time protocol);
3. to run a set distance (or to produce a set work on a cycle-ergometer) as fast as possible (constant-distance protocol).

The first protocol (Time-to-Exhaustion) is used for the estimation of \( S_{\text{Crit}} \) on a treadmill or the estimation of \( P_{\text{Crit}} \) on a cycle ergometer. The second protocol was used for prediction of one-hour running performance [16]. The third protocol was used in the studies on the modelling of running
performances that were based on the world records [17–20] or performances in the Olympic games [21] or individual performance of elite endurance runners [15]. The reliability of performances in protocol 1 (constant speed) is low, whereas the reliability of the other protocols is higher [22–27]. For example in swimming, the Coefficient of Variation of constant-speed protocol (CV = 6.46 ± 6.24%) was significantly less reliable (p < 0.001) than those of constant-time protocol (CV = 0.63 ± 0.54%) and constant-distance protocol (CV = 0.56 ± 0.60%) [27].

In a recent study [28] critical speeds measured on a treadmill with a constant-speed protocol were compared with a Single-Visit Field Test of Critical Speed. The constant-speed runs to exhaustion on treadmill were performed with 3 running speeds during 3 separate sessions. Two single-visit field tests on separate days consisted to the measurement of maximal performances over 3600, 2400, and 1200 m (constant-distance protocol) with 30-min or 60-min recovery. Unexpectedly, there was no difference in $S_{\text{Crit}}$ measured with the treadmill and 30-min and 60-min recovery field tests although the reliability of protocol 1 is lower than that of protocol 3. Thereafter, a Single-Visit Field Test of Critical Speed was tested in trained and untrained runners [29]: the reliability of $S_{\text{Crit}}$ was better in the trained runners.

### 1.3. Purpose of the Present Study

In few studies, the values of $S_{\text{Crit}}$ and $P_{\text{Crit}}$ are computed from the best maximal performances of several exhausting exercises of the same subjects [15] or world records [17–20] or performances in the Olympic games [21]. In most studies, it is not obvious that the data used in the computation of $S_{\text{Crit}}$ and $P_{\text{Crit}}$ are maximal. For example, the performance variability is important in protocol 1 that is mainly used in laboratories. Moreover, several exhausting exercises are often performed in the same session with protocols 1, 2 and 3, which could increase the performance variability because of fatigue. As suggested in a review [30], the purpose of the present study was to confirm the interest of $S_{\text{Crit}}$ and $P_{\text{Crit}}$ computed from exercises whose performances are submaximal.

In the Single-Visit Field Test of Critical Speed, there were trained and untrained runners whose reliability of $S_{\text{Crit}}$ was different [29]. Therefore, the effects of submaximal performance on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ in the present study have been compared between a low-endurance athlete and a high-endurance athlete, i.e., athletes with low and high endurance indices (for example, exponent $g$ or $S_{\text{Crit}}/\text{MAS}$ or $P_{\text{Crit}}/\text{MAP}$). The values of exponent $g$ were about 0.95 in the best elite endurance runners [15,31] as Gebrselassie whose ratio $S_{\text{Crit}}/\text{MAS}$ was equal to 0.945 ($\text{MAS}$ corresponded to the maximal running speed during 7 min). In the low-endurance runners whose ratios $S_{\text{Crit}}/\text{MAS}$ were equal to 0.764 ± 0.078, exponent $g$ was about 0.80 [31].

As $S_{\text{Crit}}$ and $P_{\text{Crit}}$ can be computed from two exhausting exercises, the effects of submaximal performances on these indices have been estimated by multiplying both theoretical maximal data by two coefficients: $C_1$ for the shortest performances and $C_2$ for the longest performances.

The effects of submaximal performances on $S_{\text{Crit}}$ and $P_{\text{Crit}}$ were estimated with arbitrary units for $t_{\text{lim}}$, $D_{\text{lim}}$ and $S$ (or $P$) in the present study. Indeed, there are many different cases:

- the range of $t_{\text{lim}}$ can be different for each athlete in protocols 1 and 3;
- the range of speeds and distances (or power-output and work in cycling) can be different for each athlete in protocol 2;
- the same endurance indices can correspond to different maximal aerobic speed (MAS) or maximal aerobic power (MAP in cycling).

