Application of Near Infrared Spectroscopy to Exercise Sports Science

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Abstract/Résumé
Over the past 15 years the use of near infrared spectroscopy in exercise and sports science has increased exponentially. The majority of these studies have used this noninvasive technique to provide information related to tissue metabolism during acute exercise. This has been undertaken to determine its utility as a suitable tool to provide new insights into the heterogeneity and regulation of local tissue metabolism, both in cerebral and skeletal muscle tissue. In the accompanying articles in this symposium, issues related to the principles, techniques, limitations (Ferrari et al., 2004), and reliability and validity of NIRS in both cerebral and skeletal muscle tissue (Bhambhani, 2004), mostly during acute exercise, have been addressed and will not be discussed here. Instead, the present paper will focus specifically on the application of NIRS to exercise sports science, with an emphasis on how this technology has been applied to exercise training and sport, and how it can be used to design training programs for athletes.

On remarque, depuis 15 ans, une augmentation marquée de l’utilisation de la spectroscopie en proche infrarouge (NIRS) dans les sciences du sport et de l’exercice. La majorité des études pratiquait cette technique non effractive pour obtenir des données concernant le métabolisme tissulaire au cours d’un effort donné. Ces études vérifiait la justesse d’utilisation de cet outil afin de jeter plus de lumière sur l’hétérogénéité et la régulation du métabolisme

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Application of NIRS

Introduction

Until recently, the majority of NIRS publications in the literature have examined the utility of NIRS to measure tissue oxygenation in the brain and in skeletal muscle using a variety of experimental models (e.g., neonatal, elderly, diseased, clinical, normal health populations, and during exercise). Recently, Quaresima et al. (2003) provided an excellent first review of the literature on the use of NIRS in sports medicine. In their review they documented the main sports that have used this noninvasive technology including Alpine skiing, cross-country running, treadmill running, rowing, power-lifting and weight-lifting, simulated cycling time-trials, speed skating, sprinting, and arm cranking. Healthy untrained individuals as well as trained athletes have served as subjects for these research projects. However, much of this review by Quaresima et al. (2003) includes a summary of NIRS instrumentation and the role of NIRS in muscle exercise physiology, but it does not discuss in detail the application of NIRS to exercise sports science.

Therefore, the present brief review will discuss the research that specifically documents the use of NIRS as a potential tool to play an important role in monitoring applied sports science and exercise prescription. A number of these studies are listed in Table 1. However, this brief review will not discuss the principles, reliability, validity, and limitations of NIRS, as this is discussed in detail by Ferrari et al. (2004) in the accompanying symposium paper. As well, the accompanying article by Bhambhani (2004) discusses the uses of NIRS for studying the peripheral response to dynamic acute exercise.

Acute Exercise and Applied Sports Science Studies

Evaluation of Physical Fitness Using NIRS

A variety of techniques and tools have been used to evaluate an individual’s physical fitness. The most common and well accepted is that of maximal oxygen consumption. Using expired air, the gas law principles (i.e., Haldane transformation), and the principles of work and bioenergetics, it is possible to indirectly measure energy metabolism during exercise (Hill et al., 1924).

