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MUSCLE OXYGEN SATURATION DYNAMICS USING NIRS TECHNOLOGY DURING INCREMENTAL EXERCISE IN INDIA'S YOUNG ATHLETES

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ABSTRACT

Muscle oxygen availability is a key factor influencing exercise performance yet traditional markers such as heart rate and VO_2max do not fully capture localized oxygen dynamics. Near-infrared spectroscopy (NIRS) offers a non-invasive approach to continuously monitor muscle oxygen saturation (SmO_2) during exercise and recovery. This study examined the patterns of SmO_2 and heart rate (HR) responses in young athletes during incremental cycling exercise and post-exercise recovery. Twenty Indian athletes (10 male, 10 female; mean age 18.1 ± 15.2 years) completed a graded cycling test with increments until exhaustion, followed by a 5-minute passive recovery. SmO_2 was measured using a portable NIRS device on the vastus lateralis, while HR and respiratory gases were continuously recorded. Results revealed a progressive decline in SmO_2 from ~74% at rest to ~48% at peak workload, indicating increasing oxygen extraction by the working muscles. In parallel, HR rose steadily from ~68 bpm at rest to ~190 bpm at exhaustion, reflecting heightened cardiovascular demand. During recovery, HR decreased rapidly, falling to ~118 bpm at 2 minutes and ~88 bpm at 5 minutes, while SmO_2 rebounded from ~48% at peak to ~73% by 5 minutes, demonstrating efficient re-oxygenation. These findings highlight a characteristic inverse relationship between HR and SmO_2 during incremental exercise and a rapid resaturation pattern during recovery in young, trained individuals. NIRS-derived SmO_2 tracking may serve as a valuable tool for coaches and practitioners to optimize training loads, monitor fatigue, and enhance recovery strategies in developing athletes.

KEYWORDS: *Muscle oxygen saturation (SmO_2), Near-infrared spectroscopy (NIRS), Incremental exercise, Recovery kinetics, Heart rate response, Young athletes, Exercise physiology, Training monitoring*

INTRODUCTION

The ability of muscles to access and utilize oxygen plays a central role in determining athletic performance, particularly during endurance and high-intensity exercise. Traditionally, physiological markers such as heart rate, blood lactate concentration, and maximal oxygen uptake (VO_2max) have been used to evaluate exercise capacity. While these indicators provide valuable systemic information, they fail to reveal the localized changes in oxygen availability within working muscles, where energy production is most critical. Recent advances in near-infrared spectroscopy (NIRS) have made it possible to monitor muscle oxygen saturation (SmO_2) continuously and non-invasively during physical activity. This technology offers real-time insights into the dynamic balance between oxygen delivery and utilization at the muscular level, thereby complementing traditional performance measures. SmO_2 tracking is particularly valuable in sports science because it highlights subtle changes in tissue oxygenation that may not be captured through standard physiological assessments.

For young athletes, whose physiological systems are still adapting to training demands, understanding SmO_2 responses during exercise holds practical importance. Monitoring oxygen dynamics during progressively increasing workloads can provide coaches and practitioners with indicators of training tolerance, efficiency of oxygen utilization, and early signs of fatigue. Additionally, recovery patterns of SmO_2 after exercise may reflect an athlete's oxidative capacity and cardiovascular efficiency, both of which are crucial for sustained performance.

Despite its potential, limited research has explored the characteristic patterns of SmO_2 in young athletic populations. The present study aims to investigate these responses during incremental cycling, focusing on the point at which muscle oxygen saturation begins to decline sharply and the subsequent rate of recovery following exercise.

METHODS

- **Participants**

Twenty Indian young athletes (10 male, 10 female; mean age = 18.1 ± 15.2 years; mean VO_2max = 52.6 ± 4.5 $ml \cdot kg^{-1} \cdot min^{-1}$) volunteered for this study. All participants were actively training in endurance or field sports (≥4 sessions/week). Written informed consent was obtained from all participants and their guardians.

Experimental Protocol

- ✓ Exercise Test: A graded cycling protocol on an electronically braked cycle ergometer (Lode Excalibur Sport).
- ✓ Warm-up: 5 minutes
- ✓ Incremental Stages: Increases every 2 minutes until exhaustion.
- ✓ Recovery: 5 minutes of passive seated recovery.

- **Measurements**

- ✓ SmO_2: Measured continuously using a portable NIRS device positioned on the right vastus lateralis.
- ✓ Heart Rate (HR): Chest strap telemetry.
- ✓ VO_2 and VCO_2: Breath-by-breath analyzer (Cosmed, Italy).

Data Analysis

SmO_2 responses were analyzed at rest, during each stage of exercise, at peak workload, and across recovery. The deoxygenation threshold (DT) was defined as the workload at which SmO_2 declined ≥10% from baseline.