The effects of submaximal performances on endurance indices have been tested for values of $t_{\text{lim}}$ equal to 1 and 4 (arbitrary units), which corresponds to the usual range of $t_{\text{lim}}$ (3–12m in [28,29]) in many study. In some studies, the range of $t_{\text{lim}}$ is 2–15 min [12,32,33]. Therefore, the effects of submaximal performances have also been tested for values of $t_{\text{lim}}$ equal to 1–7 (arbitrary unit).
2. Methods

2.1. Arbitrary Units

The values of \( t_{\text{lim}1}, D_{\text{lim}1} \) and \( S_1 \) in arbitrary units in protocols 1, 2 and 3 are equal to 1:

\[
t_{\text{lim}1} = 1 \quad \text{and} \quad S_1 = 1 \quad \text{and} \quad D_{\text{lim}1} = 1
\]

2.1.1. Arbitrary Units in Protocols 1 and 2

The values of \( t_{\text{lim}2} \) and \( t_{\text{lim}3} \) in arbitrary units in protocols 1 and 2 are equal to 4 and 7, respectively.

\[
t_{\text{lim}2} = 4 \quad \text{and} \quad t_{\text{lim}3} = 7
\]

The distances and running speeds corresponding to \( t_{\text{lim}2} \) and \( t_{\text{lim}3} \) was computed from the power-law model by Kennelly with arbitrary units of \( t_{\text{lim}} \):

\[
D_{\text{lim}1} = k t_{\text{lim}}^g = k (1^g) = 1 \quad \text{then} \quad k = 1 \quad \text{and} \quad D_{\text{lim}} = t_{\text{lim}}^g \quad \text{and} \quad S = t_{\text{lim}}^{g-1}
\]

For the high-endurance athlete, exponent \( g \) of the power-law model is equal to 0.95. Therefore, the values of \( D_{\text{lim}2}, D_{\text{lim}3}, S_2 \) and \( S_3 \) in arbitrary units are equal to:

\[
D_{\text{lim}2} = 4^{0.95} = 3.7321 \quad \text{and} \quad D_{\text{lim}3} = t_{\text{lim}3}^g = 7^{0.95} = 6.3510
\]

\[
S_2 = t_{\text{lim}2}^{g-1} = 4^{-0.05} = 0.9330 \quad \text{and} \quad S_3 = t_{\text{lim}3}^{g-1} = 7^{-0.05} = 0.9073
\]

For the low-endurance athlete, exponent \( g \) of the power-law model is equal to 0.80. Therefore, the values of \( D_{\text{lim}2}, D_{\text{lim}3}, S_2 \) and \( S_3 \) in arbitrary units are equal to:

\[
D_{\text{lim}2} = 4^{0.80} = 3.0314 \quad \text{and} \quad D_{\text{lim}3} = 7^{0.80} = 4.7433
\]

\[
S_2 = 4^{-0.2} = 0.7579 \quad \text{and} \quad S_3 = 7^{-0.2} = 0.6776
\]

2.1.2. Arbitrary Units in Protocol 3

The values of constant-distances (\( D_{\text{lim}} \)) in the present study were equal to the averages of the distances of low and high-endurance athletes, in protocols 1 and 2, i.e., 1 (\( D_{\text{lim}1} \)), 3.819 (\( D_{\text{lim}2} \)) and 5.5471 (\( D_{\text{lim}3} \)). The values of \( t_{\text{lim}2} \) and \( t_{\text{lim}3} \) corresponding to these distances were:

\[
D_{\text{lim}} = t_{\text{lim}}^g
\]

\[
(t_{\text{lim}}^g)^{1/g} = t_{\text{lim}} = D_{\text{lim}}^{1/g}
\]

\[
t_{\text{lim}1} = D_{\text{lim}1}^{1/8} = 1^{1/8} = 1 \quad \text{and} \quad t_{\text{lim}2} = D_{\text{lim}2}^{1/8} = 3.819^{1/8}
\]

\[
t_{\text{lim}3} = D_{\text{lim}3}^{1/8} = 5.5471^{1/8}
\]