Recently however, Chance and co-workers (1992) were the first to use NIRS to study human muscle bioenergetics and its application in sports science. Using a group of well-trained rowers, they examined the degree to which O2 supply and utilization occurred during a simulated (2000 m) competition on a rowing ergometer (6–6.5 min), and the recovery time for hemoglobin/myoglobin (Hb/Mb) deoxygenation after exercise, to determine whether this information could be used to
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<td>Cycling</td>
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<td>NIRS signal reflected changes in endurance training.</td>
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<td></td>
<td>%Mox</td>
<td>VT was detected using NIRS (r = 0.90).</td>
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<td></td>
<td>ΔHb/MbO₂</td>
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<td></td>
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<td>Greater muscle deoxygenation in athletes vs. sedentary.</td>
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<td>Weight-lifting</td>
<td>ΔHb/MbO₂</td>
<td>Increased deoxygenation at onset of lifting exercise; Anoxia occurred due to a</td>
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<td>restriction of venous blood flow.</td>
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<td>No difference in de-HbO₂ between resistance training protocols; Delay in postexercise</td>
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<td>Simulated 20-km</td>
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<td>Simulated 2000-m</td>
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<td>rowing</td>
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<td>– 100-m field</td>
<td>ΔHb/MbO₂</td>
<td>possibly detects fitness level.</td>
<td>Quaresima et al., 1999</td>
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Note: Blood volume (BV); ventilation threshold (VT); blood flow (BF); desaturation (de-HbO₂); change in oxygenation (ΔHbO₂); %ODΔ used to indicate change in hemoglobin/myoglobin oxygen desaturation; muscle oxygenation expressed as a % of maximal physiological range.
enhance future athletic performance. Their main findings showed that reoxygenation times following exercise increased with work intensity from 70% to 100% maximal voluntary contraction (MVC), and that recovery from maximal deoxygenation in the quadriceps muscle group was prolonged and extended with a higher intensity of exercise.

Secondary findings showed that the abrupt deoxygenation occurred within the first minute, and then continued to decline at a slower rate until termination of the test. Furthermore, it was demonstrated that reoxygenation varied between right and left thigh muscles, indicating the asymmetry of the muscle groups during dynamic bilateral leg exercise in rowing for these particular athletes. As well, the recovery time for oxy-Hb/Mb (Hb/Mb-O2) was related to the plasma lactate concentration (their Figure 11, p. C772; $r^2 = 1.00$), indicating a Bohr effect with the unloading of O2. In summary, Chance et al. (1992) suggested that the reoxygenation times determined using NIRS provided a noninvasive indication of the degree of localized O2 delivery stress. Furthermore, it was suggested that individual differences in deoxygenation and reoxygenation changes during both exercise and recovery could serve as an indication of training state of the athlete, i.e., accelerated recovery of deoxygenation in trained vs. less-trained vs. control individuals. Since the inception of this hypothesis by Chance et al. (1992), a number of studies have also provided evidence to suggest that NIRS may be a potential tool to examine the differences in physical fitness of subjects.

One such study is that of Bae et al. (1996) which explored the differences in oxygenation and total hemoglobin volume (tHb) changes between athletes (5 male triathletes; VO2max = 65.8 ml·kg$^{-1}$·min$^{-1}$) and healthy sedentary individuals (7 males; VO2max = 48.6 ml·kg$^{-1}$·min$^{-1}$) using NIRS. They found that the athletes showed a greater deoxygenation than the sedentary group at the lactate threshold (LT) (73% vs. 96%) and at VO2max (42% vs. 63%, respectively). These results suggested that the athletic group had a greater capacity for O2 supply to the working muscles both at the LT and at VO2max, and furthermore inferred that endurance athletes have a greater capacity for O2 diffusion and extraction in exercising skeletal muscle. This is consistent with the plethora of research showing the mitochondrial (enzymatic) adaptations to endurance training. Furthermore, these results by Bae et al. (1996) confirmed the observations reported by Chance et al. (1992) that NIRS has the potential to detect differences in physical fitness level.

