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ORIGINAL ARTICLE

Effects of inspiratory muscle warm-up on locomotor muscle oxygenation in elite speed skaters during 3000 m time trials

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Abstract

Purpose It has been shown that an inspiratory muscle warm-up (IMW) could enhance performance. IMW may also improve the near-infrared spectroscopy (NIRS)-derived tissue oxygen saturation index (TSI) during cycling. However, there exists contradictory data about the effect of this conditioning strategy on performance and muscle oxygenation. We examined the effect of IMW on speed skating performance and studied the underpinning physiological mechanisms related to muscle oxygenation.

Methods In a crossover, randomized, single-blind study, eight elite speed skaters performed 3000 m on-ice time trials, preceded by either IMW (2 × 30 breaths, 40% maximal inspiratory pressure) or SHAM (2 × 30 breaths, 15% maximal inspiratory pressure). Changes in TSI, oxyhemoglobin–oxymyoglobin ([O_2HbMb]), deoxyhemoglobin–deoxymyoglobin ([HHbMb]), total hemoglobin–myoglobin ([THbMb]) and HHbMbdiff ([O_2HbMb]–[HHbMb]) in the right vastus lateralis muscle were monitored by NIRS. All variables were compared at different time points of the race simulation with repeated-measures analysis of variance. Differences between IMW and SHAM were also analyzed using Cohen's effect size (ES) ± 90% confidence limits, and magnitude-based inferences.

Results Compared with SHAM, IMW had no clear impact on skating time (IMW 262.88 ± 17.62 s vs. SHAM 264.05 ± 21.12 s, effect size (ES) 0.05; 90% confidence limits, − 0.22, 0.32, $p = 0.7366$), TSI, HbMbdiff, [THbMb], [O_2HbMb] and perceptual responses.

Conclusions IMW did not modify skating time during a 3000 m time trial in speed skaters, in the conditions of our study. The unchanged [THbMb] and TSI demonstrate that the mechanisms by which IMW could possibly exert an effect on performance were unaffected by this intervention.

Keywords Elite athletes · Long-track speed skating · Muscle deoxygenation · Blood volume · Metaboreflex

Abbreviations

ES	Effect size
HbMbdiff	Difference between O_2HbMb and HHbMb
HHbMb	Deoxyhemoglobin + deoxymyoglobin
IM	Inspiratory muscle
IMT	Inspiratory muscle training
IMW	Inspiratory muscle warm-up
MIP	Inspiratory muscle pressure
NIRS	Near-infrared spectroscopy
O_2HbMb	Oxyhemoglobin + oxymyoglobin
RPB	Rating of perceived breathlessness
RPE	Rating of perceived exertion
SD	Standard deviation
SHAM	Placebo intervention
THbMb	Total hemoglobin + total myoglobin
TSI	Tissue saturation index
$\dot{V}O_{2max}$	Maximal oxygen consumption

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Introduction

An inspiratory muscle warm-up (IMW) was found to enhance performance in continuous exercises lasting between 30 s and 6 min (Volianitis et al. 2001a; Cruickshank et al. 2007; Wilson et al. 2014; Özdal et al. 2016) as well as in intermittent exercise tests (Tong and Fu 2006; Lin et al. 2007; Lomax et al. 2011). However, other research groups did not observe any ergogenic effect of this procedure on the same type of activities and thus, its impact on exercise performance remains equivocal (Cheng et al. 2013; Johnson et al. 2014; Ohya et al. 2015; Arend et al. 2016; Hartz et al. 2017; Faghy and Brown 2017). Moreover, the impact on performance of the addition of IMW to the thorough warm-up of elite athletes also remains uncertain (Volianitis et al. 2001a; Johnson et al. 2014).

From a physiological perspective, IMW was shown to improve IM function (maximal inspiratory pressure) (Tong and Fu 2006; Lin et al. 2007; Lomax et al. 2011), reduce perception of breathlessness (RPB) (Volianitis et al. 2001a; Tong and Fu 2006; Lin et al. 2007), and to lower lactate concentration during exercise (Lin et al. 2007). IMW also significantly improved the near-infrared spectroscopy (NIRS)-derived tissue oxygen saturation during high-intensity (maximal effort) intermittent cycling exercises in elite female athletes (Cheng et al. 2013). However, the impact of IMW on muscle oxygenation remains equivocal considering that Ohya et al. (2015) did not observe any changes in muscle oxygenation after IMW during the same type of exercise. Moreover, the impact of IMW on muscle hemodynamics has only been investigated in cycling and was never examined during a continuous time trial effort.

