$\dot{V}O_2$ and muscle deoxygenation kinetics during skating: comparison between slide board and treadmill skating

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Abstract

Purpose: this study aimed to compare the oxygen uptake ($\dot{V}O_2$) kinetics during skating on a treadmill and skating on a slide board and discuss potential mechanisms that might control the $\dot{V}O_2$ kinetics responses during skating. **Methods**: breath-by-breath pulmonary $\dot{V}O_2$ and near-infrared spectroscopy-derived muscle deoxygenation ([HHbMb]) were monitored continuously in 12 well-trained young long track speed skaters. On-transient $\dot{V}O_2$ and [HHbMb] responses to skating on a treadmill and skating on a slide board at 80% of the estimated gas exchange threshold were fitted as mono-exponential function. The signals were time aligned, and the individual [HHbMb]-to-$\dot{V}O_2$ ratio was calculated as the average value from 20–120 s after exercise starts. **Results**: the time constants for the adjustment of phase II $\dot{V}O_2$ ($\tau\ \dot{V}O_2$) and [HHbMb] (τ[HHbMb]) were low and similar between slide board vs. treadmill skating (18.1 ± 3.4 vs. 18.9 ± 3.6 for $\tau\ \dot{V}O_2$ and 12.6 ± 4.0 vs. 12.4 ± 4.0 s for τ[HHbMb]). The [HHbMb]/$\dot{V}O_2$ ratio was not different from 1.0 ($p > 0.05$) in both conditions. **Conclusion:** the fast $\dot{V}O_2$ kinetics during skating suggest that chronical adaptation to skating might overcome any possible restriction in leg blood flow during low intensity exercise. The [HHbMb]/$\dot{V}O_2$ ratio values also suggest a good matching of O_2 delivery to O_2 utilization in trained speed skaters. The similar $\tau\ \dot{V}O_2$ and τ [HHbMb] values between slide board and treadmill further reinforce the validity of using a slide board for skating testing and training purposes.

Keywords: muscle deoxygenation, skating, slide board, $\dot{V}O_2$ kinetics.

Introduction

The speed of adjustment of oxidative phosphorylation during the on-transient of exercise, i.e. $\dot{V}O_2$ kinetics, provides valuable information in relation to the instantaneous rate of aerobic and anaerobic energy transfer[1,2]. A faster $\dot{V}O_2$ kinetics response implies a smaller oxygen deficit and a consequent reduction in metabolites accumulation and sparing of anaerobic substrates, which could possibly lead to a reduction in fatigue and improved exercise performance[3].

In speed skating, although the relative contribution from different energy pathways depends on the distance in competition, both aerobic and anaerobic energy sources are crucial for performance[4]. In this context, a rapid adjustment of the oxidative metabolism presents an advantage, as non-oxidative sources can be spared and then used during the end-spurt. It is noteworthy that, when performing, skaters adopt low posture and long cycles of isometric contractions, which are associated to restriction of muscle blood flow to the lower limbs and high intramuscular forces[5,6] that could impair oxygen delivery. Indeed, these specific characteristics have been indicated to be responsible for a lower maximal oxygen uptake ($\dot{V}O_{2max}$) and higher muscle oxygen desaturation during skating exercise when compared to cycling[7,5,4]. However, whether or not these hemodynamic limitations that occur at higher intensities of exercise play a role in determining the speed of adjustment of oxidative phosphorylation in response to submaximal skating exercise is still unclear.

