Asymmetry of Quadriceps Muscle Oxygenation during Elite Short-Track Speed Skating

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ABSTRACT

HESFORD, C. M., S. J. LAING, M. CARDINALE, and C. E. COOPER. Asymmetry of Quadriceps Muscle Oxygenation during Elite Short-Track Speed Skating. Med. Sci. Sports Exerc., Vol. 44, No. 3, pp. 501–508, 2012. Purpose: It has been suggested that, because of the low sitting position in short-track speed skating, muscle blood flow is restricted, leading to decreases in tissue oxygenation. Therefore, wearable wireless-enabled near-infrared spectroscopy (NIRS) technology was used to monitor changes in quadriceps muscle blood volume and oxygenation during a 500-m race simulation in short-track speed skaters. Methods: Six elite skaters, all of Olympic standard (age = 23 ± 1.8 yr, height = 1.8 ± 0.1 m, mass = 80.1 ± 5.7 kg, mid-high skinfold thickness = 7 ± 2 mm), were studied. Subjects completed a 500-m race simulation time trial (TT). Whole-body oxygen consumption was simultaneously measured with muscle oxygenation in right and left vastus lateralis as measured by NIRS. Results: Mean time for race completion was 44.8 ± 0.4 s. VO2 peaked 20 s into the race. In contrast, muscle tissue oxygen saturation (TSI%) decreased and plateaued after 8 s. Linear regression analysis showed that right leg TSI% remained constant throughout the rest of the TT (slope value = 0.01), whereas left leg TSI% increased steadily (slope value = 0.16), leading to a significant asymmetry (P < 0.05) in the final lap. Total muscle blood volume decreased equally in both legs at the start of the simulation. However, during subsequent laps, there was a strong asymmetry during cornering; when skaters traveled solely on the right leg, there was a decrease in its muscle blood volume, whereas an increase was seen in the left leg. Conclusions: NIRS was shown to be a viable tool for wireless monitoring of muscle oxygenation. The asymmetry in muscle desaturation observed on the two legs in short-track speed skating has implications for training and performance. Key Words: MUSCLE OXYGENATION, NEAR-INFRARED SPECTROSCOPY, MUSCLE BLOOD VOLUME, MUSCLE BLOOD FLOW, SKATING

The aerodynamic requirements for optimal performance in speed skating impose physiological as well as biochemical constraints. For example, the unique “low sitting” position adopted during speed skating has been shown to elicit increased blood lactate (13), to lower submaximal VO2 uptake (27), and to lead to a combination of reduced blood volume change and greater deoxygenation in the quadriceps muscles (29) when compared with upright skating. Such findings support the “reduced blood flow” hypothesis (32), which asserts that blood flow to the working muscle is compromised by a combination of the high intramuscular forces, the long duty cycle of the gliding phase, and the low posture. The cumulative effect is that, although sufficient muscle groups are recruited, their aerobic capacity cannot be fully used (9); hence, a high anaerobic energy contribution is necessitated. Research into the physiological responses to the low sitting position has focused on testing involving treadmill skating and has included comparisons of different skating speeds, showing that faster treadmill skating velocity elicits a greater deoxygenation in the quadriceps muscle for a given skating position (29). Laboratory comparisons have also been made with cycling (13) and running (19,27). However, some on-ice measurements have been made. Notably, near-infrared spectroscopy (NIRS) has been used to measure muscle deoxygenation during progressive on-ice skating in both the low and high skating positions (13). This on-ice testing corroborated findings from treadmill testing; the lower position elicited a greater deoxygenation than upright skating. However, it was found that the magnitude of deoxygenation during maximal on-ice skating in the low position was significantly greater than from that observed on the treadmill. This suggests that, whenever possible, on-ice testing should be pursued to gain the most realistic understanding of the demands of speed skating. On-ice testing also enables the NIRS...
measures to be reported in relation to the position of a skater on the track. This is particularly important in short-track speed skating as traveling around the corners requires a different posture than traveling along the straight sections of track, and this may have consequences for the desaturation and/or blood volume at the muscle at any given time point.