Speed skating and cycling share similar characteristics such as the primary active muscles, a cyclic movement, and a specific crouched position (pronounced knee flexion and trunk almost parallel to the ground) (Stoter et al. 2016) that may lead to a similar ventilatory demand during maximal-intensity exercise (Van Ingen Schenau et al. 1983; Foster et al. 1999). The crouched position of cycling may raise abdominal impedance and increase diaphragmatic work, thereby leading to premature recruitment of rib cage muscles and accelerating inspiratory muscle fatigue (Boussana et al. 2001). High-intensity exercises [$\geq$ 85% of maximal oxygen consumption ($\dot{V}O_{2max}$)] are also expected to lead to this type of fatigue (Harms et al. 1997; Legrand et al. 2007). Consequently, inspiratory muscle fatigue might increase sympathetic vasoconstrictor outflow to working skeletal muscles through a respiratory muscle metaboreflex, thus reducing limbs' blood flow and accelerating the development of exercise-induced locomotor muscle fatigue (Harms et al. 1997; Legrand et al. 2007; Romer and Polkey 2008). Oueslati et al. (2016) observed that superior respiratory muscle endurance was significantly correlated with a longer delay before an accentuated deoxygenation occurred in the leg. Hence, it is plausible that IMW could improve respiratory muscle fatigue tolerance and locomotor muscles oxygenation during speed skating, thereby potentially affecting performance positively.

Therefore, the primary purpose of this study was to assess whether integrating IMW to the standard warm-up procedures of speed skaters could modify their performance during a maximal speed skating time trial. To examine the underpinning physiological mechanisms associated with this technique and considering the aforementioned discrepancies in the only two available IMW–NIRS studies, the secondary purpose of this study was to examine the effect of IMW on local blood volume and muscle oxygenation.

Materials and methods

Participants

Eight elite long-track speed skaters (5 men: $\dot{V}O_{2max}$ 61 ± 6.3 mL/min/kg, 3 women: $\dot{V}O_{2max}$ 51 ± 3.8 mL/min/kg, $n = 2$) with at least one international competition experience (junior or senior) were included in this study (mean ± SD age 21.4 ± 3.5 years, body height 177.4 ± 8.4 cm, body mass 75.4 ± 11.2 kg, experience in speed skating 16 ± 4 years, average weekly training volume ≈ 14–16 h). The investigation took place during the first on-ice training camp of the season and the timed performances do not reflect the best potential results of these athletes. All participants were informed of the experimental procedures, associated risks, and potential benefits. Informed consent was obtained from all the individual participants included in the study. The study was approved by the local Institutional Ethics Committee (*Comité d'éthique de la Recherche avec des êtres humains de l'Université Laval*) and by the local Hospital Ethics Committee (*Comité d'éthique de la Recherche de l'IUCPQ-Université Laval*), and in accordance with the principles established in the declaration of Helsinki.

Experimental design

All athletes were tested on two occasions in a randomized, single-blind, placebo-controlled, crossover design. Participants were blinded to the true purpose of the study by a misled message that they were participating in a study to compare the effects of a power-type (IMW: described to the athletes as IMW_{power}) and an endurance-type (SHAM: described to the athletes as $IMW_{endurance}$) protocol on performance and local oxygenation during speed skating (Cheng et al. 2013) which was as follows: "the aim of the study was to determine the best suitable intervention individually for each of them". They participated in a maximal inspiratory muscle pressure (MIP) testing session and were fully familiarized with IMW and SHAM procedures before the first time trial.

MIP was recorded using the integrated mouth pressure meter of the ENCORE VMax system (Carefusion, Sydney, Australia) at the local hospital. The testing session was performed by an experienced operator and in conformity to the standardized procedures (Gibson et al. 2002). A minimum of five and a maximum of nine technically satisfactory measurements were conducted, and the highest of three measurements with 5% variability or within 5 cmH_2O difference was defined as maximum (Volianitis et al. 2001a).

Inspiratory muscle warm-up

The protocol consisted of 2 sets of 30 breaths using a POWERbreath (IMT Technologies Ltd., Birmingham, United Kingdom) at 40% and 15% MIP in IMW and SHAM, respectively, with a 60 s rest between the sets (Lomax et al. 2011). During IMW, the subjects were instructed to initiate every breath from the residual volume and to continue the respiratory effort until further excursion of the thorax was not possible. During SHAM, breathing was gentle and protracted (Ohya et al. 2015). Both interventions were conducted after the athlete's off-ice warm-up (≈ 17 min before trials). This time frame mimics a realistic competition schedule allowing athletes sufficient time to prepare according to usual habits.

Warm-up

To promote a realistic context, the whole body warm-up protocol was not standardized and the athletes were asked to reproduce their regular individual competition warm-up routines. However, the athletes' awareness was raised (a warm-up checklist was provided and explained) on the fact that priming exercises can influence performance and peripheral oxygenation (Jones et al. 2006; Bailey et al. 2009; McIntyre and Kilding 2015) and thereby, possibly interact with the expected effects of the studied interventions. Precisely, it was strongly suggested that they perform intensity bouts in their warm-ups 20–40 min before their race (Burnley et al. 2006; Bailey et al. 2009; Ingham et al. 2013). Post-testing, all athletes reported having completed their specific competition warm-up routine that included intensity bouts (≈ 30 min before the race) and having reproduced the same preparation in both conditions (Table 1).