A reason why measurements of $\dot{V}O_2$ kinetics have not been performed during skating could be the challenges associated with performing physiological measurements on the track. To overcome this limitation, researchers have performed physiological evaluations of skating on instrumented motorized treadmills[5,6]. However, even though these evaluations mimic physiological responses to skating, the access to this type of equipment is limited and expensive. As an alternative and inexpensive method that simulates speed skating conditions, slide board skating platforms have gained attention for both training and testing protocols[8,9]. Our group recently compared physiological responses during a maximal incremental skating performed on a treadmill vs. a slide board and demonstrated that aerobic performance (i.e., $\dot{V}O_2$ responses associated to peak exercise as well as gas exchange threshold and the respiratory compensation point) was similar between the two conditions[10]. However, it is not known whether $\dot{V}O_2$ kinetics responses are also comparable between treadmill and slide board skating, which is important to further validate the use of a slide board as a physiologically valid option to skating on a motorized treadmill.

Thus, the goals of this study were to: 1) compare the $\dot{V}O_2$ kinetics responses during treadmill vs. slide board skating; 2) discuss potential mechanisms that might control the $\dot{V}O_2$ kinetics responses. We hypothesized that: 1) given the similarities previously reported for treadmill and slide board skating at submaximal and peak intensities of exercise[10], the $\dot{V}O_2$ kinetics response would be similar in both conditions; 2) well-trained speed skaters would have a fast (~20 s)[11] $\dot{V}O_2$ kinetics and a good matching of O_2 delivery to O_2 utilization, despite some potential restrictions in muscle blood flow associated to the posture during skating.

Methods

Participants

Twelve competitive trained long track speed skaters (8 females and 4 males), age 18.0 ± 0.9 years; body mass 65.0 ± 6.8 kg; height, 173.0 ± 8.8 cm - volunteered and gave written consent to participate in the study. The speed skaters were participating in a systematic training program with a volume of 2 hours/day, 5 days per week, for at least 3 years, and their best time for the 1500 m distance was 2.13 ± 0.14 min during competition. All procedures were approved by the Ethics Committee of Human Research where the study was conducted (REB15-2537).

Experimental protocol

In separated days, each participant performed two incremental skating tests to fatigue, one on an oversized treadmill (2.5 × 3.5 m, Athletic Republic, Salt Lake City, UT) and the other on a slide board (2.0 x 0.6 m, Athletic Innovation, Inc, Rochester, NY) fixed to the ground with double sided tape. One the treadmill, participants used their own inline skates while on the slide board, participants wore a pair of nylon socks over their sport shoes. The maximal incremental tests on a slide board and on a treadmill are described elsewhere[10]. The gas exchange threshold (GET) was defined as the $\dot{V}O_2$ at which carbon dioxide production ($\dot{V}CO_2$) began to increase out of proportion in relation to $\dot{V}O_2$ with a systematic rise in minute ventilation-to-$\dot{V}O_2$ ratio and end-tidal PO_2, whereas minute ventilation-to-$\dot{V}CO_2$ ratio and end-tidal PCO_2 were stable[12]. A moderate-intensity speed and cadence was selected from the treadmill and slide board skating tests respectively, to elicit a $\dot{V}O_2$ equivalent to ~80% of the $\dot{V}O_2$ at GET. All participants were familiarized with the treadmill skating protocols at least twice, for a minimum of 30 min total, 2 to 5 days before the data collection. Participants were familiar with the slide board skating movement as they used it regularly for training. In the subsequent days, participants performed three-step transitions of 6 min of moderate-intensities preceded by a 6-min baseline (BL) of 8 $km \cdot h^{-1}$ and 15 push-offs per minutes (ppm) on the treadmill and on the slide board, respectively. The skating cadence on a slide board was controlled by optical sensors, connected to a software specially developed for that purpose[9]. The three transitions were performed consecutively in a single session based on the recommendations of Spencer et al.[13].

Measurements

Throughout each exercise trial ventilation ($\dot{V}_E$), $\dot{V}O_2$ and $\dot{V}CO_2$ were measured breath-by-breath using a portable gas analyzer (K4b2 Cosmed®, Rome, Italy), calibrated according to manufacturer's instructions prior to each test. $\dot{V}O_{2peak}$ was considered to be the highest value averaged over a 15-s period during the last stage of the test. Heart rate (HR) data were collected using radiotelemetry (SP0180 Polar Transmitter; Polar Electro Inc., Kempele, Finland). GET was identified by two blinded experts. If a discrepancy of more than 200 $mL \cdot min^{-1}$ was detected, a third expert was involved and the average of the two closest values was used.

