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Application of critical intensity model during slide board skating.

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Abstract

Critical cadence (CC), critical power (CP) and the work above CP (W’) were determined from linear and hyperbolic modelling during skating on a slide board, in thirteen well trained speed skaters. Three to four trials to exhaustion were used for the fitting. CC from linear was higher than hyperbolic model (56.0 ± 4.8 vs 55.0 ± 4.5 push-offs/min, p= 0.01). No differences were found for CP and W’ parameters from the models analysed.

Keywords: power-time relationship, critical power, anaerobic capacity, skating, critical cadence, performance tests.
Introduction

For high-intensity exercise, the time-to-exhaustion increases as a predictable and hyperbolic function of decreasing the exercise intensity, such as power (P) or velocity. This relationship is highly conserved across different modes of exercise and is well described by two indices: the “critical power” (CP) or “critical speed” (CS), which is the asymptote for power or velocity; and the curvature constant (W’) of the relationship such that \( t = \frac{W’}{P - CP} \) (Hill 1993), which can be transformed into its linear formulation \( P = \frac{W’}{t} + CP \).

Physiologically, the critical intensity represents the boundary between the steady-state and non-steady state exercise intensity domains, and the curvature constant of the power-duration relationship, and the W’ provides a measure of the fixed amount of work that can be performed above the CP before exhaustion occurs (Vanhatalo 2011; Jones et al. 2010).

Therefore, CP may provide a more meaningful index of performance than other well-known landmarks of aerobic fitness such as lactate threshold or maximal \( O_2 \) uptake (Vanhatlalo 2011). Critical intensity and W’ have a variety of applications in sport performed at a severe-intensity exercise domain, which includes long track speed skating competitions.

The lack of investigations related to specific protocols to evaluate speed skating performance is partially related to difficulties in reproducing the skating movement in laboratory and to control test conditions on an ice track (Foster et al. 1993). To overcome this limitation, the use of slide board to simulate the skating movement has been investigated, where workload/intensity is represented by change in stroke cadence (CAD). Slide board skating has been shown to be a more specific method to evaluate stationary speed skating performance as physiological responses are similar to real skating (Piucco et al. 2017).
Despite the simplicity to investigate the P-t relationship, studies have reported that the modelling of CP estimates differ significantly depending upon the mathematical model applied to describe the power-time relationship (Bull et al. 2000; Gaesser et al. 1995). The aforementioned studies showed that the linear parameter models resulted in higher CP estimates when comparing to the hyperbolic models.

Since stroke cadence is used to control exercise intensity on the slide board, the aim of this study was to examine the critical cadence (CC), CP and W’ during slide board skating determined from linear and hyperbolic models of cadence-time and power-time relationships, while simulating the movement on a slide board.

Materials and methods

Participants

Thirteen well trained long track speed skating athletes (9 males and 4 females, 19.8 ± 4.2 years, 69.6 ± 9.06 kg), participated in this study. All participants were free of cardiac, metabolic or respiratory diseases. Participants were familiar with slide board skating and participated in a systematic training program with a volume of 2 hours/day, 5 days per week, for at least 3 years. The study was conducted in accordance with ethical standards of the local Human Research Ethics Board (HREB 100940), and all participants gave their written informed consent to the experimental procedures after having the possible risks explained to them.


**Equipment**

All tests were performed on a slide board of polyethylene surface (2.0×0.6×0.2 m), connected to custom made software to control the tests parameters such as exercise duration, cadence increment and the real-time cadence (Piucco et al. 2016). Participants wore a pair of wool socks over their shoes while simulating skating. A similar slide board and socks were used to keep the friction coefficient as close as possible to the one estimated in previous study (Piucco et al. 2016).

**Incremental protocol**

After a 10-minute warming up on a cycle ergometer and subsequent 5-min of rest, the incremental slide board skating protocol started at a cadence of 30 push-offs per minute (ppm) and increased by 3 ppm every minute until volitional exhaustion occurred, despite strong verbal encouragement (most of the cases) or when the required cadence could no longer be maintained (three strokes bellow required cadence were allowed). Total test duration ranged from 9 to 14 minutes. This protocol has been previously standardized and validated (Piucco et al. 2017).

**Constant-intensity trials**

Each subject completed three to four maximal constant work rate tests between 90 to 107% of \( \text{CAD}_{\text{max}} \), selected to elicit exhaustion between 2 and 15 min (Jones et al. 2010). The trials ended when the subjects could no longer maintain the required cadence, despite verbal encouragement.
Three strokes below the required cadence were allowed before the test termination. The time to exhaustion \(t_{\text{lim}}\) was recorded to the nearest second. Power output \(P\) was modeled by the one-dimensional power balance model assuming the skater’s body mass \(m\), gravitational acceleration \(g\), dynamic friction coefficient \(\mu_k\), and sideway speed \(v\), as follow: 
\[
Po = \mu_k mgv.
\]
The \(\mu_k\) value was assumed to be the same calculated by Piucco et al. (2016). Total work done \(W\) was calculated by multiplying \(P\) versus \(t_{\text{lim}}\) for each trial.

