Critical skating intensity on a slide board: physiological and neuromuscular responses and correlation with performance on ice

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Abstract

The aim of this study was to assess the physiological and neuromuscular responses at critical skating intensity on a slide board and to investigate the correlations between critical cadence (CC) and skating performances on ice. 13 well-trained speed skaters (19.8±4.2 years, 69.6±9.06 kg) performed a maximal skating incremental test (IT) on a slide board. CC was determined from 3 to 4 trials to exhaustion lasting from 3.1 ± 0.7 to 13.9 ± 3.1 min, using linear and hyperbolic mathematical fittings. A time to exhaustion test at CC (TTE-CC) was performed. CC values (55.3±5.0 ppm) were significantly higher than cadence at the respiratory compensation point (RCP) (53.5±4.0 ppm). Mean duration of TTE-CC was 22.9±4.8 min. Peak values of oxygen uptake ($\dot{V}O_{2peak}$), heart rate (HR), ventilation (VE), respiratory exchange ratio (RER) and ratings of perceived exertion (RPE) during TTE-CC were significantly lower ($p<0.05$) than the peak values reached during the IT. $\dot{V}O_2$, HR, VE, RER and RPE significantly increased from 25% to 100% of TTE-CC. Muscle activity (EMGi) significantly increased after 75% of TTE-CC for vastus lateralis and gluteus maximus muscles. $\dot{V}O_2$ at CC was better associated to skating performance on 500, 1000, 1500 and 5000 meters than $\dot{V}O_{2peak}$ at IT and $\dot{V}O_2$ at RCP. Physiological responses indicate that critical skating intensity on slide board occurred within the heavy exercise domain where $\dot{V}O_2$ increases but does not reach its maximum. Critical cadence could be used as a better indicator of performance and training prescription for long track speed skating distances.

Keywords: power-time relationship, critical power, critical cadence, physiological responses, slow component, EMGi, speed skating.

Introduction

During cyclic sport activities, the power-time relationship provides estimates of two parameters: (1) the asymptote of the hyperbolic curve, called the critical power (CP); and (2) the curvature constant, which represent the finite work that can be performed above the CP (W’) (Hill 1993; Jones et al 2010). The concept of CP was originally proposed for use with small muscle groups (Monod and Scherrer 1965), and later adapted for whole body exercises, including cycling, running, and swimming (Hill 1993). It has been reported that exercise at CP cannot typically be sustained beyond approximately 30 minutes (Brickley et al. 2002) instead of ‘for a very long time without fatigue' as initially proposed by Monod and Scherrer (1965) with physiological steady state not attained.

CP is a good indicator of endurance performance and is a useful parameter for training prescription, since it demarcates the heavy and severe exercise intensity domains (Poole et al. 1988; de Lucas et al. 2013). Consequently, this aerobic index provides information regarding the boundary intensity between a high-intensity continuous and the onset intensity to perform an interval exercise (Vanhatalo et al. 2011; de Lucas et al. 2012).

In long track speed skating competitions, the relative contribution from different energy pathways depends on the distance of the race; however, both aerobic and anaerobic energy sources are decisive for an optimal performance (Foster et al. 2003). The 1500-m distance, which is considered to be the single most representative event in speed skating, takes around 2 to 2.5 minutes to be completed and has nearly equal contribution from aerobic and anaerobic energy systems (Foster et al. 1993). Considering the physiological requirements of this main representative distance, the critical skating intensity could be a decisive parameter to consider for training prescription and performance assessment of speed skaters.

