

Quadriceps Oxygenation during Isometric Exercise in Sailing

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Key words

- tissue oxygenation
- sailing
- lactate concentration

Abstract

The aim of the present study was to investigate why blood lactate after prolonged quadriceps contraction during hiking is only marginally increased. Eight sailors performed five 3-min hiking bouts interspersed with 5-s recovery periods. Whole body oxygen uptake, heart rate and lactate were recorded, along with continuous-wave near-infrared spectroscopy measures of quadriceps oxygenation. The time for 50% re-oxygenation was also assessed as an indication of the degree of localized oxygen delivery stress. Hiking elicited a significant ($p = 0.001$) increase in mean (\pm SD) heart rate (124 ± 10 beats·min⁻¹) which was accompanied by a disproportionately low oxygen uptake (12 ± 2 ml·kg⁻¹·min⁻¹). Lactate

was significantly ($p = 0.001$) increased throughout hiking manoeuvres, though post-exercise it remained low (3.2 ± 0.9 mmol·l⁻¹). During the hiking bouts mean quadriceps oxygenation was significantly ($p = 0.001$) reduced compared to baseline (by $33 \pm 5\%$), indicating an imbalance between muscle oxygen accessibility and oxygen demand. During rest intervals quadriceps oxygenation was partially restored. After the end of the final bout the time for 50% re-oxygenation was only 8 ± 2 s, whereas recovery of quadriceps oxygenation and oxygen uptake was completed within 3 min. We conclude that the observed low lactate could be attributed to the small oxygen and energy deficits during hiking as the muscles' oxygen accessibility is presumably partially restored during the brief rest intervals.

Introduction

Hiking is the effort that a dinghy sailor makes in order to counterbalance a light boat in moderate and strong winds. In hiking feet are hooked under straps in the boat and the weight is borne, typically about mid-thigh, on the edge of the boat deck; the rest of the body hangs over the water. Hiking a dinghy constitutes a form of physical challenge that differs greatly from what predominates in almost every other sport, in that it imposes isometric stress on quadriceps for different duration periods (2–6 min) at a time. Consistent with the isometric nature of hiking, typically sustained at approximately 30 to 40% of quadriceps' maximal voluntary contraction (MVC) [19], are reports from simulated investigations showing large increases in blood pressure (BP) and heart rate (fc) commonly accompanied by disproportionately low increments in oxygen uptake ($\dot{V}O_2$) [1,8,11,15,19]. Confirmation of these findings comes from cardiorespiratory measurements during actual sailing conditions [7,18].

Established literature [13] has documented that during an isometric contraction sustained at more than 15–20% MVC, muscle blood flow increases several times above its resting levels [20], though it is not sufficient to meet the metabolic requirements; consequently, there is a deficit of oxygenated blood leading to significant production of muscle lactate [13]. Interestingly, mean values for capillary blood lactate concentration $[La]_b$ hardly exceed 3 mmol·l⁻¹ either on-water [18] or following several min of successive hiking bouts in the laboratory [1,8,19], thus indicating a limited oxygen deficit. Indeed, fundamental studies [15] on a leg-extension ergometer that closely simulated the quadriceps' involvement in hiking, revealed that following contractions at 20 and 30% MVC whole body $\dot{V}O_2$ returned to baseline within 2 to 3 min after contraction ceased, whereas $[La]_b$ remained low (approximately 2.5 mmol·l⁻¹), thus confirming that oxygen deficit was rather small.

A possible explanation for the low $[La]_b$ observed during hiking might be associated with the dis-

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continuous nature of this manoeuvre owing to the relief intervals. These intervals occur when sailors: 1) perform body movements fore and aft, up and down and by axial rotation, so some degree of muscle relaxation is temporally achieved and 2) change position in the boat during tacking (i.e.: change of sailing course). Hence, we hypothesized that these rest intervals would allow partial restoration of the muscles' oxygen accessibility, thus promoting a more oxidative degradation of glycogen and low lactate concentration. In addition, based on established literature [13,20] we reasoned that although blood flow through quadriceps is restricted, it is not totally obstructed, so local muscle oxygen accessibility is to a certain degree maintained throughout the contraction, thus minimizing the lactate production.

The aim of this study was, therefore, to challenge the above hypotheses by investigating the quadriceps oxygen accessibility during hiking. To approach our goal we monitored the quadriceps oxygenation status during successive bouts of hiking and in recovery by the employment of near-infrared spectroscopy (NIRS).