For the low-endurance athlete:

\[
t_{\text{lim}2} = 3.819^{1/0.8} = 4.5862 \quad \text{and} \quad t_{\text{lim}3} = 5.5471^{1/0.80} = 8.5130
\]

For the high-endurance athlete:

\[
t_{\text{lim}2} = 3.819^{1/0.95} = 3.6059 \quad \text{and} \quad t_{\text{lim}3} = 5.5471^{1/0.95} = 6.0705
\]
2.2. Coefficients \( C_1 \) and \( C_2 \)

The ranges of coefficients \( C_1 \) and \( C_2 \) used in protocol 2 and 3 were from 0.95 to 1. Indeed, in protocols 2 and 3, the submaximal performances are the results of submaximal power outputs in cycling. If the ratio \( C_1/C_2 \) is lower than 0.9330, the speed corresponding to \( t_{\text{lim2}} \) would be higher than the speed at \( t_{\text{lim1}} \) in the high-endurance athlete. In protocol 1 (constant-speed protocol), the speed (or power) does not depend on \( C_1 \) or \( C_2 \) and the variability of performances are higher [27]. Therefore, the ranges of \( C_1 \) and \( C_2 \) were larger (from 0.8 to 1).

2.3. Computation of the Effects of Submaximal Performances on \( S_{\text{Crit}} \) and \( P_{\text{Crit}} \)

2.3.1. Computation in the Constant-Speed (or Constant Power Output) Protocol (Protocol 1)

The submaximal performances are the result of the submaximal values of \( t_{\text{lim}} \). The submaximal values of \( t_{\text{lim}} \) (\( t_{\text{lim1 sub}} \) and \( t_{\text{lim2 sub}} \)) are:

\[
t_{\text{lim1 sub}} = C_1 t_{\text{lim1}} \quad \text{and} \quad t_{\text{lim2 sub}} = C_2 t_{\text{lim2}}
\]

Therefore, the submaximal values of \( D_{\text{lim}} \) (\( D_{\text{lim1 sub}} \) and \( D_{\text{lim2 sub}} \)) are equal to:

\[
D_{\text{lim1 sub}} = S_1 t_{\text{lim1 sub}} = S_1 C_1 t_{\text{lim1}} = C_1 D_{\text{lim1}}
\]

\[
D_{\text{lim2 sub}} = S_2 t_{\text{lim2 sub}} = S_2 C_2 t_{\text{lim2}} = C_2 D_{\text{lim2}}
\]

For running:

\[
S_{\text{Crit}} = (D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})
\]

\[
S_{\text{Crit sub}} = (C_2 D_{\text{lim2}} - C_1 D_{\text{lim1}})/(C_2 t_{\text{lim2}} - C_1 t_{\text{lim1}})
\]

\[
S_{\text{Crit sub}}/S_{\text{Crit}} = [(C_2 D_{\text{lim2}} - C_1 D_{\text{lim1}})/(C_2 t_{\text{lim2}} - C_1 t_{\text{lim1}})]/[(D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})] \tag{1}
\]

For cycling:

\[
P_{\text{Crit sub}}/P_{\text{Crit}} = [(C_2 W_{\text{lim2}} - C_1 W_{\text{lim1}})/(C_2 t_{\text{lim2}} - C_1 t_{\text{lim1}})]/[(W_{\text{lim2}} - W_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})]
\]

2.3.2. Computation in the Constant-Time Protocol (Protocol 2)

The submaximal performances are the result of submaximal speeds.

\[
S_{1\text{sub}} = C_1 S_1 \quad \text{and} \quad S_{2\text{sub}} = C_2 S_2
\]

\[
D_{\text{lim1 sub}} = C_1 S_1 t_{\text{lim1}} = C_1 D_{\text{lim1}} \quad \text{and} \quad D_{\text{lim2 sub}} = C_2 S_2 t_{\text{lim2}} = C_2 D_{\text{lim2}}
\]

For cycling, the submaximal performances correspond to lower powers.

\[
P_{1\text{sub}} = C_1 P_1 \quad \text{and} \quad P_{2\text{sub}} = P_2 S_2
\]

\[
W_{\text{lim1 sub}} = C_1 P_1 t_{\text{lim1}} = C_1 W_{\text{lim1}} \quad \text{and} \quad W_{\text{lim2 sub}} = C_2 P_2 t_{\text{lim2}} = C_2 W_{\text{lim2}}
\]