Despite the fact that critical intensity tests are relatively simple to perform, the CP or critical speed (CS) during skating has not yet been reported in the literature. The lack of investigations related to specific protocols to evaluate speed skating performance is partially related to difficulties in reproducing the skating movement in a laboratory environment and partially related to controlling test conditions on an ice track (Foster et al. 1993). To overcome these limitations, the use of a slide board to mimic the skating movement with intensity represented by changes in skating cadence has been investigated. Slide board skating has been shown to be a reliable and a more specific method to evaluate speed skating performance, as physiological and neuromuscular responses are similar to real world skating (Piucco et al. 2017*a*, Piucco et al. 2017*b*; Piucco et al. 2018). Recently, Piucco and de Lucas (2019) have applied the critical intensity model during skating simulated on a slide board, i.e critical cadence. However, the physiological meaning of this intensity remains to be determined.

Therefore, the purposes of this study were twofold: 1) to examine the physiological and neuromuscular responses at critical cadence (CC) while skating on a slide board ergometer until exhaustion; 2) to investigate whether CC is a meaningful parameter for speed skating performance in different distances when compared to the respiratory compensation point (RCP) and maximal O_2 uptake.

Materials and Methods

Participants

13 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. The study was conducted after the competition season. 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. All participants regularly participated in long track speed skating competitions. Mean performance time for 500m = 39.5± 2.2s, 1000m = 78.6 ± 6.4s 1500m = 123.2 ± 8.4s, 5000m = 453.4 ± 37.1s). Time-trial performances were performed by the coach at the same time and under the same conditions for all participants at the time of the testing. The study was conducted in accordance with ethical standards of the local Human Research Ethics Board (HREB 100940). All participants gave their written informed consent to the experimental procedures after having the possible risks and benefits of participation explained to them. All participants were free of cardiac, metabolic, or respiratory diseases, according to the self-reporting.

Experimental design

The subjects were tested on 5 to 6 separate occasions over the period of three weeks to complete the entire protocol. Each subject performed: (1) An incremental skating test (IT) to measure peak physiological parameters and maximal skating cadence (CAD_{max}); (2) 3 to 4 constant-cadence tests performed to exhaustion in order to model intensity-duration relationships; (3) A test to exhaustion at CC (TTE-CC) on slide board to analyse physiological and neuromuscular responses. The subjects were all familiar with simulating skating on a slide board. They were instructed to avoid heavy training prior to testing and to refrain from caffeine and alcohol consumption 6 and 24 hours before each test, respectively.

Equipment

All tests were performed on a slide board (2.0×0.6 ×0.2 m) which was connected to a custom-made software to control the parameters of the test (Piucco et al. 2017*a*). Participants wore a pair of wool socks over their shoes while simulating skating (i.e a proper skating posture and technique was visually controlled by the researcher during each test). The slide board was polished before each test. Pulmonary gas exchange was continuously measured during test (1) and (3) by using a TrueMax 2400 computerized metabolic system (Parvo Medics, Utah, USA). Before each test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas of known O_2 and CO_2 concentration according to the manufacturer's instructions, while the gas analyzer turbine flow-meter was calibrated using a 3-L syringe. Heart rate was monitored throughout each test (Polar, Kempele, Finland). Muscle activity of the vastus lateralis (VL) and gluteus maximum (GM) was continuously measured at 2000 Hz during test (3) using a Miotool system (MioTec Biomedical, Porto Alegre, Brazil) with 16-bit resolution and pairs of Ag/AgCl electrodes (bipolar configuration) with a diameter of 22 mm (Kendall Meditrace, Mansfield, USA) as recommended by SENIAM. A reference electrode was placed over the tibial tuberosity.

Incremental test

After a 10-minute warm up on a cycle ergometer and a subsequent 5-minute rest period, the incremental skating protocol started at a cadence of 30 push-offs per minute (ppm) and increased by 3 ppm every minute until volitional exhaustion, despite strong verbal encouragement (Piucco et al 2017*a*). Pulmonary ventilation ($\dot{V}E$), respiratory exchange ratio (RER), and oxygen consumption ($\dot{V}O_2$) were reduced to 15-s averages. The peak 15-s averaged value recorded during the incremental test was considered as peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$). The respiratory compensation point (RCP) was visually identified by two examiners as the point where end-tidal PCO_2 began to fall after a period of isocapnic buffering (Whipp et al. 1989). This point was confirmed by examining $\dot{V}E/\dot{V}CO_2$ plotted against $\dot{V}O_2$ and by identifying the second breakpoint in the $\dot{V}E$-to-$\dot{V}O_2$ relationship. The rate of perceived exertion (RPE) during the tests was assessed using a Borg scale (6-20 points) at the end of each stage (Borg 1982).