Time trials

The trials involved two on-ice 3000 m time trials on an indoor long-track (400 m) speed skating oval approved for international competition. This race was selected because similar ventilation was reported in speed skating compared to cycling on efforts of similar duration (Van Ingen Schenau et al. 1983; Foster et al. 1999), because the time to cover this distance (4–5 min) is enough to speed up aerobic energy delivery (Van Ingen Schenau et al. 1983) and because 2000–3000 m maximal time trials were previously used as specific $\dot{V}O_{2max}$ speed skating tests (Van Ingen Schenau et al. 1983; Kandou et al. 1987; de Boer et al. 1987).

Trials (7 days apart) took place during a national centre training camp in which the training prescription was similar 48 h before trials. For ice availability reasons, the first trial was performed at ≈ 12h30 and the other at ≈ 17h30. Athletes were asked to replicate the same routine before both trials. Barometric pressure was similar in both testing days (88.69 vs. 89.01 kPa). All athletes started in the inner lane for both conditions (solo time trials) and were asked to complete the 3000 m in the fastest time possible by applying their individual pacing strategy. During the time trials, all lap times were recorded using a timing system approved for international competition and verbal feedback was given by the coach to ensure competition-like conditions (Born et al. 2014). Immediately after the time trials, rating of perceived exertion (RPE) and rating of perceived breathlessness (RPB) were measured using CR-10 Borg's scale.

Table 1 Individual warm-up routine characterization including priming exercises and recovery time before the race for all speed skaters

Athlete	*Low intensity exercises*	*Mobility drills and progressive dynamic exercises*	*Off-ice priming exercises*	*Time between priming exercises and race*	*On-ice warm-up (position and pace)*
1			1.5 min (5-6/10)		
2			2 min (7/10)		
3			2 min (7/10)		
4			1 min (6/10)		
5	≈ 5-10 min	≈ 5-10 min	2.5 min (7/10) + 45 s (8/10)	≈ 30 min	≈ 5 min
6			2 min (7/10) + 1 min (8/10)		
7			50 s (8.5/10)		
8			4 min (7/10)		

NIRS measurements

Oxygenation patterns in the right vastus lateralis muscle were determined with a portable NIRS device (Portamon MkII, Artinis Medical System, Zetten, The Netherlands). Bilateral oxygenation measurements would have provided a more complete dataset considering the asymmetric oxygenation patterns reported in speed skating (Born et al. 2014; Hettinga et al. 2016). However, only one Portamon device was available for this project. The right leg was particularly investigated as long-track speed skaters display a greater deoxygenation in the right leg compared to the left leg (Born et al. 2014; Hettinga et al. 2016).

The NIRS device was installed on the distal part of the vastus lateralis belly (15 cm above the proximal border of the patella). Skin fold thickness was measured at the site of application of the device (8.7 ± 3.3 mm) using a Harpenden skinfold caliper and was less than half the distance between the emitter and the detector (i.e., 20 mm). This thickness is adequate to let near-infrared light through muscle tissue (McCully and Hamaoka 2000). The device was solidly fixed and covered to eliminate background light.

A modified form of the Beer–Lambert law, using two continuous wavelengths (760 and 850 nm) and a differential optical path length factor of 4.95 allowed the detection of micromolar changes in tissue oxyhemoglobin + oxymyoglobin [O_2HbMb] and deoxyhemoglobin + deoxymyoglobin [HHbMb]. The sum of both signals [THbMb] was used as an indicator of the blood volume (Van Beekvelt et al. 2001). The equilibrium between oxygen supply and consumption was calculated using the tissue saturation index (TSI [%]) (Jones et al. 2016). The difference between [O_2HbMb] and [HHbMb] (HbMbdiff = [O_2HbMb] − [HHbMb]) was also interpreted as a muscle oxygenation index (Van Beekvelt et al. 2001; Cunniffe et al. 2017).

Data were acquired continuously at 10 Hz. A 10th order zero-lag low-pass Butterworth filter was applied to smooth NIRS signal (Faiss et al. 2013). Data were analyzed over the first, third and last minute of the time trials as previously described (Born et al. 2014) and normalized to express the magnitude of changes from baseline. The last 30 s and the last 15 s of the time trials were also analyzed because the effort is at the maximum at this moment and thus, the likeliness of respiratory muscle fatigue is increased.