Methods

Subjects

Eight male Laser-class National Squad sailors gave informed consent to participate in this study, which had received approval by the Faculty Ethics Committee. The subjects mean (\pm SD) age, stature and body mass were 21 ± 2 years, 1.80 ± 0.05 m and 79 ± 2 kg, respectively.

Study design

Each subject completed five successive 3-min hiking bouts, separated by 5 s rest intervals to simulate tacking on a Laser dinghy simulator as previously described [19]. The choice for the duration of each hiking bout was based on the results of a previous study [19] performed on the same dinghy simulator, where electromyography activity measurements from quadriceps indicated that hiking was sustained at 30 to 40% MVC. The application of this protocol on the specific sailing ergometer has been evaluated to closely reproduce the physiological demands of actual dinghy sailing conditions [18,19]. In order therefore to be able to reproduce the actual sailing conditions and compare our results to those of a previous study [19], we decided to implement the aforementioned protocol.

Experimental protocol

During hiking the subjects were required to keep the force exerted on the toe-strap constant and to reproduce the same force throughout all five bouts. Simulation of tacking involved sitting in from the hiking position and 5 s later moving back out to a full hiking posture. $\dot{V}O_2$, f_c and quadriceps oxygenation measurements were carried out for 3 min at baseline, throughout the hiking and tacking manoeuvres and for 3 min during recovery. BP was measured at baseline and during the last 30-s of each hiking bout using a standard clinical sphygmomanometer cuff. Subjects rated their perceived exertion (RPE) immediately after the end of each hiking bout using the 6–20 Borg scale [2]. Blood samples for the analysis of lactate concentration were taken at baseline, at the end of the second, fourth and fifth bouts and 3 min after the end of the last bout.

NIRS

We utilized a commercially available NIR spectrometer (InSpecra Tissue Spectrometer, Model 325, Hutchinson Technology Inc., Hutchinson, MN, USA) to monitor tissue oxygenation. The spectrometer comprised the following components: 1) A tissue spectrometer that contains light detection circuitry, a microprocessor and a display screen. 2) A disposable calibrator module used to calibrate and normalize the tissue spectrometer. 3) An optical integrator probe comprising a fibre optic light integration cable that contains one set of optical fibres to integrate wavelengths of light and transmit to the tissue, and a second set of optical fibres that receives light from the tissue and returns it to a photosensitive detector. Measurements indicate that the average path length of the NIR light in the skeletal muscle is 70–80 mm on average, yielding an average penetration depth of 25–30 mm [5]. Accordingly, the optical integrator probe used in the present study was chosen to allow an average penetration depth of 25 mm. The optical probe was calibrated immediately prior to each test and was then positioned over the vastus lateralis muscle 100–120 mm from the knee, parallel to the major axis of the thigh. The probe was inserted into a rubber shell which, in turn, was firmly attached by an adhesive tape to the skin, thus securing its position.

The spectrometer measures tissue absorbance values at wavelengths between 650 nm and 900 nm; its absorption characteristics depend on the relative saturation of haemoglobin (Hb) and myoglobin (Mb). Changes in the difference between the signal strengths at 650 and 900 nm were used to estimate changes in the relative oxygenation of total Hb/Mb in the tissue being monitored [4]. A commonly derived parameter from NIRS studies reflecting an index of tissue de-oxygenation [3] is the ratio of oxygenated Hb (HbO_2) to total Hb volume (HbT). This parameter indicates the balance between O_2 delivery and O_2 consumption. HbT, in turn, is the sum of HbO_2 and de-oxygenated Hb (HHb). Tissue oxygenation, HbT (typically representing blood volume), and the difference between oxy- and deoxy-fractions of Hb (HbO_2 -HHb: frequently taken as the oxygenation index), were recorded every 3 s during baseline for 3 min, throughout the hiking bouts and the rest intervals and for 3 min into recovery. Since NIRS measurements of tissue oxygenation do not specifically reflect muscle O_2 consumption, but rather the balance between muscle oxygen delivery and muscle O_2 demand [10], we also analyzed the post-exercise re-oxygenation rate as this has been proven to be a good index of the time for repayment of O_2 and energy deficits during exercise. Therefore the time for 50% re-oxygenation ($T_{R1/2}$) to the post-exercise peak tissue oxygenation was also calculated [5].