Local muscle deoxygenation profiles of the quadriceps vastus lateralis (VL) muscle of the right leg were measured using a wireless near-infrared spectroscopy (NIRS) system (Moxy Muscle Oxygen Sensor, Hutchinson, Minnesota USA) that functions by sequentially sending light waves (630–850 nm) from four light emitting diodes into the tissue beneath it and recording the amount of returned scattered light at two detectors positioned 12.5 and 25 mm from the light source. This allows the system to estimate oxygenation status of the muscle with a penetration depth of about 12 mm. Data support the validity of the Moxy to measure local oxygen saturation, with statistical analyses showing a strong or excellent correlation between trials for all participants (SROC: $r = 0.842–0.993$, ICC: $r = 0.773–0.992$, $p < .01$)[14]. The system was inserted into a dark rubber shield and then placed on the belly of the medial belly of VL muscle, midway from the greater trochanter, using double side tape and wrapped with an elastic bandage. Changes in light intensities were recorded continuously at 2 Hz. Given the uncertainty of the optical path length in the VL at rest and during exercise, NIRS data are presented as delta concentration changes expressed in arbitrary units (AU).

Data analysis

Individual breath-by-breath $\dot{V}O_2$ data were edited by removing the outlier data that laid 3 SD from the local mean. The data for each moderate transition were linearly interpolated second-by-second and time aligned such that time "zero" represented the onset of the transition. Data from each transition were ensemble-averaged into 5-s bins to provide a single profile for each participant. The on-transient response for $\dot{V}O_2$ was fitted using a mono-exponential function (Eq 1):

$$\dot{V}O_2\,(t) = \dot{V}O_{2BL} + A_P\,(1 - e^{-(t-TD)/\tau})$$

where $\dot{V}O_2$ (t) represents $\dot{V}O_2$ at any time (t), $\dot{V}O_{2BL}$ is the baseline value, A_P is the steady-state increase in $\dot{V}O_2$ above the baseline value, τ is the time constant defined as the duration of time for $\dot{V}O_2$ to increase to 63% of the steady-state increase, and TD is the time delay of the model. The initial 20 s of data where excluded to avoid inclusion of data points from phase I of the $\dot{V}O_2$ response in the fitting of phase II $\dot{V}O_2$ - since including data from the phase I in the mono-exponential model results in overestimation of the actual time constant (i.e., τ) of the increase in $\dot{V}O_2$ - while still allowing TD to vary freely to optimize accuracy of parameter estimates[11]. $\dot{V}O_2$ data were modeled from 20 s to 4 min (240 s) of the step transition, but always ensuring that each participant had attained a $\dot{V}O_2$ steady-state within this time frame[11]. The model parameters were estimated by least-squares nonlinear regression (Origin, OriginLab, Northampton, MA). The 95% confidence interval (CI) for the estimated τ was determined after preliminary fitting of the data and with baseline, A_P and TD fixed to the best-fit values and τ allowed to vary.

The calculated TD (CTD) for the NIRS-derived deoxyhemoglobin [HHbMb] response (reflecting a physiological TD before the [HHbMb] begins to increase) was visually determined using second-by-second data and corresponded to the time, after the onset of exercise, at which the [HHbMb] signal began a systematic increase from its nadir value[11]. Following the time alignment and ensemble averaging, the [HHbMb] data were averaged into 5 s bins as described above for $\dot{V}O_2$. The [HHbMb] data were modeled from the end of the CTD-[HHbMb] to 90 s of the transition using an exponential model as described in Eq.1. Different fitting strategies (i.e., 90–180 s) resulted in minimal differences in [HHbMb] kinetics parameters previously explained[15]. Whereas the τ [HHbMb] described the time course for the increase in [HHbMb], the overall change of muscle deoxygenation was described by the effective [HHbMb] response (τ' [HHbMb] = TD-[HHbMb] + τ' [HHbMb]) from the onset of exercise to provide a description of the overall time course for muscle deoxygenation.