For running:

\[
S_{\text{Crit}} = (D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})
\]

\[
S_{\text{Crit sub}} = (D_{\text{lim2 sub}} - D_{\text{lim1 sub}})/(t_{\text{lim2}} - t_{\text{lim1}}) = (C_2 D_{\text{lim2}} - C_1 D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})
\]

\[
S_{\text{Crit sub}}/S_{\text{Crit}} = [(C_2 D_{\text{lim2}} - C_1 D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})]/[(D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})]
\]
For cycling:

\[ S_{\text{Crit sub}}/S_{\text{Crit}} = (C_2 D_{\text{lim2}} - C_1 D_{\text{lim1}})/(D_{\text{lim2}} - D_{\text{lim1}}) \]  

(2)

For running:

\[ P_{\text{Crit sub}}/P_{\text{Crit}} = (C_2 W_{\text{lim2}} - C_1 W_{\text{lim1}})/(W_{\text{lim2}} - W_{\text{lim1}}) \]

2.3.3. Computation in the Constant-Distance Protocol

The submaximal performances are the result of submaximal speeds.

\[ S_{1\text{sub}} = C_1 S_1 \quad \text{and} \quad S_{2\text{sub}} = C_2 S_2 \]

For cycling, the submaximal performances correspond to lower powers.

\[ P_{1\text{sub}} = C_1 P_1 \quad \text{and} \quad P_{2\text{sub}} = C_2 P_2 \]

Hence:

\[ t_{\text{lim1sub}} = D_{\text{lim1}}/S_{1\text{sub}} = D_{\text{lim1}}/C_1 S_1 = t_{\text{lim1}}/C_1 \]

and

\[ t_{\text{lim2sub}} = D_{\text{lim2}}/S_{2\text{sub}} = D_{\text{lim2}}/C_2 S_2 = t_{\text{lim2}}/C_2 \]

For running:

\[ S_{\text{Crit}} = (D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}}) \]

\[ S_{\text{Crit sub}} = (D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2sub}} - t_{\text{lim1sub}}) = (D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}}/C_2 - t_{\text{lim1}}/C_1) \]

\[ S_{\text{Crit sub}}/S_{\text{Crit}} = [(D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}}/C_2 - t_{\text{lim1}}/C_1)]/[((D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})) \]

\[ S_{\text{Crit sub}}/S_{\text{Crit}} = (t_{\text{lim2}} - t_{\text{lim1}})/(t_{\text{lim2}}/C_2 - t_{\text{lim1}}/C_1) \]  

(3)

For cycling:

\[ P_{\text{Crit sub}}/P_{\text{Crit}} = (t_{\text{lim2}} - t_{\text{lim1}})/(t_{\text{lim2}}/C_2 - t_{\text{lim1}}/C_1) \]

3. Results

The interest of the use of arbitrary units is demonstrated in Tables 1 and 2 for protocol 1. Athletes A, B, C, D, E and F who have the same ratio \( t_{\text{lim1}}/t_{\text{lim2}} \) (4) and the same ratio \( S_2/S_1 \) (0.7579) have the same effects \( (S_{\text{Crit sub}}/S_{\text{Crit}}) \) corresponding to the same coefficients \( C_1 \) and \( C_2 \) (Table 1). Moreover, the use of the same arbitrary units can also been applied to cycling exercises (Table 2): the effects \( (P_{\text{Crit sub}}/P_{\text{Crit}}) \) of submaximal performances are the same when ratio \( t_{\text{lim1}}/t_{\text{lim2}} \) and ratio \( P_2/P_1 \) are similar as in running exercises.