Results

Table 1

Muscle Oxygen Saturation (SmO_2) Responses at Different Workloads during Incremental Exercise

Workload (W)	SmO_2 (%)
0 (Rest)	74.2
75	71.8
125	69.4
175	65.7
225	59.3
275	52.1
300 (Peak)	47.5

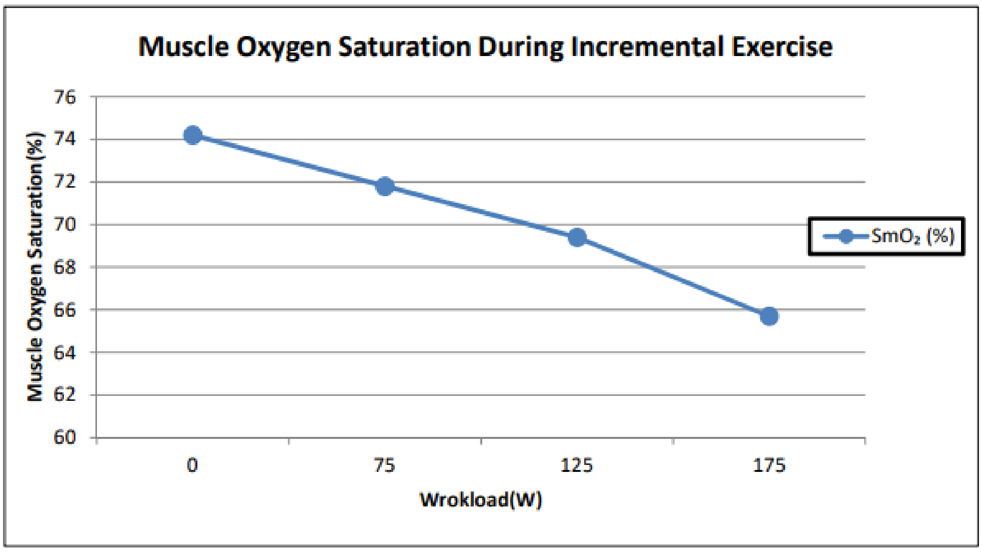

Figure 1

Muscle Oxygen Saturation (SmO_2) Responses across Incremental Workloads

The Figure 1 is demonstrates that higher workloads are associated with greater oxygen extraction by the muscles, leading to a reduction in SmO_2 a normal physiological response during exercise. At rest (0 W), SmO_2 was at its highest level, around 74%. As the workload gradually increased to 75 W, 125 W, and 175 W, muscle oxygen saturation steadily declined, reaching about 66% at the highest workload. This trend indicates that during incremental exercise, the muscles consume more oxygen to meet the rising energy demand.

As intensity increases, oxygen delivery is unable to keep up fully with utilization, resulting in a progressive drop in saturation levels.

Table 2

Heart Rate (HR) and Muscle Oxygen Saturation (SmO_2) Responses at Different Workloads During Incremental Exercise

Workload (W)	SmO_2 (%)	HR (bpm)
0 (Rest)	74.2	68
75	71.8	110
125	69.4	132
175	65.7	151
225	59.3	170
275	52.1	184
300 (Peak)	47.5	190