The second-by-second [HHbMb] and $\dot{V}O_2$ data modelled from the parameter estimates derived from the kinetics analysis were normalized for each participant from 0%, corresponding to the baseline, to 100% reflecting the steady-state response. The $\dot{V}O_2$ data were time-aligned with the onset of exercise left-shifted by 20 s to account for the phase I duration[11]. Data were further averaged into 5-s bins for statistical comparison of the rate of adjustment for [HHbMb] and $\dot{V}O_2$. Additionally, an overall [HHbMb]/$\dot{V}O_2$ ratio for the adjustment during the exercise on-transient was derived for each individual as the average value from 20–120 s into the transition. To analyze the [HHbMb] response in relation to the $\dot{V}O_2$ the data were modelled based on the calculated BL, A_P, TD and τ parameter estimates[16].

Statistical analysis

Data are presented as mean ± SD. Normality of the data was assessed using the Shapiro-Wilk test. Two-tailed pairwise t-tests were used to determine statistical significance between the variables studied during skating on the treadmill and on the slide board. Pearson product-moment correlation coefficients were used to determine the degree of association of $\dot{V}O_2$ and [HHbMb] kinetics parameters between the two skating protocols. All statistical analyses were performed using Graph Prism (v. 5.0 GraphPad Prism Software Inc, San Diego, CA). Statistical significance was accepted at an alpha level less than 0.05.

Results

The $\dot{V}O_{2peak}$ values for the skaters during the maximal incremental skating test on the treadmill and on the slide board were 46.7 ± 6.1 $mL \cdot kg^{-1} \cdot min^{-1}$ and 46.4 ± 4.4 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. These data were published and discussed elsewhere[10]. The moderate intensity exercise bouts, performed at 80% GET, required workloads of 15.2 ± 0.3 $km \cdot h^{-1}$ on the treadmill and 34.8 ± 0.3 ppm on the slide board.

The $\dot{V}O_2$ and [HHbMb] kinetics parameter estimates are described in Table 1. No differences were observed between the two experimental conditions for $\dot{V}O_{2BL}$, $\dot{V}O_{2Ap}$, $\dot{V}O_{2TD}$, τ $\dot{V}O_2$ and CI τ $\dot{V}O_2$. Similarly, no differences were observed in $[HHbMb]_{BL}$, $[HHbMb]_{Ap}$, $[HHbMb]_{TD}$, τ [HHbMb], $[HHbMb]_{CTD}$, and τ' [HHbMb] when parameters were derived from treadmill or slide board skating protocols. The 95% CI for the estimated [HHbMb] was smaller when skating on treadmill compared to slide board ($p = 0.03$). Figure 1 displays the $\dot{V}O_2$ and [HHbMb] kinetics during skating of a representative participant during moderate transitions on the treadmill and on the slide board.

The [HHbMb]/$\dot{V}O_2$ ratio was not different from 1.0 during treadmill skating (1.007 ± 0.007) and slide board (1.003 ± 0.005) skating, and it was similar in both conditions. The normalized responses for the [HHbMb] and $\dot{V}O_2$ signal as well as the normalized [HHbMb]/$\dot{V}O_2$ ratio are presented in Figure 2.

Discussion

The main goal of this study was to examine the $\dot{V}O_2$ kinetics responses observed during treadmill compared to slide board skating. The main findings were that: (i) well-trained speed skaters demonstrated τ $\dot{V}O_2$ values that were similar during treadmill and slide board skating; (ii) the pattern of O_2 extraction (reflected by the dynamic adjustment of the [HHbMb]) and the matching of O_2 provision to O_2 utilization (represented by the [HHbMb]/$\dot{V}O_2$ ratio) during skating on treadmill and slide board were similar; (iii) The τ $\dot{V}O_2$ values were ~20 s, which is comparable to results from other sports modalities when trained athletes are tested [17,18].