Cardiorespiratory and other variables

Whole body $\dot{V}O_2$ was recorded on a breath-by-breath basis by a computerized system (CardiO₂ System, Med Graphics Corp., St. Paul, MN, USA) and averaged over 30-s intervals. Heart rate was monitored throughout by means of short-range telemetry (Polar Vantage NV, Polar Electro, Kempele, Finland) every 30 s.

Blood sampling and analysis

10 μ l of arterialized capillary blood samples for the determination of $[La]_b$ were drawn from the earlobe and were analyzed immediately using a portable lactate analyzer (AccuSport, Boehringer Mannheim, Mannheim, Germany).

Table 1 Mean \pm SD values in recorded variables across the five successive hiking bouts and in recovery. Values for $\dot{V}O_2$, NIRS parameters and heart rate (fc) are averages over 3-min at baseline, during each hiking bout and recovery

	Rest	1st bout	2nd bout	3rd bout	4th bout	5th bout	Recovery
$\dot{V}O_2$ (ml·kg ⁻¹ ·min ⁻¹)	5.5 \pm 0.5	8.9 \pm 1.0	12.0 \pm 0.6*	12.9 \pm 1.5*	13.8 \pm 1.3*	13.7 \pm 1.6*	8.9 \pm 2.0†
% Tissue-oxygenation	95 \pm 2	70 \pm 6†	64 \pm 4†*	63 \pm 4†*	60 \pm 5†*	58 \pm 4†*	90 \pm 2
% HbT	100 \pm 1	97 \pm 1†	90 \pm 1†	96.0 \pm 1†	98 \pm 1	98 \pm 1	111 \pm 1†
HbO ₂ -HHb (% change)	-	-42 \pm 12	-28 \pm 7*	-15 \pm 4*	-17 \pm 7*	-17 \pm 7*	-11 \pm 3*
fc (beats·min ⁻¹)	82 \pm 9	111 \pm 9	118 \pm 12*	123 \pm 14*	132 \pm 16*	136 \pm 13*	98 \pm 14†
BP syst. (mmHg)	136 \pm 9	171 \pm 9	184 \pm 14*	187 \pm 11*	192 \pm 11*	195 \pm 18*	147 \pm 13†
Toe-strap force (% max)	-	38 \pm 6	41 \pm 4	46 \pm 6*	51 \pm 10*	50 \pm 5*	-
[La] _b (mmol·l ⁻¹)	1.5 \pm 0.4	-	2.3 \pm 0.4†	-	2.5 \pm 0.4†	3.0 \pm 0.6†	3.2 \pm 0.9†
RPE	-	11 \pm 2	13 \pm 1	14 \pm 1*	15 \pm 1*	16 \pm 1*	-

Oxygenation index (HbO₂-HHb) is shown as percentage (%) change from baseline. % HbT: percentage total haemoglobin volume; fc: heart rate; BP: blood pressure; [La]_b: blood lactate concentration; RPE: rate of perceived exertion. Crosses denote significant differences ($p < 0.05$) compared to rest, whereas asterisks denote significant differences ($p < 0.05$) compared to the first bout

Statistical analysis

Data are group means \pm SD. Data recorded by the NIRS and by the computerized gas exchange system were averaged over 30 s intervals. To calculate the half time of tissue oxygenation during recovery we used the NIRS signal recorded every 3 s. One-way ANOVA with repeated measures was used to determine whether changes in the recorded variables were significant. When ANOVA detected a significant main effect, post-hoc comparisons were carried out by Student's *t*-test for paired observations, followed by a Bonferroni-type adjustment for multiple comparisons. Linear regression analysis was performed using the least square method. When this analysis was carried out using tissue oxygenation as dependent variable, the independent variables included gas exchange and NIRS parameters. The strongest significant contributors to tissue oxygenation were selected by forward stepwise multiple regression analysis. For all analyses the level of significance was set at $p < 0.05$.