**Mathematical modeling**

All the parameters (CAD, \(P\), \(W\) and \(t_{\text{lim}}\)) were fit to the linear or hyperbolic mathematical models to estimate CC, CP and \(W'\). Time to exhaustion \(t_{\text{lim}}\) was the dependent and CAD and \(P\) the independent variables for the hyperbolic model, while \(t_{\text{lim}}\) was the independent and CAD, \(P\) and \(W\) dependent variables for the linear model (Bull et al. 2000; Gaesser et al. 1995), as follow:

1. Hyperbolic-CAD: 
\[
t_{\text{lim}} = W'/(\text{CAD} - \text{CC})
\]
2. Hyperbolic-P: 
\[
t_{\text{lim}} = W'/(P - \text{CP})
\]
3. Linear-CAD: 
\[
\text{CAD} = W' \times (1/t_{\text{lim}}) + \text{CC}
\]
4. Linear-P: 
\[
P = W' \times (1/t_{\text{lim}}) + \text{CP}
\]
5. Linear-W: 
\[
W = (\text{CP} \times t_{\text{lim}}) + W'
\]

The CC and CP parameters are represented by the CAD and \(P\) asymptote in the Hyperbolic-CAD (Hyp-CAD) (1) and Hyperbolic-P (Hyp-P) (2) models respectively; by the y-intercept in the Linear-CAD (Lin-CAD) (3) and Linear-P (Lin-P) (4) models; and by the slope in the Lin-W (5)
model. The $W'$ parameter is derived by the curvature constant for the hyperbolic models (equations 1 and 2), by the slope for the Lin-P and Lin-CAD models (equations 3 and 4); and by the y-intercept for the Lin-W (5) model (Bull et al. 2000). It is important to highlight that we only analyse and compare the $W'$ derived from the power-time relationships (unit in kilojoules). Considering that critical cadence is the rate of push-offs, the $W'$ derived from cadence-time represents the number of push-offs above critical cadence.

Statistical analysis

The coefficient of determination ($r^2$) and the standard error of estimate (SEE) were calculated to examine the goodness of fit from the mathematical models. The SEE values were reported as a percentage of the parameter value (SEE%). Student’s paired t test was used to compare CC, CP, $r^2$ and SSE% from linear and hyperbolic models. One-way repeated measures ANOVA (Tukey’s Multiple Comparison test) was used to compare $W'$ and goodness of fit determined from the Lin-W, Lin-P, and Hyp-P models. Cohen’s effect size (ES) was also calculated for selected parameters. The Pearson product–moment correlation was used to test relationship of CC, CP and $W'$ calculated from different fitting models, and correlations between CC and CP. All the analyses were carried out using the GraphPad Prism software package for Windows (version 5.0; GraphPad Prism Software Inc., San Diego, CA, USA). The level of significance was set at $P < 0.05$.

Results
Time for trials to exhaustion ranged from 185.4±3.0 to 836.7±13 s. A summary of the CC and CP parameters estimates from the hyperbolic and linear models and the goodness of fit are provided in Table 1. The Lin-CAD resulted in a significantly higher CC than the Hyp-CAD (p = 0.01). On the other hand, the ES calculation presented a value of 0.21 (i.e. small).

**TABLE 1**

As for goodness of fit, SEE (%) was not significantly different between Lin-CAD and Hyp-CAD and between Lin-P and Hyp-P models, while $r^2$ was significantly higher for Hyp-P compared to Lin-P (p = 0.001). The work above CP ($W'$) derived from Lin-W (5.4 ± 2 kJ), Lin-P (5.2 ± 2.2 kJ) and Hyp-P (5.6 ± 1.8 kJ) were similar (p= 0.54). The coefficient of determination for Lin-W model ($r^2 = 0.99$) was significantly higher than Lin-P ($r^2 = 0.94$) and Hyp-P ($r^2 = 0.96$) models for the $W'$ parameter (p < 0.001) but no differences were found between Lin-P and Hyp-P. Curve fitting examples for each mathematical model and parameters are displayed in Figure 1.

**FIGURE 1**

Correlation coefficients between parameters from different fitting models are shown on Table 2. Parameters calculated from the two fitting methods were highly correlated. CP and CC parameters were also significantly correlated.

**TABLE 2**

Discussion
The innovation of the current study is the applicability of CP modelling during skating simulation on a slide board. The individual $r^2$ values for the linear and hyperbolic mathematical models for CC and CP calculation ranged from 0.91 to 1.00. These findings were consistent with previous studies that have reported $r^2$ values from 0.84 to 1.00 for the P-time or speed-time relationships, regardless of the mathematical modelling, during cycling (Bull 2000).