Statistical analyses

All variables were compared at the different time points of the race simulation with repeated-measures analysis of variance. If global changes over time were identified, Bonferroni post hoc analysis was employed to detect where the differences occurred. Ratings of perceived exertion were compared with a Student's paired *t* test. Statistical significance was set at an alpha value of $p < 0.05$. IMW–SHAM differences were also analyzed using Cohen's effect size (ES) ± 90% confidence limits, and magnitude-based inferences (Hopkins et al. 2009). Variables were log-transformed before analysis, but raw data are reported as means or peaks ± SD for clarity. Magnitudes of difference between conditions were determined with an effect size of 0.2 set to evaluate the smallest worthwhile change. Standardized effects were classified as small (> 0.2–0.5) or moderate (> 0.5–0.8). Quantitative chances of greater or smaller values were assessed qualitatively as follows: 50–75%, possibly; 75–95%, likely; 95–99%, very likely; > 99%, almost certainly. The effect was deemed "unclear" if chances of having better/greater and poorer/lower change in performance and physiological variables were both > 5%.

Given that trained individuals present an attenuated inspiratory muscle metaboreflex (Callegaro et al. 2011) and that respiratory muscle work is inversely correlated with the blood flow in the working leg during maximal exercise (Harms et al. 1997), in a post-analysis, we further hypothesized that the impact of IMW on peripheral blood volume could be accentuated in athletes with lower MIP values. Therefore, Pearson's correlations were used to determine the relationship between the athletes' baseline MIP and the percent change in [THbMb] after IMW. The following criteria were adopted to interpret the magnitude of the correlation (r): ≤ 0.1 trivial, > 0.1–0.3 small, > 0.3–0.5 moderate, > 0.5–0.7 large, > 0.7–0.9 very large, and > 0.9–1.0 almost perfect (Hopkins et al. 2009) and statistical significance was also identified by an alpha value of $p < 0.05$.

Results

Total racing time (IMW 262.88 ± 17.62 s vs. SHAM 264.05 ± 21.12 s, difference between IMW and SHAM, 0.04%, effect size (ES) 0.05; 90% confidence limits − 0.22, 0.32, $p = 0.7366$), RPE (9.56 ± 0.62 vs. 9.44 ± 1.05: − 1.7%, ES − 0.23; − 1.13, 0.67, $p = 0.6383$) and RPB (7.69 ± 1.03 vs. 7.63 ± 2.13: − 4.9%, ES − 0.33; − 1.98, 1.32, $p = 0.7173$) were unaffected by the intervention.

Tissue oxygenation indexes (TSI and HbMbdiff) were not significantly modified by IMW throughout the race. Similarly, [THbMb], a surrogate of blood volume, and [O_2HbMb] were also not significantly altered by IMW for all studied sections of the race.

[HHbMb] was possibly higher in the third (3%, ES 0.31; − 0.18, 0.81) and the last (2.9%, ES 0.3; − 0.19, 0.80) minutes of the time trial in IMW compared with SHAM, but these changes did not reach statistical significance ($p = 0.2682$ and $p = 0.2862$, respectively).

The detailed results are presented in Table 2. Figure 1 illustrates the pacing (lap times) in both conditions. Figure 2