Critical cadence trials

Subjects warmed up on the slide board for 5-minutes at a low cadence (around 30 ppm). The subjects performed three to four maximal constant work rate tests until exhaustion from 90 to 107% of maximal cadence achieved during the IT (CAD_{max}). CC was determined from 3 trials in three participants due to competition schedule. The SEE was less than 2% for these athletes, so we decided to include them in the analysis. The trials lead the subjects to exhaustion between 3 and 15 min, which is the recommended range of predictive trial to minimize the influence of aerobic inertia in CP or CV values (Hill and Ferguson 1999; Bishop et al. 1998). The trials were ended when the subjects could no longer maintain the required cadence, despite verbal encouragement, and the time to exhaustion (t_{lim}) was recorded to the nearest second. HR values were 191 ± 9.2, 195 ± 7.5, 198 ± 13.1 and 199 ± 6.2 bpm for trial 1, 2, 3 and 4, respectively. Individual CC was estimated using two models: the hyperbolic ($CAD–t_{lim}$) model, where the workload is plotted against time (Eq. 1); the linear model (CAD-1/t_{lim}) where the workload is plotted against inverse of time (Eq. 2).

(Eq. 1) $t_{lim} = W'/(CAD - CC)$

(Eq. 2) $CAD = (W'/t_{lim}) + CC$

The work-time relationship model was not considered in this study due to difficulties to proper estimate power output on the slide board, as recently reported by our group (Piucco and de Lucas, 2019).

The standard error of the estimate (SEE) associated with the CC was expressed as coefficients of variation (CV %). The CC was individually selected from the best fit model, i.e. lower SSE followed by higher coefficient of determination (R^2) when SEE values were the same (Vanhatalo et al. 2011).

Test to exhaustion at CC (TTE-CC)

On a separate day, following a 10-min warm-up on a cycle ergometer and subsequent 5-min of rest period, subjects were encouraged to skate for as long as possible at the CC determined individually. VE, RER, $\dot{V}O_2$, and HR were continuously measured and RPE was registered every 5 min. Peak values were defined as the highest average 15-s value recorded during the test. Physiological values during TTE-CC were also averaged starting from 25 to 100% of TTE-CC duration (TTE-CC_{avg}) to avoid the adjustment phase of cardiovascular responses. To analyse the physiological responses, we used the 45-sec averaged values at 25%, 50%, 75% and 100% of TTE-CC test. We opted to not start from time zero to avoid the adjustment phase (i.e. on-kinetics) of physiological parameters. In addition, the absolute increase in $\dot{V}O_2$ from the third minute of exercise to the end of TTE-CC was calculated ($\Delta\dot{V}O_2$) (Bull et al. 2008).

EMG of VL and GM muscles was recorded continuously during the test. Raw signals were filtered using a combination of 5th order band-pass Butterworth filters between 20 and 500 Hz. The rectified EMG was integrated with respect to time (EMGi), with an EMGi value computed 45-sec at 25%, 50%, 75% and 100% of total TTE-CC test time. This data was individually normalized by the value at 25% of total time. Due to technical problems, data of only 6 participants were considered for the EMG analysis. The test was completed when the subject could no longer maintain the pre-determined cadence or at voluntary exhaustion. The time to failure was described to the nearest second.