**Table 1.** Athletes A, B and C have the same values of \( t_{\text{lim1}} \) and \( t_{\text{lim2}} \) but different running speeds \( (S_1 \) and \( S_2) \). Athletes D, E and F have the same values of running speed as athletes A, B and C, respectively. The values of \( t_{\text{lim1}} \) and \( t_{\text{lim2}} \) are higher in athletes D, E and F but ratio \( t_{\text{lim2}}/t_{\text{lim1}} \) is the same and equal to 4.

|   | \( S_1 \) | \( S_2 \) | \( t_{\text{lim1}} \) | \( t_{\text{lim2}} \) | \( S_{\text{Crit}} \) | \( S_{\text{Crit sub}} \) | \( S_{\text{Crit sub}}/S_{\text{Crit}} \) | \( C_1 = 0.9 \) and \( C_2 = 1 \) | \( C_1 = 1 \) and \( C_2 = 0.9 \) |
|---|---------|---------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|   | \( \text{m.s}^{-1} \) | \( \text{m.s}^{-1} \) | \( \text{s} \) | \( \text{s} \) | \( \text{m.s}^{-1} \) | \( \text{m.s}^{-1} \) | \( \text{m.s}^{-1} \) | \( \text{m.s}^{-1} \) | \( \text{m.s}^{-1} \) |
| A | 4       | 3.0316  | 180           | 720            | 2.709          | 2.750          | 1.015          | 2.659          | 0.982          |
| B | 5       | 3.7895  | 180           | 720            | 3.386          | 3.438          | 1.015          | 3.324          | 0.982          |
| C | 6       | 4.5474  | 180           | 720            | 4.063          | 4.126          | 1.015          | 3.989          | 0.982          |
| D | 4       | 3.0316  | 240           | 960            | 2.709          | 2.750          | 1.015          | 2.659          | 0.982          |
| E | 5       | 3.7895  | 240           | 960            | 3.386          | 3.438          | 1.015          | 3.324          | 0.982          |
| F | 6       | 4.5474  | 240           | 960            | 4.063          | 4.126          | 1.015          | 3.989          | 0.982          |
Table 2. Athletes A, B and C have the same values of $t_{lim1}$ and $t_{lim2}$ but different power-outputs ($P_1$ and $P_2$). Athletes D, E and F have the same values of power-outputs as athletes A, B and C, respectively. The values of $t_{lim1}$ and $t_{lim2}$ are higher in athletes D, E and F but ratio $t_{lim2}/t_{lim1}$ is the same and equal to 4.

|       | $P_1$ | $P_2$ | $t_{lim1}$ | $t_{lim2}$ | $P_{Crit}$ | $P_{Critsub}$ | $P_{Critsub}/P_{Crit}$ | $P_{Critsub}$ | $P_{Crit}/P_{Crit}$ |
|-------|-------|-------|------------|------------|------------|---------------|------------------------|---------------|---------------------|
| A     | 240   | 182   | 180        | 720        | 163        | 165           | 1.015                  | 160           | 0.982               |
| B     | 320   | 243   | 180        | 720        | 217        | 220           | 1.015                  | 213           | 0.982               |
| C     | 400   | 303   | 180        | 720        | 271        | 275           | 1.015                  | 266           | 0.982               |
| D     | 240   | 182   | 240        | 960        | 163        | 165           | 1.015                  | 160           | 0.982               |
| E     | 320   | 243   | 240        | 960        | 217        | 220           | 1.015                  | 213           | 0.982               |
| F     | 400   | 303   | 240        | 960        | 271        | 275           | 1.015                  | 266           | 0.982               |

C1 = 0.9 and C2 = 1

C1 = 1 and C2 = 0.9

The effects of submaximal performances on endurance indices are presented in Figure 1 (constant-speed protocol), Figure 2 (constant-time protocol) and Figure 3 (constant-distance protocol).

**Figure 1.** Effects of submaximal performances in protocol 1 (constant speed or constant power) on ratios $S_{Critsub}/S_{Crit}$ or $P_{Critsub}/P_{Crit}$ for the different values of $C_1$ and $C_2$. Figures A and B correspond to the range $t_{lim1}$-$t_{lim2}$ (1–4) whereas Figures C and D correspond to the range $t_{lim1}$-$t_{lim3}$ (1–7). The specifications of the lines are presented in Figure 1A. Empty circles correspond to $C_1$ equal to $C_2$. 

Low-endurance athlete and High-endurance athlete.
3.1. Results for Protocol 1 (Constant Speed or Power Output Protocol)

For protocol 1, five curves of ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ corresponding to five values of $C_1$ (0.80, 0.85, 0.90, 0.95 and 1.00) were computed from equation 1 with an increment of $C_2$ equal to 0.001.