Results

NIRS and whole body $\dot{V}O_2$

Fig. 1 shows changes in quadriceps tissue oxygenation at intervals of 30 s throughout the 5 successive hiking bouts and in recovery. Compared to baseline tissue oxygenation was significantly ($p = 0.001$) reduced during hiking. The relief intervals resulted in a non-significant elevation of tissue oxygenation. Therefore, during the first 30 s of each successive hiking bout mean tissue oxygenation was not significantly different ($p > 0.05$) compared to its preceding value. Following the first 30 s of each bout, tissue oxygenation decreased again and levelled off within 60 s (Fig. 1). In recovery there was a rapid increase in quadriceps tissue oxygenation towards baseline. The half time of tissue oxygenation recovery was 8 ± 2 s. Thereafter, a slow recovery persisted over 2 1/2 min. Similarly to tissue oxygenation, HbT was significantly ($p = 0.001$) reduced compared to baseline throughout the hiking bouts (Table 1). During recovery HbT significantly ($p = 0.001$) increased to a value higher than baseline and remained elevated during the whole recovery period. Whole body mean $\dot{V}O_2$ (Table 1) increased significantly ($p = 0.005$) across the bouts. However, during the rest intervals and the first 30 s of each successive hiking bout, mean $\dot{V}O_2$ reached a value significantly ($p < 0.05$) higher compared to its preceding value (Fig. 1). Quadriceps tissue oxygenation significantly correlated with whole body $\dot{V}O_2$ ($r = -0.62$,

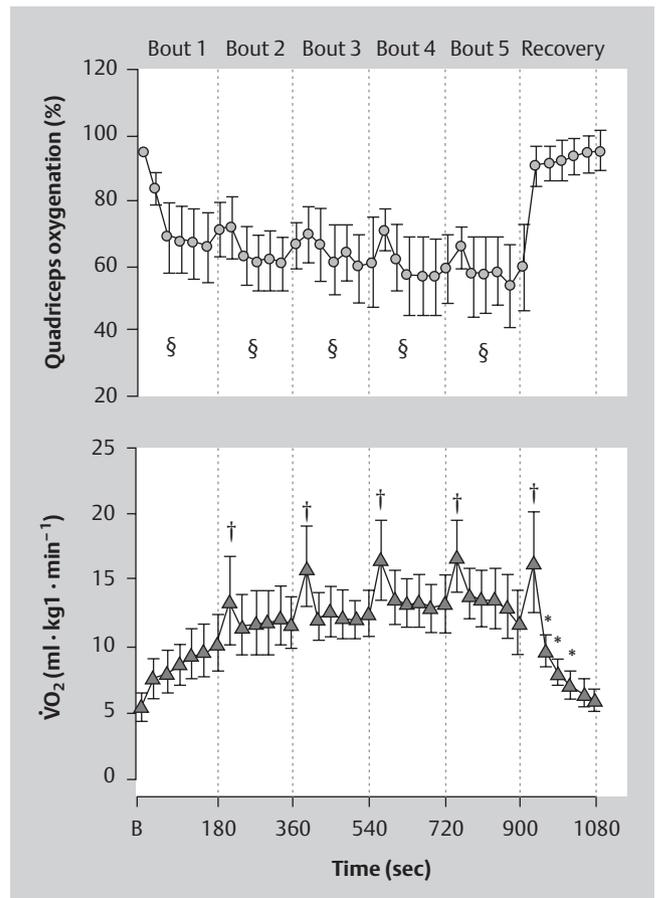


Fig. 1 Quadriceps tissue oxygenation (Panel A) and whole body oxygen uptake (Panel B) are shown as mean \pm SD values at baseline (B), at 30 s intervals during the 5 hiking bouts and in recovery. Relief intervals between hiking bouts are shown by vertical dashed lines. Panel A: § denotes significant difference of the mean 3-min value compared to baseline. Panel B: † denotes significant difference between the mean value of the first 30 s of each hiking bout in comparison with the preceding 30 s mean value. * Denotes significant difference compared to baseline.

$p = 0.005$) and HbT ($r = -0.76$, $p = 0.001$). Using a forward stepwise multiple regression analysis, quadriceps oxygenation was best described by the combination of HbT and $\dot{V}O_2$ ($R^2 = 0.77$, $p = 0.001$). In recovery, $\dot{V}O_2$ was significantly ($p = 0.001$) increased during the first 30 s and then returned to baseline, with-

in 3 min (● Fig. 1). Finally, the oxygenation index ($\text{HbO}_2\text{-HHb}$) was significantly decreased ($p = 0.001$) across the 5 hiking bouts (● Table 1).