The majority of research in speed skating reports on long-track, rather than short-track. There are several important differences between the two Olympic skating disciplines, the physiological consequences of which have not been explored. Long-track ovals are 400 m long. The much shorter (111 m) short-track oval leads to more acute cornering angles and a greater number of corners for comparable distances. Cornering forces in a 1000-m race have been calculated at 866 N in the short track as opposed to 482 N for the long track (28). Given these important differences between the disciplines, it seems appropriate to differentiate between them when conducting physiological investigations.

To correctly inform training and race strategy, it is desirable to understand changes at the local muscular level, in addition to information about whole-body VO_2 changes. NIRS has been widely used to investigate local oxygenation changes in exercising muscle, and this work has been reviewed extensively (11,15,21,25,37). The development of portable NIRS devices has allowed local muscle measurements to be made away from a laboratory setting to investigate local muscle changes in sports such as speed skating (13), alpine skiing (34), and running (4,23).

Spatially resolved spectroscopy (SRS) probes deeper into tissue and minimizes interference from movement and light scattering artifacts (33) and provides a measurement of absolute tissue oxygen saturation. The aim of this study was to explore whether a recently developed wearable wireless-enabled SRS device could feasibly be used in a nonlaboratory setting mimicking the real speed skating race environment. We measured local oxygenation and blood volume changes in the quadriceps muscles on both legs of elite short-track speed skaters during on-ice race simulation over the 500-m race distance. First, we hypothesized that the low sitting position used would lead to high levels of muscle hemoglobin desaturation, and this would be directly related to skating velocity. Second, there would be asymmetry in desaturation and blood volume changes observed between right and left legs, induced by constantly skating in an anticlockwise direction, eliciting different demands on each leg.

METHODS

Subjects

Six elite male short-track speed skaters (mean ± SD age = 23 ± 1.8 yr, height = 1.8 ± 0.1 m, mass = 80.1 ± 5.7 kg, mid thigh skinfold thickness = 7 ± 2 mm), of Olympic standard, took part in this study. Thickness of the adipose tissue overlying the quadriceps muscle was measured using a skinfold caliper (British Indicators, Harpenden, UK) with the procedures and landmarks indicated in the ISAK protocol. All subjects gave their written informed consent before participation. The study was approved by the ethics committee of University College London.

Experimental Procedures

Testing took place on a short-track speed skating oval (111.12 m) approved for international competition. Each subject completed a race simulation time trial over the 500-m race distance (TT), an official Olympic race distance in this sport. Before completing race simulation, subjects were informed to undertake their own warm-up, as they would when preparing for a competitive race. Race simulation TTs were completed individually, and subjects were informed to try and achieve the fastest time possible.

NIRS Measurements

During race simulation, muscle oxygenation in both left and right vastus lateralis was continuously monitored using a recently developed wireless SRS dual-wavelength oximeter (Portamon; Artinis Medical Systems, BV, The Netherlands). This model has previously been used to investigate muscle oxygenation and hemodynamics (4,26,31). The unit is self-contained and compact, measuring 83 × 52 × 20 mm and weighing 84 g, including battery. It houses three pairs of light-emitting diodes that emit light of wavelengths 760 and 850 nm and are positioned 30, 35, and 40 mm from the detector. In the present study, chromophore concentrations detected using the furthest light-emitting diode (40 mm) are presented. Photon migration and Monte Carlo simulations suggest a maximum penetration depth of half the distance between emitter and detector, that is, 20 mm for this device (7,38); for a review of this, see Hamaoka et al. (15). These wavelengths allow for the detection of concentration changes in the chromophore’s hemoglobin (Hb) and myoglobin (Mb). Using a two-wavelength spectrometer, it is not possible to discriminate between the oxy and deoxy forms of the globins. However, it is generally considered that the Mb contribution is the more minor component, so in line with previous workers, we will ignore it for the sake of clarity (5,6).

Changes in the sum of the two signals (Δ[HbO2] + Δ[Hb]) reflect changes in the concentration of the chromophores. Changes in this parameter reflect changes in the concentration of total Hb (tHb) and hence report on the volume of blood in the muscle interrogated by the NIR light. If there are no opposing changes in red cell velocity, NIR-measured changes in blood volume will reflect the change in volume blood flow and hence in oxygen delivery to the muscle tissue (35). We report the data here as has been suggested by previous authors (6) in units of micromoles per liter per centimeter (μM·cm).