Table 2 Physiological variables and performance during time trials

Variable	Time point	Intervention				*d*	Likelihood of chances		*p* value
		SHAM	SD	IMW	SD		CL	+ive/trivial/−ive	
Tissue Saturation Index (TSI%)/baseline (% baseline)	First minute	73.1	10	73.1	7	0.02	−0.39; 0.43	22/62/17	0.9268
	Third minute	72.3	9.8	73.1	7	0.08	−0.28; 0.45	28/63/9	0.6740
	Last minute	71.3	9.4	72.5	8.9	0.11	−0.28; 0.49	33/59/9	0.6094
	Last 30 s	71.2	9.5	72.3	9	0.10	−0.30; 0.51	33/58/10	0.6421
	Last 15 s	71.1	9.5	72.3	8.8	0.11	−0.29; 0.52	34/56/9	0.6054
Oxyhemoglobin (O_2HbMb)/baseline (% baseline)	First minute	77.1	9.7	77.1	7.5	0.01	−0.32; 0.34	16/71/13	0.9398
	Third minute	79.3	7.9	79.4	6.6	0.02	−0.32; 0.36	17/70/13	0.9151
	Last minute	78.9	8	78.8	6.9	0.01	−0.33; 0.34	16/70/14	0.9777
	Last 30 s	78.8	8.1	78.7	7.1	0.00	−0.35; 0.35	16/68/16	0.9927
	Last 15 s	78.7	8.1	78.6	7.1	0.00	−0.36; 0.35	16/68/16	0.9935
Deoxyhemoglobin (HHbMb)/baseline (% baseline)	First minute	125.5	10	129.9	14.8	0.33	−0.24; 0.91	66/27/6	0.3065
	Third minute	132	15.2	136.2	18.6	**0.31**	−0.18; 0.81	**66**/29/4	0.2682
	Last minute	134	15.8	138.2	18.7	**0.3**	−0.19; 0.80	**65**/31/5	0.2862
	Last 30 s	134.5	15.9	138.5	18.9	**0.29**	−0.20; 0.79	**65**/32/5	0.3020
	Last 15 s	134.7	16.1	138.7	19.1	**0.29**	−0.20; 0.78	**65**/32/5	0.3023
HbMbdiff (HHbMb − O_2HbMb) (change from baseline μM)	First minute	−21.97	13.03	−23.30	12.85	0.10	−0.05; 0.26	14/86/0	0.2549
	Third minute	−23.37	13.94	−24.45	13.72	0.09	−0.07; 0.26	13/87/1	0.3062
	Last minute	−24.18	13.93	−25.27	13.95	0.09	−0.06; 0.23	9/90/0	0.3013
	Last 30 s	−24.37	13.98	−25.45	14.09	0.08	−0.06; 0.23	9/91/0	0.3194
	Last 15 s	−24.45	13.99	−25.5	14.1	0.08	−0.06; 0.23	9/91/0	0.3212
Total hemoglobin (THbMb)/baseline (% baseline)	First minute	97.9	5.6	99.1	7	0.19	−0.35; 0.73	48/41/11	0.5336
	Third minute	101.9	7	103.2	8.9	0.18	−0.25; 0.61	46/47/7	0.4628
	Last minute	102.5	8.2	103.6	9.4	0.15	−0.30; 0.61	43/48/9	0.5431
	Last 30 s	102.7	8.3	103.7	9.5	0.14	−0.32; 0.61	41/49/10	0.5575
	Last 15 s	102.8	8.5	103.7	9.7	0.14	−0.33; 0.61	40/49/11	0.5965
3000 m time trial time (s)	Total	262.88	17.62	264.05	21.12	0.05	−0.22; 0.32	16/78/6	0.7366
Rate of perceived exertion (RPE) (Borg CR-10)	Post	9.56	0.62	9.44	1.05	−0.23	−1.13; 0.67	20/28/53	0.6383
Rate of perceived breathlessness (RPB) (Borg CR-10)	Post	7.69	1.03	7.63	2.13	−0.33	−1.98; 1.32	28/16/56	0.7173

Bold values indicate the combination of a small or greater effect size and a clear effect size as defined in the statistical section of the manuscript

illustrates the NIRS-derived oxygenation patterns during the races.

MIP baseline values of the skaters were 144 ± 45 cmH_2O. No significant correlation was found between the percent change in [THbMb] and MIP values for the first (r = 0.37, p = 0.37), third (r = 0.47, p = 0.24), and last minutes (r = 0.49, p = 0.21) as well as for the complete 3000 m time trial (r = 0.45, p = 0.26).

Discussion

This study examined, for the first time, the effect of IMW on performance and muscle oxygenation in speed skating. This technique did not modify skating time during a 3000 m time trial in elite speed skaters, in the conditions of our study. This field-specific speed skating investigation that took place during the first on-ice training camp of the season revealed no acute ergogenic effect of IMW on perceptions of effort and breathlessness, and very limited changes were observed in muscle oxygenation.

The unchanged performance in elite athletes observed in the present investigation contrasts with the results of several IMW exercise studies (Volianitis et al. 2001a; Tong and Fu 2006; Cruickshank et al. 2007; Lin et al. 2007; Lomax et al. 2011; Wilson et al. 2014; Özdal et al. 2016). Interestingly, among these studies, Volianitis et al. (2001a) was the only research group to examine the effect of IMW on a continuous effort of similar duration to that of our study (6 min) and to investigate elite athletes who completed a thorough warm-up. They reported decrease in dyspnea and in inspiratory muscle fatigue as the probable responsible mechanisms

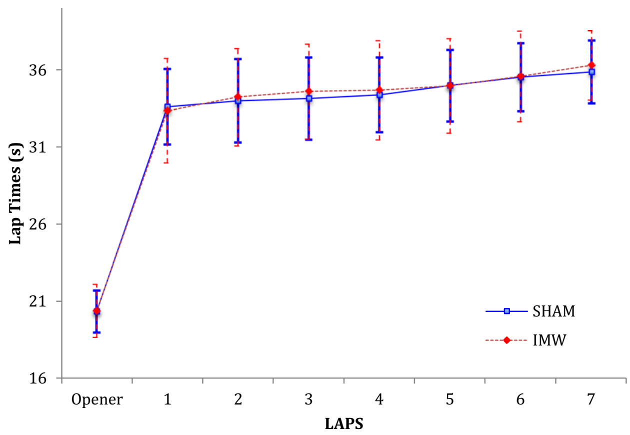

Fig. 1 Lap times during the 3000 m speed skating time trials. Full line (SHAM) and dashed line (IMW). Data are presented as mean ± SD