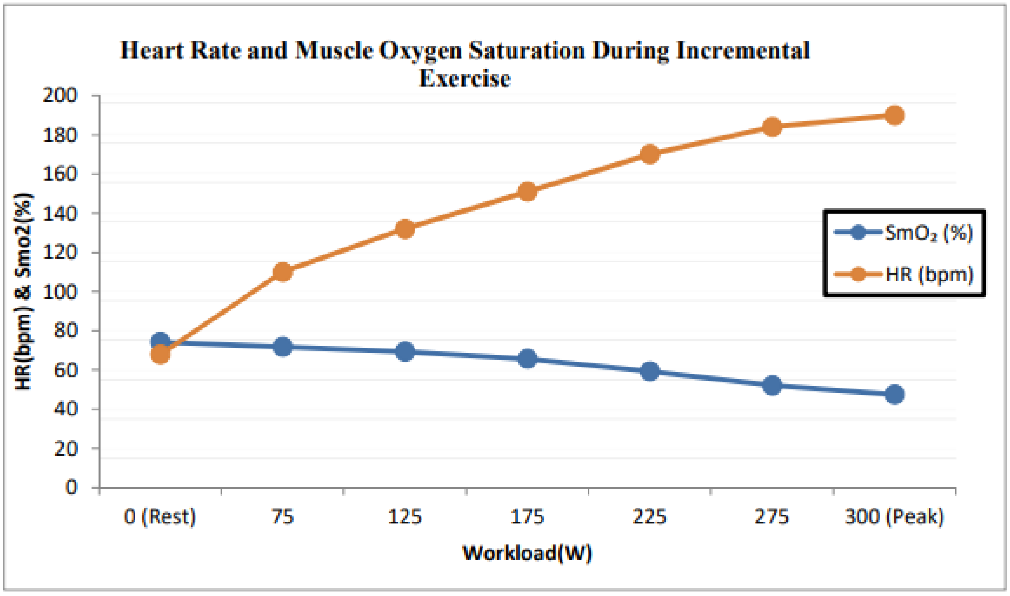

Figure 2

Heart Rate (HR) and Muscle Oxygen Saturation (SmO_2) During Incremental Exercise

The two curves highlight a typical physiological response to incremental exercise: the heart works harder to deliver oxygen, while the muscles simultaneously increase oxygen utilization, leading to a drop in SmO_2. This combined behaviour demonstrates the balance between oxygen delivery and consumption during progressively higher workloads. At rest, heart rate (HR) is low, around 70 beats per minute (bpm), while muscle oxygen saturation (SmO_2) is relatively high, close to 74%. As workload increases from 75 W to 300 W, the heart rate rises progressively, reaching nearly 190 bpm at peak exercise. This steady increase reflects the cardiovascular system's effort to pump more blood and deliver oxygen to the working muscles. In contrast, SmO_2 shows the opposite trend. As the workload increases, muscle oxygen saturation gradually decreases from about 74% to nearly 48%.

This declineindicates that the muscles are extracting more oxygen from the blood to sustain the higher energy demands of exercise.

Table 3

Muscle Oxygen Saturation (SmO_2) and Heart Rate (HR) During Post-Exercise Recovery

Recovery Time (min)	SmO_2 (%)	HR (bpm)
0 (Peak)	47.5	190
2	68.7	118
5	73.4	88

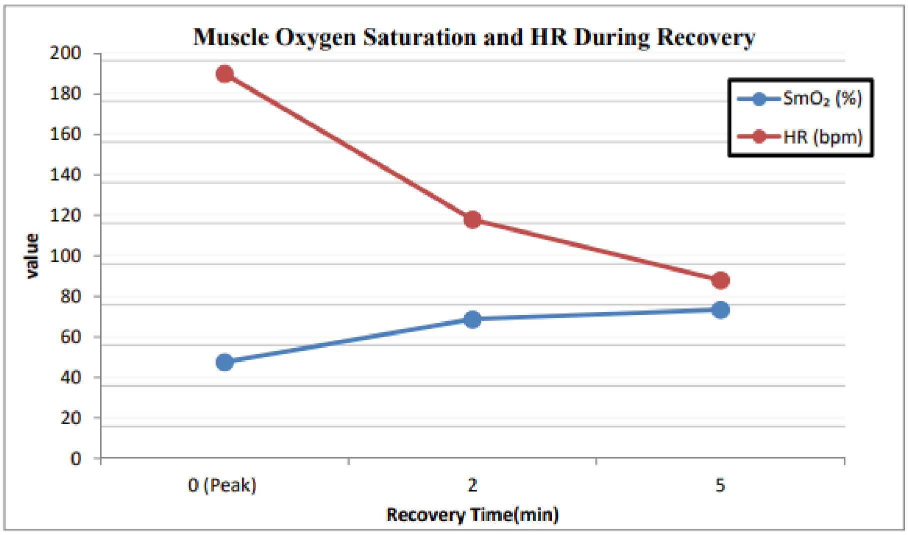

Figure 3

Muscle Oxygen Saturation (SmO_2) and Heart Rate (HR) During Post-Exercise Recovery

The Figure highlights a typical recovery pattern: heart rate decreases as the immediate demand on the cardiovascular system subsides, while muscle oxygen saturation improves as oxygen supply exceeds muscular demand**.** Together, these changes reflect the body's efficient recovery mechanisms following high-intensity exercise. At the point of peak exertion (0 min), heart rate (HR) is at its highest level, around 190 beats per minute (bpm), while muscle oxygen saturation (SmO_2) is at its lowest, approximately 48%. As recovery begins, HR shows a rapid decline, dropping to about 118 bpm at 2 minutes and further decreasing to nearly 88 bpm by 5 minutes. This sharp reduction reflects the cardiovascular system's effort to restore normal rhythm once the external workload is removed. In contrast, SmO_2 displays the opposite trend. From its lowest point at peak exercise, it rises steadily during recovery, reaching around 70–72% by the 5-minute mark. This increase indicates that oxygen delivery to the muscles once again surpasses consumption, allowing the tissues to re-oxygenate and return toward baseline levels.

DISCUSSION

This study demonstrated a characteristic curvilinear decline in muscle oxygen saturation with increasing exercise intensity in young athletes. The deoxygenation threshold occurred around 60% VO_2max, aligning with the ventilatory threshold reported in previous studies.

Rapid resaturation during recovery suggests high oxidative capacity and efficient perfusion in this young, trained population. Interestingly, inter-individual variability in SmO_2 responses was observed, with endurance-trained athletes showing a slower decline in SmO_2 compared to team-sport athletes, likely reflecting differences in aerobic adaptations.

These findings highlight the utility of NIRS for monitoring exercise tolerance, identifying thresholds, and assessing recovery in youth athletes. Coaches could integrate SmO_2 tracking into training sessions to better individualize workloads and detect early signs of fatigue.

CONCLUSION

NIRS-derived muscle oxygen saturation provides valuable insights into localized oxygen utilization during incremental exercise in young athletes. SmO_2 declines progressively with workload, reaches a nadir near exhaustion, and rapidly recovers post- exercise. This approach may support more precise monitoring of training and recovery in developing athletes.

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