In the Portamon device, the three light sources are in a spatially resolved configuration, which allows an absolute measure of tissue oxygen saturation (TSI%) to be derived (33) according to the equation. The Portamon device used in this study refers to this value as TSI, but it is essentially identical with the tissue oxygen index, which is the
SRS-derived measure of tissue oxygen saturation measured by the transportable tissue oximeters made by Hamamatsu Photonics Japan (5,6).

The devices were positioned on the belly of the vastus lateralis muscle, midway between the greater trochanter of the femur and the lateral femoral epicondyle. To ensure the optodes and detector did not move relative to the subject’s skin, the device was fixed into position using surgical tape and was then secured with a bandage. Care was taken to ensure that this affixation was sufficient to prevent any movement of the device during the testing, without limiting the subject’s movement in any way. All subjects reported that the device was comfortable to wear and did not restrict their movements in any way. It has previously been shown that quadriceps muscle oxygenation is nonuniform during exercise (17,18,20,22), so precise and consistent optode placement was crucial.

**Video Capture**

Each race simulation was filmed using a Sony HDV 1080i miniDV camcorder (Sony, Tokyo, Japan). Frame-by-frame tracking was subsequently carried out by coding every stage of each lap using Dartfish® Video Analysis Software (Dartfish, Fribourg, Switzerland), and synchronizing the video and physiological data for the purposes of visual analysis.

**Global Physiological Measurements**

In addition to the NIRS measurements obtained during each race simulation, respiratory gases were monitored using a breath-by-breath pulmonary gas analyzer (K4b²; Cosmed, Pomezia, Italy). This information was required to assess whether global metabolic indicators such as VO₂ were related to the observations seen from NIRS at a local muscle level.

**Assessing body position throughout the lap.** To better understand the changes that have been presented relating to the whole race, it is necessary to examine more closely the differing body position and physiological demands during one lap. The illustrations in Figure 1 are still-images produced from the video footage recorded during each trial. The four separate elements (which are all repeated twice per lap) have been defined in the following way for the purposes of this analysis:

- **Straight (A)**—the section of the lap between the two corners. The straight starts when the left blade touches the ice after the crossover of legs while exiting the corner. The straight contains one glide on each blade and ends when the left blade touches the ice after the right foot glide. This is the only stage of the lap at which full knee extension is observed.
- **Entry (B)**—the phase between the end of the straight and the moment at which the right blade touches the ice to begin the hang. This phase is categorized by a series of leg crossovers and a lower “sitting” position than during the straight.
- **Hang (C)**—during this phase, the skater travels around the apex of the corner supported solely on the right blade. This phase ends when the left blade makes contact with the ice again.

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**FIGURE 1**—Schematic diagram depicting the sections of one lap and the body positions typically adopted at each stage.
• Exit (D)—the skater performs a series of leg crossovers while maintaining a very low position. This phase ends when the skater’s left blade touches the ice to begin the gliding phase of the straight.

Data analysis. Data were collected wirelessly and displayed in real time in one leg (right) and collected offline and subsequently downloaded in the other. There were no data dropouts for either method. Data collection started 30 s before the start of TT; however, variability observed in this period was very small compared with changes observed on commencement of the race. Therefore, all chromophore concentration changes were presented relative to a baseline value taken immediately before the start of the race simulation. All NIRS data were captured at 10 Hz, and for the purposes of further analysis, a 10-point moving average was applied. Data of all subjects were subsequently averaged during the race for the first step of the analysis to identify significant differences over time. Student’s t-tests were used to compare right and left leg data averaged over laps. After the immediate desaturation (t = +8 s), linear regression was applied to investigate the subsequent asymmetry in right and left leg TSI. The Pearson product–moment correlation coefficient was used to analyze the relationship between hang time and ΔtHb and ΔTSI in both legs. All statistical analyses were carried out using GraphPad Prism 5 (GraphPad Software, San Diego, CA). α was set at P < 0.05 level.