for the performance improvement after IMW in a population of elite rowers. Respiratory sensations represent one subcategory of the overall perceived exertion that is responsible for exercise intolerance (Weiser et al. 1973; Volianitis et al. 2001a) and at maximal exercise capacity, dyspnea can be at least as important as leg fatigue in limiting exercise (Killian et al. 1992; Volianitis et al. 2001a). While we did not measure inspiratory muscle fatigue, we observed no changes in perceived breathlessness and perceived exertion in our study. These unaffected perceptual sensations may contribute to explaining the absence of changes in skating time. Similarly, both dyspnea and performance were unaffected by the addition of IMW to a thorough warm-up in competitive road cyclists performing a 10 km cycling time trial (Johnson et al. 2014). In that perspective, not only our results are in accordance with the previously observed absence of ergogenic impact of IMW on exercise performance (Cheng et al. 2013; Johnson et al. 2014; Ohya et al. 2015; Arend et al. 2016; Hartz et al. 2017; Faghy and Brown 2017), but also reinforce the argument against the relevance to add IMW to a complete warm-up protocol in elite athletes (Johnson et al. 2014).

Respiratory muscle fatigue results from increased respiratory muscle work combined with a competition for blood flow with locomotor muscles (Romer and Polkey 2008). When respiratory muscle work is increased (above respiratory compensation point) during high-intensity exercise (≥ 85–100% $\dot{V}O_{2max}$), leg blood volume and oxygenation are reported to decrease (Harms et al. 1997; Legrand et al. 2007). In this context, if any, one could expect an impact of IMW on locomotor muscles perfusion and tissue saturation indexes (that are influenced by blood flow) in a 3000 m speed skating time trial that seems to cloister several

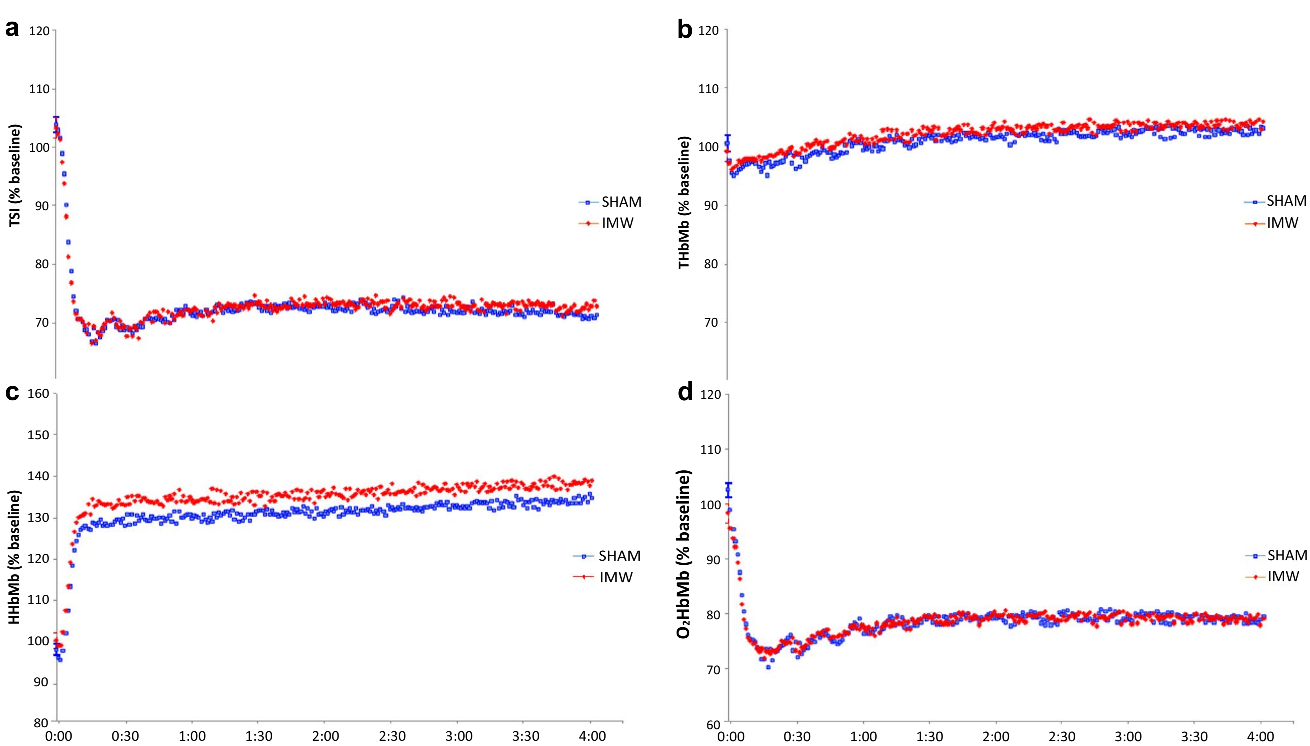

Fig. 2 Oxygenation patterns: TSI (**a**), [THbMb] (**b**), [HHbMb] (**c**) and [O_2HbMb] (**d**) for the 3000 m time trials in SHAM (blue) and IMW (red) conditions. (Color figure online)

characteristics that could lead to inspiratory muscle fatigue (high ventilation rates, high intensity, exercise of a sufficient duration) (Van Ingen Schenau et al. 1983; Foster et al. 1999; Stoter et al. 2016). However, the NIRS-derived data rather suggest that the mechanisms by which IMW could possibly exert an effect on performance were not affected in the present study.