The effects of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or ratio $P_{\text{Crit sub}}/P_{\text{Crit}}$) are lower in the high-endurance athlete (Figure 1B, D) than in the low-endurance athlete (Figure 1A, C).

In Figure 1B, D, the effects of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ are lower when the range of $t_{\text{lim}}$ is longer (1–7 instead of 1–4).

In Figure 1A, the lowest and the highest ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ are equal to 0.9567 and 1.0295, respectively.

When $C_1$ is equal to $C_2$ (empty circles), i.e., when the levels of submaximal performances are the same for both exhausting exercises, there is no effect of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or ratio $P_{\text{Crit sub}}/P_{\text{Crit}}$) according to Equation (1):

$$S_{\text{Crit sub}} / S_{\text{Crit}} = \left[ \frac{(C_2 D_{\text{lim2}} - C_2 D_{\text{lim1}})/(C_2 t_{\text{lim2}} - C_2 t_{\text{lim1}})}{(D_{\text{lim2}} - D_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}})} \right] = 1$$

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**Figure 2.** Effects of submaximal performances in protocol 2 (constant time-protocol) on ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ for the different values of $C_1$ and $C_2$. Figures A and B correspond to the range $t_{\text{lim1}}$–$t_{\text{lim2}}$ (1–4) whereas Figures C and D correspond to the range $t_{\text{lim1}}$–$t_{\text{lim3}}$ (1–7). The specification of the lines is presented in Figure A. Empty circles in Figure A correspond to $C_1$ equal to $C_2$. 
3.2. Results for Protocol 2 (Constant-Time Protocol)

The values of coefficients $C_1$ and $C_2$ were limited from 0.95 to 1. Six curves of ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ corresponding to six values of $C_1$ (0.95, 0.96, 0.97, 0.98, 0.99 and 1.00) were computed from Equation (2) with an increment of $C_2$ equal to 0.001.

As for protocol 1, the effects of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or ratio $P_{\text{Crit sub}}/P_{\text{Crit}}$) are lower in the high-endurance athlete (Figure 2B,D) than in the low-endurance athlete (Figure 2A,C).

In Figure 2C,D, the effects of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ are lower when the range of $t_{\text{lim}}$ is longer (1–7 instead of 1–4).

In Figure 2A, the lowest and the highest ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ are equal to 0.9254 and 1.0246, respectively.

When $C_1$ is equal to $C_2$ (empty circles in Figure 2A), i.e., when the levels of submaximal performances are the same for both exhausting exercises, the ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or $P_{\text{Crit sub}}/P_{\text{Crit}}$) are equal to $C_2$ (or $C_1$) according to Equation (2):

$$\frac{S_{\text{Crit sub}}}{S_{\text{Crit}}} = \frac{(C_2 D_{\text{lim2}} - C_2 D_{\text{lim1}})}{(D_{\text{lim2}} - D_{\text{lim1}})} = C_2 \ (\text{or } C_1)$$
3.3. Results for Protocol 3 (Constant-Distance Protocol)

Six curves of ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ corresponding to six values of $C_1$ (0.95, 0.96, 0.97, 0.98, 0.99 and 1.00) were computed from equation 3 with an increment of $C_2$ equal to 0.001.

In contrast with protocols 1 and 2, the effects of submaximal performance on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or $P_{\text{Crit sub}}/P_{\text{Crit}}$) are more important in the high-endurance athlete. However, in the high-endurance athlete, the ranges of $t_{\text{lim1}}-t_{\text{lim2}}$ (1-3.6059) and $t_{\text{lim1}}-t_{\text{lim3}}$ (1–6.0705) is shorter than the ranges of $t_{\text{lim1}}-t_{\text{lim2}}$ (1–4.5862) and $t_{\text{lim1}}-t_{\text{lim3}}$ (1–8.5130) in the low-endurance athlete.

In Figure 3B, the lowest and the highest ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ are equal to 0.9321 and 1.0206, respectively.