In agreement with our hypothesis, the average time-constant of the $\dot{V}O_2$ kinetics found for the well-trained speed skating group (18.9 ± 3.6 on the treadmill and 18.1 ± 3.4 on the slide board) were similar to values obtained for endurance trained athletes in cycling and running[17,18]. These results suggest that, despite the previously reported leg blood flow restriction and increased O_2 muscle desaturation that occur during skating, even during moderate intensity, due to low skating position[5,6], the rate of adjustment of $\dot{V}O_2$ was not impaired. This might be surprising as adequate delivery of O_2 to the active muscles has been considered by some authors as a limiting factor for the kinetics of $\dot{V}O_2$[19]. Different explanations can be proposed for this fast adjustment of $\dot{V}O_2$. First, the large amount of training at a low skating position likely induces chronic peripheral and central adaptations that might help overcoming a possible interference in the dynamics of adjustment of leg blood flow, and thus a greater $\tau\ \dot{V}O_2$. For example, increased stroke volume[20], increased microvascular filtration capacity a greater number of capillaries per fiber[21] and intracellular adaptations associated to a higher sensitivity to changes in partial pressure of oxygen and oxygen metabolism activation[22] have been found as consequences of different blood flow restriction or ischemic training regimes. Additionally, blood flow restriction training has been associated to increased muscle glycogen content[23], higher percentage of type-I fibers and a lower percentage of IIb fibers and higher citrate synthase activity[24]. These specific adaptations to skating training regimens in conditions of partial blood flow occlusion would be expected to result in improved oxygen transport and utilization that are likely to speed the $\dot{V}O_2$ kinetics response at moderate intensities of exercise. A direct association between $\dot{V}O_2$ kinetics and muscle fiber properties has previously been reported[25], where in-vitro $\dot{V}O_2$ kinetics of single muscle fibers, obtained across fiber types, was strongly related to the oxidative capacity of the muscle fiber.

Despite some indications that blood flow to the legs might be compromised during skating at moderate intensity [5,6], chronic exposure to skating results in adaptation in oxygen delivery and utilization as described above. The relationship between O_2 extraction and O_2 utilization during the exercise on-transient (represented by the ([HHbMb]/$\dot{V}O_2$ ratio), allows to make inferences on the dynamic behavior of microvascular delivery of O_2 during the on-transient of exercise[2]. The [HHbMb]/$\dot{V}O_2$ ratio values during the exercise on-transient were 1.0 for both skating-treadmill and skating on a slide board (Figure 2). The indication of a well-matched O_2 delivery to a given O_2 utilization during the transition from lower to higher metabolic demands supports the idea that, for moderate intensities of skating exercise on a slide board and on a treadmill, blood flow provision to the muscle was not a limiting factor determining the speed of the $\dot{V}O_2$ response. In relation to this, a recent review proposed that when $\tau\ \dot{V}O_2$ is smaller than ~20 s, O_2 delivery to the active tissues is likely sufficient (i.e., not a rate limiting factor) and that intracellular mechanisms of control are presumably determining how fast the dynamic adjustment of $\dot{V}O_2$ is[2].