RESULTS

All TTs were completed successfully. Skaters reported that they were unaffected by wearing the two near-infrared devices. It was possible to collect data wirelessly during the races on one leg and therefore obtain instantaneous information relating to TSI, oxyhemoglobin (HbO2), deoxyhemoglobin (HHb), and tHb. Data were successfully collected for both legs for every time trial; no data dropout occurred.

The time (mean ± SD) required for the completion of the race simulations was 44.8 ± 0.41 s. The 500 m is raced over 4.5 laps of the short-track oval. The first half lap, in which the skater accelerates from a standing start through a “running” action, as has been previously described (10), was completed in 6.89 ± 0.41 s. After this, the four full laps were completed in 9.49 ± 0.16, 9.28 ± 0.24, 9.4 ± 0.10, and 9.74 ± 0.11 s, respectively. Figure 2 displays NIRS-detected changes in tHb and the relative contributions to this signal of HbO2 and HHb. At the start of the TT, there is a rapid decrease in the concentration of HbO2 and a smaller increase in HHb, resulting in an initial decrease in tHb. This is followed by a steady rise in tHb.

During the TT, the minimum absolute TSI value reached was 37.0% ± 5.3%. The lowest TSI observed in the vastus lateralis of any skater was 31.5%. There was no significant correlation between the time taken to complete the race and the maximum muscle desaturation in either the right

\( r = -0.02, P = 0.97 \) or the left vastus lateralis \( r = 0.11, P = 0.84 \). In Figure 3, it can be seen that the steady state in the local measurements (TSI%) is reached at around 8 s into the race, whereas the steady state in the global measurement of VO2 is not reached until later, approximately 20 s into the race. There was no significant difference between the rates of

FIGURE 2—Mean data of all subjects showing temporal changes in right and left vastus lateralis during the 500-m race: tHb (A), HbO2 (B), and HHb (C).
desaturation of the two legs during the initial stage of the race or the minimal values reached after this stage. However, once steady state was reached, a gradual resaturation was seen in the left vastus lateralis, whereas there was no apparent resaturation in the right vastus lateralis. This trend is displayed in Figure 3B and suggests that there is an asymmetry between the saturation of the 2 legs during the race. Linear regression analysis of the post-8 s TSI% changes in each leg yielded a significant nonzero slope value of 0.162 ± 0.003 ($P < 0.001$) in the left leg and a slope in the right leg that was not significantly different from zero (0.012 ± 0.011, $P = 0.289$). In the right and left legs, 95% confidence intervals of $y$ intercept at time = 0 was calculated as −20.16 to −18.90 and −19.04 to −18.06, respectively. Also, see Video, Supplemental Digital Content 1, http://links.lww.com/MSS/A120, which simultaneously displays the athlete’s position and the right and left leg TSI values throughout the race.

To compare right and left leg NIRS parameters during different laps, the straight is the optimal lap section to use because both legs perform the same task—one full push and glide. Table 1 compares the mean measured NIRS parameters in right and left vastus lateralis during the second straight section of lap 1 (1.13 ± 0.23 s) and the first straight section of lap 4 (1.12 ± 0.21 s). These sections were chosen because they are the first and last full straights to be completed purely skating after the end of the initial “running” phase, that is, during the main body of the race. By lap 4, the left leg showed a significantly higher oxygenation than the right leg, as evidenced by a lower concentration of the deoxygenated globins and a higher TSI relative to baseline.

The analysis of specific sections of the race (Fig. 4) showed an increase in tHb in the left leg during the “hang” phase (position C in Fig. 1) and a concurrent decrease in right leg tHb (see Video, Supplemental Digital Content 2, http://links.lww.com/MSS/A121, which displays the regular pattern of tHb changes during the entire race). Although Figure 4 and Supplemental Digital Content 2, http://links.lww.com/MSS/A121 show data for individual subjects, it should be noted that, in every hang completed by every skater ($n = 36$), the increase in left leg tHb, and a decrease in right leg tHb was observed. In the right leg, the decrease in tHb seems to be primarily due to a decrease in HHb, whereas increases in both HbO$_2$ and HHb contribute to the rise in the left leg. These data show that, when using this NIR device, and collecting data at 10 Hz, it is possible to detect changes in the concentration of chromophores during small individual sections even of a short-track lap.