Statistical analysis

Student's paired t-test was used to compare peak values during IT (IT_{peak}) and TTE-CC ($TTE\text{-}CC_{peak}$) as well as submaximal values at IT test (IT_{RCP}) and $TTE\text{-}CC_{avg}$. One-way repeated-measures ANOVA was performed and Scheffe post-hoc comparisons were used to determine changes in physiological and neuromuscular parameters along the TTE-CC test. Correlation between cadence and $\dot{V}O_2$ values at different intensities was determined using the Pearson product moment correlation test. 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

Averaged values for CC was 55.3 ± 5.0 ppm (the linear model was selected for 11 participants and the hyperbolic model for 2 participants). The R^2 values for the fitting model used to calculate CC was 0.94 ± 0.05 and the SEE was 1.99 ± 1.74%.

Table 1 depicts the mean values of the maximal and submaximal physiological responses and cadence values during IT and TTE-CC.

TABLE 1

$\dot{V}O_2$ (p = 0.02), HR (p = 0.03), VE, RER, CAD, and RPE ($p < 0.001$) values at TTE-CC_{peak} were significantly smaller than the values during the IT_{peak}. $\dot{V}O_2$, HR, VE ($p < 0.001$), CAD (p = 0.02), and RPE (p = 0.01) were significant higher during TTE- CC_{peak} compared to IT_{RCP} values. CC was correlated to CADmax (r = 0.88) and to CAD at RCP (r = 0.89).

Figure 1 shows the $\dot{V}O_2$ during IT and during TTE-CC test of one representative subject.

FIGURE 1

The mean duration of TTE-CC test was 23.0 ± 4.8 min, ranging from 12.2 to 30.1 minutes. $\dot{V}O_2$, HR, VE, RER, and RPE significantly increased 4.9% (p = 0.002), 13.0% (p = 0.04), 24.3% ($p < 0.001$), 4.8% (p = 0.002), and 41.5% ($p < 0.001$) from 25 to 100% of TTE-CC, respectively. Figure 2 shows the HR and $\dot{V}O_2$ responses during TTE-CC test.

FIGURE 2

$\dot{V}O_2$ at 25% of TTE-CC test represented 83% of $\dot{V}O_{2peak}$., while $\dot{V}O_2$ at 100% of TTE-CC represented 88% of $\dot{V}O_{2peak}$. The averaged $\Delta\dot{V}O_2$ value was 686.5±396 mL·min^{-1}.

Figure 3 represents the mean EMG amplitude values for the VL and GM muscles during the TTE-CC test.

FIGURE 3

Correlations between RCP, CC and $\dot{V}O_2$ ($L \cdot min^{-1}$) at different intensities and performance time on different skating distances are presented in table 2.

TABLE 2

Figure 4 shows the linear regression and correlation between CC and performance on 1500 meters skating distance (panel A) and between $\dot{V}O_{2\ at}$ CC and performance on 1500 meters skating distance (panel B) are presented in figure 4.

FIGURE 4

Discussion

The main findings to this study were: a) the CC was significantly higher than the cadence at the RCP and significantly lower than CADmax, although the variables were strongly correlated; b) physiological parameters and the EMGi increased significantly over time during the TTE-CC test. c) $\dot{V}O_2$ at CC presented better correlations with skating performances on ice than $\dot{V}O_{2peak}$ and $\dot{V}O_2$ at RPC.