From a practical perspective, a fast $\dot{V}O_2$ kinetics is associated to less muscle fatigue, delayed anaerobic substrate depletion and enhanced tolerance to high-intensity exercise independent of the overall fitness levels or $\dot{V}O_{2max}$[3]. However, although having a faster $\dot{V}O_2$ kinetics may be connected to performance in different type of events, no study has previously investigated $\dot{V}O_2$ kinetics parameters on inline or ice speed skating. Only two studies[26,27] reported a very fast rate constant for the increase in $\dot{V}O_2$ of $0.153\ s^{-1}$ and $0.125\ s^{-1}$ during simulated skating competitions based on 1500 m time-trial. This value could be equated to a $\tau\ \dot{V}O_2$ value of 15.2 s from the start of the exercise[26]. However, proper analysis of $\dot{V}O_2$ kinetics parameters during skating is challenging due to difficulties to mimic the skating movement in a laboratory environment where all variables can be controlled. On the track, the main limitations are related to difficulties to control the skating intensities for the moderate intensities transitions[28,29], as well as the difficulties related to the relative long time needed for the athlete to reach a pace corresponding to the moderate skating intensity workload (i.e., a true square-wave rest to exercise transitions is not possible and thus the increase in metabolic demand, and thus $\dot{V}O_2$ is delayed). A delay in the rest to exercise transitions will increase the time constant of $\dot{V}O_2$ kinetics leading to underestimation of the real kinetic speed values.

To overcome such testing limitations, previous studies have used different methods to mimic skating movement to investigate physiological and biomechanical responses in laboratory[30,31,10,8]. Although a previous study has shown similar $\dot{V}O_2$ responses during a maximal incremental skating test on a treadmill and on a slide board, as well as very good agreement for $\dot{V}O_2$ and heart rate both at maximal intensity of performance and at different threshold intensities[10], this study was the first to characterize the dynamic adjustment of $\dot{V}O_2$ to two different skating modes, and shows a similar rate of adjustment of pulmonary $\dot{V}O_2$ and muscle O_2 extraction to a given increase in work rate between skating on a slide board and skating on a treadmill (Figure 1).

A limitation of this study is that the VL adipose tissue thickness was not considered. It is known that scattering coefficients and absorbance are affected by adipose tissue thickness, reducing absorbance by underlying muscle tissue[32]. Although it is possible that adipose tissue thickness may influence the absolute values for the [HHbMb] in this study, the dynamic changes in the response and normalized [HHbMb]/$\dot{V}O_2$ ratio, which were the main focus of the analysis, are independent of adipose tissue thickness. Also, asymmetries have previously been observed in oxygenation between the right and left leg of elite short-track speed-skaters[33]. Therefore, these aforementioned asymmetries between legs should also be considered in future studies with long-track speed skaters and NIRS. Nonetheless, $\dot{V}O_2$ and [HHbMb] responses observed in this study have to be considered within the boundaries of the responses predicted to occur when exercising in the moderate intensity domain. It should be acknowledged that limitations in leg blood flow might have a more significant impact in O_2 extraction when skating at higher intensities and at a lower skating position.

Practical Applications

The similar profiles in the $\dot{V}O_2$ and O_2 extraction kinetics and the good matching of O_2 delivery to O_2 utilization during both skating modalities tested in this study adds validity to the use of the slide board as a testing and training device. Thus, these data combined with those from a previous study[10], indicate that the slide board can be used as a practical and feasible alternative to evaluate a large group of athletes or for different research purposes that require a laboratory environment control.

Conclusions

In conclusion, this study demonstrated that the fast $\dot{V}O_2$ kinetics responses of well-trained speed skaters (~18 s) that were observed on the motorized treadmill were similar to those observed when skating on a slide board. This fast $\dot{V}O_2$ kinetics might be explained by training adaptations from skating at low posture, which have been shown to induce positive adaptations in oxygen delivery and utilization. This study further supports the use of a slide board as a training and testing tool that elicits similar cardiovascular response to those observed during skating on a motorized treadmill.

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Table 1. $\dot{V}O_2$ and [HHbMb] kinetics calculated parameters for moderated intensity skating transitions on treadmill and slide board. Values are presented as means ± SD.