Despite the generally good fit, the Lin-CAD model resulted in a slightly better adjustment (i.e. same $r^2$ and lower SEE) than the Hyp-CAD model to estimate CC. The Lin-CAD model also resulted in significantly higher CC values (Table 1). Similar results were found by Bull (2000) and Gaesser et al. (1995) where the linear parameter models resulted in higher CP and CS estimates when comparing to the 2 and 3-parameter hyperbolic models. These findings support the suggestion of Gaesser et al. (1995) that the selection of the independent and dependent variables used in the model can affect the resulting $r^2$ values because the weighting of each data point in each model is not the same. The CP estimates did not differ between linear and hyperbolic models, probably because of the small SEE.

Regardless of the statistical significance, the difference observed between linear and hyperbolic models for CC values could be considered small, when the effect size and the percentage difference are considered. A mean difference of 1.8% was found when comparing the CC from the two models analysed. Thus, this ‘difference’ could be considered non meaningful in a practical perspective.

Linear and hyperbolic models for each parameter were highly correlated ($r > 0.9$), while correlation coefficient between CP and CC parameters were a little bit smaller (Table 2). That could be attributed to the fact that the power output used to calculate CP on slide board was estimated using a mathematical formula and not directly measured.
Estimates of \( W' \) were not significantly different between the linear and hyperbolic models, being the Lin-W model slightly superior to the others as indicated by a higher \( r^2 \). In addition, the magnitude of \( W' \) in the present study was lower than values reported for cycling exercise (~5kJ vs ~20kJ) (Bull et al. 2000). This could be explained by the fact that the Lin-W model utilizes an estimate of work based on an estimation of power output, which could be underestimated in this study due to the non-accurate \( \mu_k \) value used. However, beside this limitation, a smaller power output can be expected during speed skating when compared to cycling due to the lower stroke frequency and difficulties to perform a fast push-off due to the simultaneous activation of antagonist and postural muscles (Geijsel et al. 1984).

In conclusion, the practice of skating on a slide board allows deriving the \( CC \) from the relationship of cadence and time, as applied in the \( CP \) concept. This assessment based on slide board could be applied to any sport that involves skating movement, such as speed skating, ice hockey and cross-country skiing. The different mathematical modelling seems to provide similar values of \( CC \), \( CP \) and \( W' \), and based on the simplicity we recommend the utilization of linear model \( CAD \) vs. time in the practical context.

We decided to not use the 3-paramenter hyperbolic model because it is considerably more complex and requires determination of one more parameter (i.e one more test is necessary beside the trials to exhaustion). Therefore, it is less attractive for a practical application perspective. The validity of the parameters estimated in this study still needs to be further investigated.

Acknowledgements
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The authors have no conflicts of interest to report.

References


Table 1. Critical cadence and critical power derived from different fitting models.

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<th>Model</th>
<th>Mean</th>
<th>r²</th>
<th>SEE (%)</th>
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<tbody>
<tr>
<td>Lin-CAD (ppm)</td>
<td>56.0±4.8*</td>
<td>0.94±0.05</td>
<td>1.5±0.3</td>
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<tr>
<td>Hyp-CAD (ppm)</td>
<td>55.0±4.5</td>
<td>0.95±0.05</td>
<td>2.6±0.8</td>
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<tr>
<td>Lin-P (W)</td>
<td>176.6±24.8</td>
<td>0.94±0.03</td>
<td>1.4±0.9</td>
</tr>
<tr>
<td>Hyp-P (W)</td>
<td>175.4±25.7</td>
<td>0.96±0.03*</td>
<td>0.8±0.5</td>
</tr>
</tbody>
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r² = coefficient of determination; SEE(%) = standard error of estimate relative to individual values of CC and CP. * significant difference between linear and hyperbolic models.
Table 2. Correlation coefficients among linear and hyperbolic models for Critical Cadence (CC), Critical Power (CP) and work above CP (W’)

<table>
<thead>
<tr>
<th></th>
<th>CC-Hyp</th>
<th>CP-Lin</th>
<th>CP-Hyp</th>
<th>W’-HypP</th>
<th>W’-LinW</th>
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<tr>
<td>CC-Lin</td>
<td>0.97**</td>
<td>0.77*</td>
<td>0.75*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CC-Hyp</td>
<td>0.75*</td>
<td></td>
<td>0.74*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP-Lin</td>
<td></td>
<td>0.99**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W’-LinP</td>
<td></td>
<td></td>
<td></td>
<td>0.78*</td>
<td>0.95**</td>
</tr>
<tr>
<td>W’-HypP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.92**</td>
</tr>
</tbody>
</table>

*Significant correlation p > 0.05
** Significant correlation p > 0.001
Figure 1. Curve fit for each model for one representative subject. The dependent variable is presented on the y-axis. CC: Critical cadence; CP: Critical power; W': work above CP.