Numerous studies have shown that CP or CS is significantly higher than the mean power output/speed associated with the second lactate threshold and/or maximal lactate steady state during swimming, running, and cycling (Hill 1993; Dekerle et al. 2005; Dekerle et al., 2010; de Lucas et al. 2002; Denadai et al. 2005; de Lucas et al. 2012; Mattioni et al. 2016), but no study has investigated the critical intensity parameter during skating. The results of this study corroborate with the aforementioned studies, where skating exercise performed at CC was non-sustainable and physiologically non-steady (Figure 2B). The $\dot{V}O_2$, HR, VE, RER, and RPE significantly increased overtime during skating at CC. The exhaustion time around 23 minutes and the oxygen uptake increased from a mean of 83% to 88% $\dot{V}O_{2peak}$ between the beginning (25%) and at the end (100%) of TTE-CC. These values are similar to that reported by de Lucas et al. (2013), whom reported mean TTE of 22.9 min, and Brickley et al. (2002) and Pringle and Jones (2002) whom reported a significant $\dot{V}O_2$ increase from around 80% to 90% of maximum values, and time durations slightly below 30 minutes when cycling at the CP. The $\Delta\dot{V}O_2$ value of 686.5±396 mL·min^{-1} found in this study was higher than the $\dot{V}O_2$ slow component found during cycling at CP of 247 ml·min^{-1} (de Lucas et al. 2013) and during running at CV of 442 ml·min^{-1} (Bull et al. 2008), when critical intensity was determined using the linear model.

Muscle activity (i.e. EMGi) of GM and VL also increased during the TTE-CC test for all athletes (Figure 3). The increase in EMGi represents the recruitment of previously inactive motor units and/or increased firing rate of the activated motor units required to maintain force production in the face of muscle fatigue (Hunter et al. 2001). The simultaneous slow rise in pulmonary $\dot{V}O_2$ and increases in EMGi from the exercising muscles during heavy and severe exercise has been taken as evidence that the serial recruitment of the less-efficient type II motor units is related to the $\dot{V}O_2$ slow component (Barstow et al. 1996; Jones et al. 2011).

However, Pringle and Jones (2002) and Scheuermann et al. (2001) were unable to detect significant increase in EMGi during cycling at a heavy intensity that elicited a $\dot{V}O_2$ slow component. A noteworthy characteristic that should be considered is the relative long duty cycle during skating (contraction-relaxation cycle) when compared to cycling and running exercises. The increased intramuscular pressure accompanied by the low posture is known to trigger blood flow occlusion altering O_2 delivery and increasing metabolites accumulation during skating (Foster et al. 1999; Rundell 1996). These characteristics could be related to the significant increase in muscle activity found in the present study, since an increase in EMGi have been shown in response to moderate blood flow restriction and local accumulation of metabolites (Loenneke et al. 2010; Yasuda et al. 2009). In addition, the metabolites accumulation has also been considered to be a putative mediator of the $\dot{V}O_2$ slow component (Jones et al. 2011).

Interestingly, the GM presented a more pronounced increase in EMGi than VL (Figure 3). Despite both GM and VL significantly contributing to power output during skating, only the GM showed significant changes in frequency components during skating to exhaustion, suggesting that this muscle is more sensitive to fatigue (Piucco et al. 2017*a*).

Recent studies have shown that CP is decreased with reduced O_2 delivery induced by hypoxia or blood flow occlusion (Dekerle et al. 2012; Broxterman et al. 2015) and lower for 50% duty cycle than the 20% duty cycle as a result of reduced blood flow (Broxterman et al. 2014). However, if CC intensity is affected or not during skating due to these characteristics remains to be investigated.

As expected, in the present study, exercising at CC did not result in an increase in oxygen consumption to the maximal level as attained during the incremental protocol (Figure 1). One could speculate that the attainment of the $\dot{V}O_2max$ does not occur when exercising at critical intensity since the rate of increase in $\dot{V}O_2$ is slow (0.4 L·min^{-1} over ~23 minutes duration of TTE-CC) and exercise is terminated due to other factors before the aerobic system is fully recruited (Brickley et al. 2002; de Lucas et al. 2013). Indeed, de Lucas et al. (2013) showed that only at intensity 5% above CP could lead $\dot{V}O_2$ to the maximal values at the termination of exercise.

Although the characteristics of technique and body posture of speed skating could suppose a limitation in the sustainability of endurance time such as at TTE-CC on slide board, no important difference was observed when compared to running (Penteado et al. 2014; Bull et al. 2008) and cycling exercises (Brickley et al. 2002; Pringle and Jones 2002).