	Treadmill	Slide board
$\dot{V}O_{2BL}$($L \cdot min^{-1}$)	1.14±0.18	1.27±0.23
$\dot{V}O_{2Ap}$ ($L \cdot min^{-1}$)	0.94±0.26	1.03±0.19
$\dot{V}O_{2TD}$ (s)	12.8±4.2	12.2±3.4
τ $\dot{V}O_2$ (s)	18.9±3.6	18.1±3.4
CIτ$\dot{V}O_2$ (s)	5.1±1.9	4.6±0.8
$[HHbMb]_{BL}$ (AU)	3.0±1.3	3.1±1.4
$[HHbMb]_{Ap}$ (AU)	1.2±0.4	1.7±0.9
$[HHbMb]_{TD}$ (s)	9.4±3.6	7.9±3.0
τ [HHbMb] (s)	12.4±4.0	12.6±4.0
CIτ[HHbMb] (s)	3.8±1.0	5.0±1.5 [a]
τ' [HHbMb] (s)	21.7±5.3	20.5±4.5

$\dot{V}O_{2BL}$, baseline $\dot{V}O_2$; $\dot{V}O_{2Ap}$, $\dot{V}O_2$ amplitude; τ $\dot{V}O_2$, $\dot{V}O_2$ time constant; $\dot{V}O_{2TD}$, $\dot{V}O_2$ time delay; CIτ $\dot{V}O_2$, $\dot{V}O_2$confidence interval; $[HHbMb]_B$, HHb baseline; $[HHbMb]_{Ap}$, HHb amplitude; $[HHbMb]_{TD}$, HHb time delay; τ[HHbMb], HHb time constant; CIτ[HHbMb], HHb confidence interval. a, different from treadmill.

Figure 1. Group mean $\dot{V}O_2$ and [HHbMb] responses to moderate-intensity (80% GET) exercise during treadmill (panels A and C) and slide board (panels B and D) skating. Signal at the bottom of each graph represents residual of three transitions.

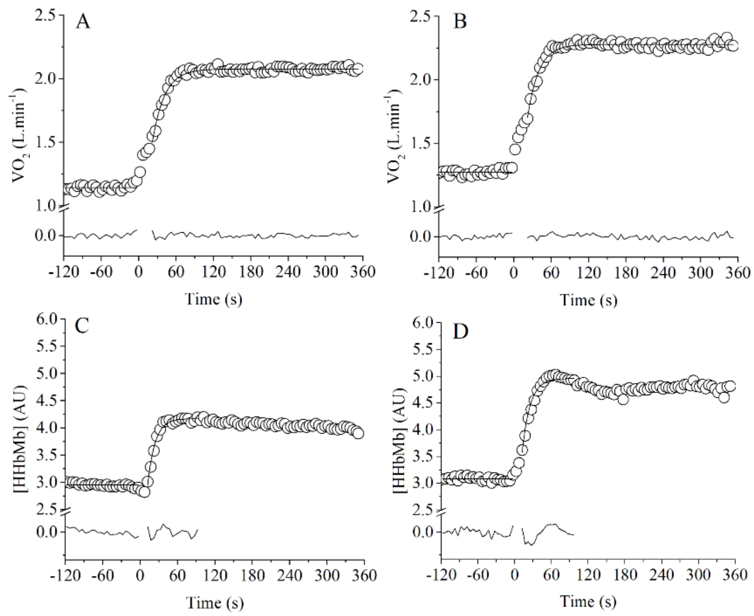

Figure 2. Group mean profiles for the adjustment of [HHbMb] (squares) and $\dot{V}O_2$ (triangles) during the step transition to moderate intensity (5-s averaged data) normalized from the baseline (0%) to steady state (100%) of the amplitude in the signal on a treadmill (panel A) and on a slide board (panel C), and [HHbMb]/$\dot{V}O_2$ group mean profiles for skating transitions on treadmill (panel B) and on slide board (panel D). Dashed horizontal line indicates [HHbMb]/$\dot{V}O_2$ = 1.0.