A relationship between the mean length of time a skater spent in the hang phase and the mean change in tHb in the left leg during the hang was identified (Fig. 5). The Pearson correlation analysis revealed that there was a significant positive correlation between hang time and $\Delta$tHb in the left leg ($r = 0.376$, $P = 0.024$). There was a negative correlation between hang time and $\Delta$tHb in the right leg, but this was not statistically significant ($r = -0.25$, $P = 0.133$). This supports the suggestion that it is while the left leg is

![Figure 3](image)

**Figure 3**—A, Changes in right and left vastus lateralis TSI% and whole-body VO$_2$ during the 500-m race (average values of pooled subjects). B, Right and left mean TSI% changes once race start (running action) has occurred. Straight lines show slope of line of best fit calculated in linear regression from $t = 8$ s onward.

| Table 1. Mean changes from baseline (±SD) in the left and right vastus lateralis during one straight in laps 1 and 4. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                 | Lap 1           |                 |                 |                 |
|                                 | Right           | Left            | Right           | Left            |
| $\Delta$TSI (%)                 | $-21.0 \pm 5.9$ | $-16.5 \pm 5.1$ | $-22.3 \pm 7.2$ | $-13.1 \pm 4.8^*$ |
| $\Delta$HbO$_2$ (µM cm$^{-1}$)  | $211.4 \pm 67.4$ | $219.6 \pm 134.5$ | $287.7 \pm 58.4$ | $242.6 \pm 123.0$ |
| $\Delta$HHb (µM cm$^{-1}$)     | $204.4 \pm 127.8$ | $225.9 \pm 77.0$ | $375.9 \pm 172.2$ | $261.5 \pm 94.8^*$ |
| $\Delta$tHb (µM cm$^{-1}$)     | $-16.9 \pm 83.5$ | $-94.2 \pm 81.2$ | $88.2 \pm 141.1$ | $19.9 \pm 93.8$ |

Data shown are solely from the “straight” sections of the laps, during which time the movements of the right and left legs are biomechanically comparable.

* Significantly different from the right leg ($P \leq 0.05$).
laid from the ice that an increase of blood volume occurs, presumably as a result of the reduction of intramuscular pressure caused by muscle contraction. When time spent in the hang phase was compared with changes in TSI, a similar trend was observed: a weak positive correlation was seen in the left leg ($r = 0.199$, $P = 0.7$) and a negative correlation was seen in the right leg ($-0.736$, $P = 0.1$).

**DISCUSSION**

The results presented offer the first reported measurement of quadriceps muscle saturation during short-track speed skating race simulation and show that it is possible to obtain real-time measurements of muscle desaturation during short-track speed skating in elite athletes. Although previous studies have investigated the metabolic effects of the “low sitting” position adopted in speed skating (13,29), the results presented in this article display the effects of the differing lower limb and trunk positions adopted during each lap, and the race as a whole, rather than solely comparing “low” and “high” sitting positions. By placing a NIRS probe on each leg, it has also been possible to examine any differences between the two legs. Finally, by using a relatively high frequency of the data collection (10 Hz), and combining physiological data with race video, it has been possible to examine the changes that occur during each section of a lap.