[La]_b and cardiovascular responses

[La]_b increased significantly ($p = 0.001$) throughout the hiking bouts and in the first 3 min of recovery (● Table 1). Similarly, across the hiking bouts there was a significant increase in systolic BP ($p = 0.003$) and in fc ($p = 0.001$). After 3 min of recovery fc and systolic BP were still significantly higher ($p = 0.035$ and $p = 0.042$, respectively) compared to baseline (● Table 1). The RPE also increased significantly ($p = 0.007$) across the 5 hiking bouts (● Table 1).

Discussion

This study was performed to investigate why blood lactate concentration after prolonged quadriceps contraction during hiking is only marginally increased. The investigation of quadriceps oxygen accessibility during hiking revealed that quadriceps oxygenation was sufficiently preserved during the contraction, thus limiting the accumulated oxygen deficit and the significant rise in blood lactate concentration.

An additional finding of the present study was the course of quadriceps de-oxygenation during repeated bouts of isometric contraction in simulated hiking and the time course of recovery from de-oxygenation. Our findings are in agreement with those [14] obtained during isometric forearm muscle contraction indicating significant reduction in muscle oxygenation during the period of contraction and also recovery periods in tissue oxygenation within the range reported in the present study.

Furthermore, the results from our hiking simulation are in agreement with those from other simulated investigations [1,8,11,16] by showing that hiking elicited large increases in blood pressure and heart rate that were accompanied by a disproportionately low increase in $\dot{V}\text{O}_2$ and blood lactate concentration. Importantly, our findings for $\dot{V}\text{O}_2$, heart rate, blood pressure, [La]_b and the rate of perceived exertion closely replicated those from an earlier study [19] that was carried out on the same boat simulator employing a similar protocol of successive hiking bouts. In that study the intensity of quadriceps muscle isometric force (assessed by its electromyograph activity) ranged from 31 to 39% of maximum. Although the intensity of isometric exercise was not assessed in the present study, the observed lactate concentration values closely resembled those reported after actual sailing and simulated hiking conditions [18,19].

In the present study, it was demonstrated that during the successive bouts of hiking there was a significant decrease in quadriceps muscle oxygenation reflecting an imbalance between muscle O_2 accessibility and O_2 demand; this can be inferred by the significant increase in lactate concentration. The imbalance between muscle O_2 accessibility and O_2 demand resulted not only because of the inadequate blood supply to the quadriceps, but also because quadriceps O_2 demand was increased. The inadequate quadriceps blood supply was reflected by the significant decrease in total blood haemoglobin volume (representing blood volume [3]), possibly owing to the high intramuscular pressure [13]. As such, quadriceps oxygenation and total blood haemoglobin volume were shown to be significantly correlated ($r = -0.76$). On the other hand, whole body oxygen uptake increased across

the five hiking bouts and it was significantly correlated with the quadriceps tissue oxygenation ($r = -0.62$).

More detailed information on quadriceps oxygenation status was observed by the oxygenation index that was shown to significantly diminish during hiking, thus confirming muscle de-oxygenation [9]. De-oxygenation was greater during the first two hiking bouts, as was the increase in whole body oxygen uptake. Furthermore, the observation that tissue oxygenation was reduced to approximately 60% at the beginning of each hiking bout and was maintained at this level throughout the rest of the bout (● Fig. 1) indicates that an equilibrium point was reached [6]. This finding is compatible with our original hypothesis that although blood flow through quadriceps is impeded, it is not totally so.

Fundamental studies of blood flow in the human quadriceps muscle [20] have shown that in an attempt to overcome the high intramuscular pressure occurring during isometric contractions, there is an increase in blood flow velocity that is estimated to reach ten times that at rest. In the hiking simulation studies by Spurway and Burns [15] and by Vogiatzis et al. [17] (where Laser Doppler femoral blood flow velocity measurements were available) it was shown that blood flow velocity during quadriceps isometric contraction sustained at 30% MVC, increased several times above resting levels. Therefore, it is reasonable to suggest that peripheral O_2 accessibility is likely to be sufficiently preserved during hiking, thus limiting the accumulated oxygen deficit and the significant rise in blood lactate concentration.