First, ventilation may not explain this absence of ergogenic impact of IMW considering that our results (unchanged [THbMb] and TSI) contrast with the improved tissue saturation index (TSI) observed after IMW during a submaximal cycling exercise (150 W) in which ventilation was notably lower (≈ 61 L/min) (Cheng et al. 2013) than the ventilation reported elsewhere in a 3000 m time trial in elite skaters (137.6 ± 5.8 L/min) (Van Ingen Schenau et al. 1983). Second, greater exercise intensities (> 85% $\dot{V}O_{2max}$) increase the likelihood for diaphragmatic fatigue to develop (Johnson et al. 1993; Illi et al. 2012). Given that 2000–3000 m maximal time trials were previously used as specific $\dot{V}O_{2max}$ (100%) speed skating tests (Van Ingen Schenau et al. 1983; Kandou et al. 1987; de Boer et al. 1987), it is likely that the intensity of the 3000 m skating time trial was sufficient to induce respiratory muscle fatigue. Third, the duration of the effort may also impact inspiratory muscle fatigue. In fact, in trained male cyclists ($\dot{V}O_{2max}$: 4.6 L/min), maximal incremental exercise performance (≈ 355–380 W max) remained unchanged in both an inspiratory muscle training (IMT) group and a placebo group, while the former group completed a 20 km (≈ 83–85% W max, ≈ 29 min) and a 40 km (≈ 77–78% W max, ≈ 57 min) time trial faster than the latter after the intervention (≈ 3.8 and 4.6%, respectively) (Romer et al. 2002).

Interestingly, TSI was modified by IMW (compared to control and placebo) in the last two tests of a sequence of three tests (total effort duration = 18 min) that were all interspersed by 5 min of passive rest: two 6 min submaximal tests (100 and 150 W) and an intermittent sprint tests (6 × 10 s interspersed by 60 s of active recovery at 50 W for a total of ≈ 6 min) (Cheng et al. 2013). Given that the TSI modification was only observed in the last two tests of this sequence (after at least 6 min of effort), one can argue that the total duration of the protocol could have played a role in inducing respiratory muscle fatigue (Romer et al. 2002). In that perspective, we cannot rule out that the ≈ 4.4 min speed skating effort was not long enough to induce respiratory muscle fatigue in our study. However, this seems extremely unlikely considering that the thorough individual warm-up that was performed before the speed skating time trials (Table 1) was longer (and probably more intense) than the combination of the first test (100 W, 6 min) and the warm-up that was performed prior to testing in the study of Cheng et al. (2013) (4 min of submaximal cycling at 50 W, 3 × 5 s unloaded sprints and 5 min of stretching exercises). Moreover, the current time trial lasting 4–5 min may have been sufficient to induce respiratory muscle fatigue, considering that performance was improved after IMT during a 6 min exercise in trained rowers (Volianitis et al. 2001b) and given that IMW also led to performance improvement in shorter duration performance tests (≈ 57 s and 30 s) (Wilson et al. 2014; Özdal et al. 2016). Another possibility is that the attenuation of the inspiratory muscle fatigue may not be the only mechanism responsible for the ergogenic impact of IMW (Johnson et al. 2014).

Alternatively, the peculiar nature of speed skating may contribute to explaining our results. In fact, [THbMb] and TSI were unaffected by leg compression garments during a 3000 m time trial in speed skaters (Born et al. 2014), and the authors highlighted that the effects of compression clothing on the muscle pump's function might not overcome the high static muscle contractions evident in elite speed skating. Similarly, in our study, it can be hypothesized that, if any, the potentially beneficial effects of vasodilation (or avoided vasoconstriction) on blood flow secondary to IMW might have been impeded by the sport specific occlusions resulting from high intramuscular pressure (Sjogaard et al. 1988).