CC and $\dot{V}O_2$ at CC were better associated to skating performance on ice in selected distances (i.e. 500m, 1000, 1500m, and 5000m) than RCP, $\dot{V}O_2$max and $\dot{V}O_2$ at anaerobic threshold intensity (Table 2 and Figure 4). Critical intensity has been suggested as a good indicator of endurance performance (Florence and Weir 1997), and especially for continuous activities performed at a severe-intensity exercise domain (Vanhatalo et al. 2011). Therefore, good correlation values between CC and performance on long track speed skating distances were expected since these competitions take around less than 1-10 minutes of maximal intensity effort.

Therefore, for a more individual training prescription that represents the highest limit of heavy exercise intensity it is worth to submit the athletes to short predictive trials to exhaustion and calculate the CC to get a more precise value than RCP. Because slide board skating promotes similar physiological stress to actual skating, the HR at CC on slide board could be used as an indicator of workload intensity for training prescription on ice.

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Table 1. Maximal and submaximal values during the incremental (IT) and constant cadence tests (TTE-CC).

	IT_{peak}	IT_{RCP}	TTE-CC_{peak}	TTE-CC_{avg}
$\dot{V}O_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	48.0 ± 6.1	41.0 ± 5.2	46.3 ± 6.8*	41.6 ± 6.0
HR (bpm)	202.2 ± 8.6	185.9 ± 7.3	198.7 ± 9.2*	188.3 ± 12.6
VE ($L \cdot min^{-1}$)	130.6 ± 26.3	86.8 ± 17.0	118.9 ± 27.5*	100.2 ±20.2$^\#$
RER	1.16 ± 0.03	1.01 ± 0.05	1.02 ± 0.05*	0.97 ± 0.03$^\#$
RPE	19.6 ± 0.6	15.6 ± 1.3	17.7 ± 1.16*	15.0 ± 1.4
CAD (ppm)	61.6 ± 4.3	53.5 ± 4.0	55.3 ± 5.0*	55.3 ± 5.0$^\#$

$IT_{\mathbf{peak}}$ peak values during incremental test; IT_{RCP} respiratory compensation values; TTE-CC_{peak} peak values during time to exhaustion at critical cadence test. *significantly different than IT_{peak} value $p<0.05$. # significantly different than IT_{RCP} $p<0.05$.

Table 2. Correlations between $\dot{V}O_{2peak}$, RCP, $\dot{V}O_2$ at RCP, CC and $\dot{V}O_2$ at CC and performance on 500, 1000, 1500 and 5000m long track skating distances on ice.

	500 m	1000 m	1500 m	5000 m
$\dot{V}O_{2peak}$	-0.70**	-0.58*	-0.70**	-0.79**
RCP (ppm)	-0.56*	-0.62*	-0.63*	-0.55
$\dot{V}O_2$ at RCP	-0.69*	-0.59*	-0.70**	-0.77**
CC (ppm)	-0.60*	-0.66*	-0.75**	-0.84**
$\dot{V}O_2$ at CC	-0.77**	-0.68*	-0.79**	-0.84**

* significant correlation at $p < 0.05$. ** significant correlation at $p < 0.01$.

Figure 1. $\dot{V}O_2$ during IT (panel A) and during TTE-CC test (panel B). Dashed horizontal lines indicate the peak value at IT.

Figure 2. Heart rate (panel A) and relative oxygen uptake (panel B) responses during TTE-CC test. * significant difference from 25%; § significant difference from 50%; # significant difference from 100%. $p < 0.05$.

Figure 3. Integrated EMG values of VL (open circles) and GM (solid circles) during TTE-CC test. § significantly different from 100% for VL. * significantly different from 100% for GM. $p < 0.05$.

Figure 4. Linear regression (95% CI and identity line) between CC (panel A) and $\dot{V}O_2$ at CC (panel B) and skating performance on 1500m.