The present study relied upon the tissue oxygenation recovery time as the most useful index of oxygen delivery deficit of the muscle in relation to its oxygen demand [5]. This method has two advantages: firstly, the measurement does not depend upon the initial and final states of the absorbance change, thus avoiding difficulties of quantifying Hb/Mb saturation changes and secondly, the measurements were taken while subjects remained stationary on the deck of the ergometer, thus avoiding measurement artefacts due to movement. Analysis was, therefore, focused on the recovery data assuming that a similar pattern of change might have occurred during the brief (5 s) tacking intervals.

We found that upon cessation of the last hiking bout there was an abrupt recovery of tissue oxygenation with a half-time of only 8 ± 2 s. Recovery times in the range of 10 to 15 s have been shown to be associated with low levels of lactate concentration during whole-body dynamic exercise (approximately $3 \text{ mmol}\cdot\text{l}^{-1}$) and are indicative of a moderate imbalance of oxygen supply in relation to the oxygen demand [5]. In fact after isometric exercise the re-oxygenation rate is known to be influenced more by the muscle oxygen demand than by its oxygen supply, thereby closely reflecting the muscle's oxidative status [12]. Accordingly, the small re-oxygenation rate found in the present study after hiking suggests that the quadriceps oxidative capacity during the contraction was adequately preserved.

Post-exercise quadriceps re-oxygenation was completed in $2\frac{1}{2}$ min, whereas as in the study by Spurway and Burns [15], whole body $\dot{V}\text{O}_2$ returned to pre-exercise levels within 3 min, thus confirming that the oxygen deficit during hiking was rather small. Interestingly, as in the study by Spurway and Burns [15], recovery was characterized by an overshoot in $\dot{V}\text{O}_2$ lasting 30 s before returning towards baseline. The overshoot phenomenon was also apparent during the first 30 s of each bout in this study. A possible explanation of this phenomenon is that blood with high CO_2 and low O_2 content together with lactate and other metabo-

lites, having been partly trapped in the contracting muscles, may have surged into the circulation at cessation of each bout, thus transiently stimulating ventilation. Transient hyperventilation during the relief tacking intervals and early into the recovery has been previously demonstrated in a similar simulation study [19]. Furthermore, 3-min into recovery total haemoglobin volume was significantly higher compared to baseline, indicating marked hyperaemia following muscle relaxation. This finding is in agreement with the findings by Spurway and Burns [15] who reported that femoral blood flow velocity subsided towards baseline after several minutes following cessation of a 3-min contraction at 30% MVC, but contrasts the findings by Wesch [20] who reported that post-exercise hyperaemia lasted 1 ½ min following a briefer (2-min) isometric contraction sustained at 30% MVC.

Upon cessation of exercise we observed a rapid restoration of blood volume, which was clearly faster than that of quadriceps re-oxygenation, similarly to what has been reported for dynamic and static exercise [5,12]. Presumably, during the tacking manoeuvres such brief periods of blood flow between bouts of restriction were of great benefit, as they allowed partial tissue re-oxygenation. Indeed, we observed that tissue oxygenation during the first 30 s of each successive bout was elevated, thus reflecting partial tissue re-oxygenation and re-synthesis of bioenergetics. Collectively, both factors would be expected to reduce the magnitude of the oxygen deficit during hiking, thus explaining to some degree the commonly reported low blood lactate concentration [1,8,15,18,19]. However, it should be emphasized at this stage that our findings apply to the specific protocol employed in the present study since the duration of both hiking bouts and resting intervals may influence the physiological demands of quadriceps.

Our findings have important implications not only for the specific sport but also for exercise physiology, since the present study demonstrated that isometric exercise can be sustained for relatively long periods of time by the introduction of brief periods of muscle relaxation. As with interval dynamic exercise, this type of intermittent isometric exercise can be endured with little lactate production at intensities that otherwise could not be sustained without intervals of muscle relaxation between the bouts of isometric work. Thus, it is suggested that the intermittent nature of hiking allows sailors to perform this physically challenging effort for several minutes during each regatta participating in two or even three regattas per day.

In conclusion, it is suggested that the observed modest blood lactate concentration values seen during dinghy hiking are attributed to the small oxygen and energy deficits, as quadriceps blood supply is moderately preserved throughout the contraction, whereas during the brief rest intervals the muscles' oxygen accessibility is partially restored. Accordingly, sailors should practice during hiking to continuously adjust boat trim by fore and aft body movements so as to momentarily relax to some degree the lower limb muscles, thus facilitating muscle perfusion.

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