Finally, the MIP baseline values of the skaters in our study are characterized by a strong heterogeneity and are comparable to those observed in competitive road cyclists (148 ± 32 cmH_2O) (Johnson et al. 2014) in some cases, and to those of sedentary individuals (111 ± 8 cmH_2O) (Callegaro et al. 2011) in other cases. Therefore, we reasoned that the impact of IMW on peripheral blood volume could be accentuated in athletes with lower MIP values. However, no significant correlation was found for the first, third and last minutes as well as for the complete 3000 m time trial, thereby invalidating our assumption. In that perspective, it would be relevant to investigate muscle oxygenation during speed skating and to conduct this type of analysis, after a more impactful respiratory conditioning strategy such as IMT (Lomax et al. 2011), to delineate if the amplitude of the IMW effect was too limited to modify perfusion in the present study. Similarly, the intensity of the IMW (Kivastik et al. 2015) may also have influenced performance and physiological outcomes and future investigation will need to address these questions.

Limitations

Considering the limited number of subjects, we have to consider the possibility of a type II statistical error in the present study. Although elite athletes are scarcely investigated and effect sizes were calculated to assess the practical application and meaningfulness of the findings, the sample size is very limited to test the hypothesis and find results, if any. The current investigation took place during a training

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camp. While very similar training conditions preceded both testing days, this context may also implicate varied fatigue levels among athletes (19 training sessions in 14 days with 5 intense training sessions including the trials). The two trials did not take place at the same time of the day because of limited availability of the 400 m iced oval and this may have impacted the physiological outcomes (Drust et al. 2005), although athletes replicated a very similar pre-trial routine in both conditions. Moreover, although athletes are used to skating 3000 m as a practice racing distance at this time of the year, since our investigation took place during the first long-track speed skating training camp of the season, changes in pacing related to technical and tactical adjustments may have confounded the impact of IMW, especially in sprint-specialized athletes (competing in distances ≤ 1000 m) (Ahmetov et al. 2011). In fact, the pacing strategy adopted by the sprinters (as the difference between the average time of the first and the last lap of each race) varied in a particularly important manner (11.3% difference) and this could have altered the performance and oxygenation data sets. Although we used a crossover design and pacing strategy was similar in both conditions for the whole group of athletes (Fig. 1), the sprinters' inconsistent pacing behavior could contribute to explaining the IMW-induced possible increase in [HHbMb] in the third and last minutes of the race. However, these changes were also noticeable throughout the trial (Fig. 2c) and may not be attributable to IMW. In fact, NIRS may implicate a large inter- and intra-subject variability and it can be hazardous to assess what proportion of the muscle oxygenation variations obtained at a single site of a single muscle is derived from the NIRS measurement itself (methodological limitation) or from physiological origins (Thiel et al. 2011). Financial and logistic concerns were the main reasons behind the choice to focus mainly on the NIRS data in this study. A more elaborate set of measurements including oxygen consumption and ventilation, variables that may have been impacted by the IMW intervention, would have added value to the present study. For the same reasons, MIP could not be tested after the two conditions. This measurement would have validated the effect of IMW on inspiratory muscle strength in speed skaters.

Perspective and conclusions

The comparison of accessory respiratory and leg muscles oxygenation during speed skating (with and without IMW) would be of great interest, but technical restraints, such as the movement of the arms of the skaters during a simulated race (especially during corners), may prevail. The study of this relationship during in-line speed skating, on an oversized treadmill may be an interesting investigation avenue. It is plausible that the stress of an acute IMW may be limited to lead to significant locomotor muscle oxygenation changes, in performance-specific tasks performed by elite athletes. A certain level of permeability was previously observed in elite speed skaters in regard to techniques that have the potential to modify performance and muscle oxygenation [remote ischemic preconditioning (Richard and Billaut 2018), beetroot juice (Richard et al. 2018), compression garments (Born et al. 2014)]. Considering these results, and, since elite athletes present a narrower window of adaptation compared to less-trained individuals (Marocolo et al. 2016) and tend to combine different methods to enhance their performances (Kilduff et al. 2013; McGowan et al. 2015), the aggregation of such techniques could be necessary to trigger an ergogenic response and to enhance performance in this population. This hypothesis remains to be tested. Moreover, further investigations will need to examine specifically the individual effect of IMT and the combined effect of IMT and IMW (Lomax et al. 2011) on peripheral oxygenation in elite speed skaters.

In conclusion, this investigation was the first to assess the effect of IMW on muscle hemodynamics during a continuous time trial. This acute strategy had a very limited impact on timed performance and muscle oxygenation during 3000 m in elite speed skaters, in the context of our study. The unchanged [THbMb] and tissue saturation indexes demonstrate that the mechanisms by which IMW could possibly exert an effect on performance were unaffected by this intervention.

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Compliance with ethical standards

Conflict of interest The student researcher was employed (strength and conditioning coach) by the group involved in this study. The authors declare that the research was conducted in the absence of any commercial relationships that could be construed as a potential conflict of interest. On behalf of all the authors, the corresponding author states that there is no financial or non-financial conflict of interest associated with the current research.

Ethical approval All procedures performed involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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