Consistent with our first hypothesis, at the start of the TT, there is a decrease in tissue oxygenation (TSI%), which then settles at a lower steady state. In contrast, after an initial rapid decrease, blood volume (tHb) rises throughout the TT. Similar NIRS profiles have been seen in other laboratory-based NIRS studies where exercise is started at high power (1). The transition from the resting state to exercising state increases the demand for $O_2$ in the working muscles. This demand is met by an increase in both delivery (blood flow) and extraction of $O_2$ from HbO$_2$. The oxygenation profile can therefore be explained by the increase in $O_2$ consumption outstripping the increase in $O_2$ delivery. The simplest explanation of the tHb profile is that there is a constriction of blood flow (decreasing volume) at the start of the TT followed by a subsequent blood flow (and hence volume) increase. The high level of muscle desaturation, caused by a combination of body position and intermittent static contractions used in short-track skating, is comparable to findings in previous studies of exercise of a similar nature: the
hiking action in sailing (36) and alpine skiing (34). In this subject group, and for this race distance, maximum muscle desaturation is not correlated with TT duration. Races over the 500-m distance tend to be less tactical than races over longer distances because the 500-m distance generally involves skating at maximal speed for the race duration. The skaters completed the TT in very similar times (SD = ±0.41 s), so it is not possible to determine the effects of varying velocities on muscle desaturation in this case. It is suggested that TTs over longer distances would be more suitable for examining this relationship. The second hypothesis—that there would be differences noted between right and left legs—proved to be correct. However, the differing pattern of desaturation in the two legs was not predicted. Because the direction of travel in short-track speed skating is constant (anticlockwise), the demands placed on the two legs are different, because the right leg is always the “outside leg.” The present study shows that, during the whole race, right leg tissue saturation initially drops rapidly and then sustains at a relatively constant level for the remainder of the race. In contrast, the left leg desaturates to a similar degree, but then gradually resaturates through the course of the race. The differing patterns of tissue saturation during this “steady-state” section of the race result in significantly different mean tissue-saturation values between the two legs during the final lap of the race.

Close investigations of changes in tHb and its two components suggest that it is the “hang” phase of the lap, when the skaters travel around the apex of the corner, which causes the greatest difference between the two legs. At this point, there is an increase in left leg tHb, caused by the release of intramuscular pressure (as the leg is lifted from the ice for the duration of the “hang”), thus allowing perfusion of oxygenated blood into the muscle. In contrast, at this time, the right leg performs a one-legged static contraction to maintain speed while overcoming the centrifugal force of the corner. It can be seen that right leg tHb reduces at this time. It has previously been shown that one-legged static contraction in the low position yields greater desaturation than two-legged static contraction (13). Other phases of the lap elicited similar tHb and responses from both legs.

Although the limitations of NIRS measurements have been highlighted in several reviews (11,25), many of these are overcome by the study design and subject group used. Recent studies have reported regional heterogeneity in vastus lateralis oxygenation as measured by NIRS (17,24). However, it has also been shown that, during a higher-intensity exercise, the spatial heterogeneity of oxygenation changes is greatly reduced (3,18) and that quadriceps blood flow is less heterogeneous during a high-intensity exercise in highly trained individuals, such as the subjects of the present study (16). Another commonly cited limitation of the use of NIRS is the influence of adipose tissue thickness on the measured parameters (8,14,30). However, the low adipose tissue thickness of all six subjects (6.83 ± 2.24 mm) in this study would suggest that this aspect would not have altered the reliability of the data; the probe’s maximum penetration depth of approximately 2 cm, being adequate to interrogate the vastus lateralis muscle. Because measurements of blood volume changes in the quadriceps muscles were being made, it was important to know whether any of the athletes had any underlying conditions that would impair blood flow to this area. Approximately one in five endurance-trained speed skaters develop sports-related flow limitations in the iliac arteries (2), which could reasonably be expected to affect near-infrared measurements made in the quadriceps muscle group. However, because none of the athletes in our subject group have been diagnosed with this condition, or reported any of the common symptoms (12), it is unlikely that such a condition would have impaired quadriceps blood flow in this particular subject group.

It is clear that there is significant physiological disadvantage to skating in the low position and, in particular, to the performance of the “hang” phase, rather than using a crossover technique to travel around each corner. The biomechanical and therefore performance advantages overcome this because the technique is used by all elite male skaters when they travel around the apex of the corner at high speed. Nevertheless, this study draws attention to the asymmetry in muscle saturation during a 500-m race simulation, evidence that cannot be provided by any global physiological measures, such as VO₂. The implications for this in performance have not yet been examined in detail, but we note that this study reports a significant ability to resaturate the vastus lateralis in the left leg, but not the right leg, as the race evolves. More studies are needed to understand the implications of this phenomenon; for example, whether alterations in biomechanical technique and/or training methods can improve performance by enhancing blood flow and oxygen delivery.

There are no conflicts of interest for any author on this article.

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REFERENCES