When $C_1$ is equal to $C_2$ (empty circles in Figure 3B), i.e., when the levels of submaximal performances are the same for both exhausting exercises, the ratios $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or $P_{\text{Crit sub}}/P_{\text{Crit}}$) are equal to $C_2$ (or $C_1$) according to Equation (3):

$$S_{\text{Crit sub}}/S_{\text{Crit}} = (t_{\text{lim2}} - t_{\text{lim1}})/(t_{\text{lim2}}/C_2 - t_{\text{lim1}}/C_2) = C_2 (t_{\text{lim2}} - t_{\text{lim1}})/(t_{\text{lim2}} - t_{\text{lim1}}) = C_2$$

4. Discussion

The effects of submaximal performances on $S_{\text{Crit 1/3}}$ and $P_{\text{Crit 1/3}}$ in the model proposed by Whipp et al. [11] are not presented in the present study. Indeed, $S_{\text{Crit 1/3}}$ (or $P_{\text{Crit 1/3}}$) is equal to $S_{\text{Crit}}$ (or $P_{\text{Crit}}$) when both indices are computed only from two exhausting exercises with constant-distance [15] or constant-power [34] protocols in running and cycling. Similarly, in the present study, the effects of submaximal performances were the same for $S_{\text{Crit 1/3}}$ and $S_{\text{Crit}}$ (or $P_{\text{Crit 1/3}}$ and $P_{\text{Crit}}$) when they were computed from two submaximal exercises whatever the protocol. Consequently, the Figures about the effects of submaximal performances on $S_{\text{Crit 1/3}}$ or $P_{\text{Crit 1/3}}$ are not added in the present study.

Previous experimental studies [22–27] showed that performance reliability with constant-speed protocol is significantly lower than those with the other protocols (constant-time or constant-distance protocols). However, for $S_{\text{Crit}}$ or $P_{\text{Crit}}$ in the present theoretical study, the effects of 20%-submaximal performances in protocol 1 are lower than the effects of 5%-submaximal performances in protocols 2 and 3. For example, the lowest ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ in protocol 1 is equal to 0.9567 (Figure 1A) whereas the lowest ratio in protocol 2 is equal to 0.9254 (Figure 2A).

Ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$ (or ratio $P_{\text{Crit sub}}/P_{\text{Crit}}$) is equal to 1 when the maximal and submaximal $D_{\text{lim}}$-$t_{\text{lim}}$ relationships are parallel i.e., when the distances of both submaximal performances to the maximal $D_{\text{lim}}$-$t_{\text{lim}}$ line are similar:

- $C_1$ is equal to $C_2$ for protocol 1 (empty circles in Figure 1);
- $D_{\text{lim1}} (1 - C_1)$ is equal to $D_{\text{lim2}} (1 - C_2)$ for protocol 2;
- $t_{\text{lim1}} (1 - 1/C_1)$ is equal to $t_{\text{lim2}} (1 - 1/C_2)$ for protocol 3.

In protocol 1, the submaximal performances correspond to similar decreases in $D_{\text{lim}}$ and $t_{\text{lim}}$ whereas, in protocol 2 and 3, they only correspond to a decrease in $D_{\text{lim}}$ or $t_{\text{lim}}$ (Figure 4). These simultaneous decreases in $D_{\text{lim}}$ and $t_{\text{lim}}$ limit the distance between the submaximal performance and the maximal $D_{\text{lim}}$-$t_{\text{lim}}$ line, which explain the lower effects of submaximal performances on ratio $S_{\text{Crit sub}}/S_{\text{Crit}}$. 

In protocols 2 and 3, when \( C_1 \) is equal to \( C_2 \) (empty circles in Figure 2A, Figure 3B) ratios \( S_{\text{Crit sub}}/S_{\text{Crit}} \) are equal to \( C_1 \) and are not very low \( (S_{\text{Crit sub}}/S_{\text{Crit}} \geq 0.95) \). When \( C_2 \) is lower than \( C_1 \), ratios \( S_{\text{Crit sub}}/S_{\text{Crit}} \) are lower and sometimes not negligible in protocols 2 and 3 (for example, in Figure 2A, \( S_{\text{Crit sub}}/S_{\text{Crit}} = 0.9254 \) for \( C_2 = 0.95 \) and \( C_1 = 1 \)). However, although the range of \( C_1-C_2 \) is much larger \((0.8–1.0)\), ratios \( S_{\text{Crit sub}}/S_{\text{Crit}} \) are not very low \((\geq 0.9567)\) in protocol 1, even when \( C_2 \) is lower than \( C_1 \) (Figure 1A).

The effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \) (or ratio \( P_{\text{Crit sub}}/P_{\text{Crit}} \)) may be low \((S_{\text{Crit sub}}/S_{\text{Crit}} \geq 0.95)\) for both low-endurance and high-endurance athletes in the three protocols. These possible low effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \) could explain that it is possible to compute \( S_{\text{Crit}} \) from the values of \( t_{\text{lim}} \) of 3 trials performed with protocol 3 in a same session with only 30 min of recovery between the trials as in a Single-Visit Field Test [28,29]. This low sensitivity of \( S_{\text{Crit}} \) or \( P_{\text{Crit}} \) to submaximal performances was previously suggested in a study on the comparison of critical speeds of continuous and intermittent running exercise on a track [35] and also in a review [30].

The effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \) are lower in the high-endurance athlete for constant-speed and constant-time protocols (Figures 1 and 2). That said, the effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \) in constant-distance protocol (protocol 3) are higher in the high-endurance athlete (Figure 3). However, the effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \) (or ratio \( P_{\text{Crit sub}}/P_{\text{Crit}} \)) are lower when the range of \( t_{\text{lim}} \) is longer (for example, 1–7 instead of 1–4) as illustrated in Figures 1–3. Therefore, in protocol 3, the shorter ranges of \( t_{\text{lim1}}-t_{\text{lim2}} \) and \( t_{\text{lim1}}-t_{\text{lim3}} \) in the high-endurance athlete explain these computed higher effects of submaximal performances on ratio \( S_{\text{Crit sub}}/S_{\text{Crit}} \). In contrast, the coefficient of variation of the Single-Visit Field Test that corresponds to this constant-distance protocol was lower in trained runners whose \( S_{\text{Crit}} \) were faster than untrained runners [29]. It was likely that the reliability of \( S_{\text{Crit}} \) in the trained runners was higher because of control of the maximal running speed corresponding to a given distance and better recovery.

In the Single-Visit Field Test [28], the running performances were submaximal because the values of \( D' \) (equivalent of ADC) were significantly lower in the 30-min (106.4-m) and 60-min-recovery (102.4-m) than in the 3-session treadmill test (249.7 m). However, \( S_{\text{Crit}} \) in the Single-Visit Field Test was not different of \( S_{\text{Crit}} \) in the 3-session treadmill test. These results were consistent with those of a previous experimental study on the effects of a 6-min exhausting exercise on \( S_{\text{Crit}} \) in cycling [36].
In the present theoretical study, the submaximal performances have also effects on parameter “a” (ADC). For example, in protocol 1, parameter “a” decreases when C₁ and C₂ are equal and lower than 1 (empty circles in Figure 1) but increases when C₁ is equal to 1 and C₂ is lower than 1. These effects of submaximal performances on parameter “a” are not computed in the present study because this parameter is not an endurance index and its meaning is questionable [11].

The present method can also be used for the submaximal-performance effects on the exponent g of the power-law model by Kennelly [1] and the endurance index (EI) of the logarithmic model by Péronnet and Thibault [4] as they are 2-parameter models:

\[ D_{\text{lim}} = k t_{\text{lim}}^g \quad \text{and} \quad S = k t_{\text{lim}}^{g-1} \]  

power-law model

\[ 100 \, S/\text{MAS} = 100 - \text{EI} \log(t_{\text{lim}}/t_{\text{MAS}}) \]  

logarithmic model

5. Conclusions

The results of the present theoretical study confirm the interest of S_{\text{Crit}} and P_{\text{Crit}} computed from exercises whose performances are submaximal and performed in the same session. Indeed, for the 3 protocols, the theoretical effects of submaximal performances on ratio S_{\text{Crit sub}}/S_{\text{Crit}} (or ratio P_{\text{Crit sub}}/P_{\text{Crit}}) are low in many cases. The effects of submaximal performances are lower when the ratio \( t_{\text{lim}2}/t_{\text{lim}1} \) is larger. In protocol 3, it is likely that, in practice, the reliability of S_{\text{Crit}} is better in trained runners due to the control of the maximal running speed corresponding to a given distance.

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