In another study to address this issue, Ding et al. (2001) used a group of elite male athletes ($n = 18$) and normal healthy control male subjects ($n = 8$). The subjects performed cycle ergometry exercise in 50-watt increments until volitional fatigue. The data were analyzed and number of variables were compared that can be used to potentially assess oxidative metabolism, including speed of recovery of muscle oxygenation after cessation of exercise ($R_R$), the half recovery increment of oxygenation saturation during the recovery period ($h$), and the relative value of effective decrease in muscle oxygenation, i.e., change from baseline to maximal deoxygenation. Ding et al. concluded from their research that: (a) these variables are appropriate for assessing oxidative metabolism by NIRS during exercise; (b) significant differences were found in these variables between the elite athletes and the healthy controls; and (c) this methodological approach could have application in areas such as athletic training, rehabilitation, and sports medicine.
Takaishi et al. (2002) used NIRS to examine the differences in cycling experience and pedal cadence, and showed that these parameters had an effect on muscle oxygenation and blood volume changes. Using competitive cyclists ($n = 6$), recreational triathletes ($n = 6$), and healthy male subjects ($n = 6$), Takaishi et al. found significant differences in muscle oxygenation between the experimental groups at higher cycling cadences. Their results revealed a significant main effect for cycling experience when comparing triathletes and cyclists vs. noncyclists during acute exercise at cycling cadences of 50, 75, and 85 rpm. This demonstrated that cycling experience and pedal cadence had a significant effect on the NIRS parameters (Takaishi et al., 2002), and that NIRS could be used to differentiate between fitness levels (i.e., experience) based on the oxygenation and blood volume vs. crank angle pattern.

Other acute-exercise studies which indirectly support the contention that NIRS can be used to monitor physical fitness include those by Neary et al. (2001; 2002) using a simulated 20-km time trial, both during acute exercise and following chronic exercise training; Puente-Maestu et al. (2003) documented that after endurance training in a group of patients with chronic obstructive pulmonary disease, post-training reoxygenation kinetics was faster; and Costes et al. (2001) revealed that after 4 weeks of endurance training in a group of health untrained male ($n = 5$) and female ($n = 2$) subjects, the pattern of NIRS during constant workload exercise could provided some insight into the subject’s physical fitness.

However, not all studies support the use of NIRS in its application as a noninvasive technique for muscle metabolism or hemodynamics, and thus for the evaluation of physical fitness. Recent studies by Hicks et al. (1999) and MacDonald et al. (1999) did not find a correlation between muscle oxygenation by NIRS and venous blood $O_2$ saturation measured by direct venous blood sampling and Doppler ultrasound. These studies showed that hemodynamic differences were found using these techniques during isometric forearm exercise (10% and 30% MVC), and during mild-intensity dynamic leg exercise (48 W), respectively.

Contrary to these results, Fadel et al. (2003) used both NIRS and Doppler ultrasound to examine reflex sympathetic activation evoked by lower body negative pressure. They demonstrated that the decreases in NIRS signals observed during sympathetic activation primarily reflected arteriolar and not venular constriction. These results are also supported by the work of Boushel et al. (1998), who found that changes in NIRS-$O_2$ saturation of the forearms during handgrip exercise (15% and 30% MVC) was consistent with magnetic resonance spectroscopy (MRS) which determined metabolic rate, but was not reflected by regional changes in oxygen saturation in venous blood ($SvO_2$). Furthermore, Boushel et al. (1998) suggested that the discrepancies between NIRS-$O_2$ and $SvO_2$ indicated there are significant limitations in sampling regional venous blood to measure metabolic rate.

This is also supported by the work of van Beekvelt et al. (2001), who showed that there are differences between local and global muscle VO$_2$ data using NIRS, and that are derived from the Fick method and plethysmography. Thus, the discrepancy between the NIRS and femoral results reported by both MacDonald et al. (1999) and Hicks et al. (1999) is likely related to the area of sampling of the NIRS probe (localized to the small vessels) vs. the regional venous return from the entire
leg musculature (obtained from direct venous blood sampling). However, it is agreed, as suggested by these authors, that further research is needed to examine the contribution of myoglobin to the NIRS signal, and to what extent the contribution of the signal is related to arteriolar vs. venular sampling. This would add significantly to this area of research.

EVALUATION OF HEMODYNAMICS USING NIRS

A series of studies undertaken by Foster, Rundell, and co-workers (Foster et al., 1999; Rundell et al., 1997; Szmedra et al., 2001) used NIRS to examine what they termed the “Reduce Blood Flow Hypothesis” in sporting events such as speed skating and downhill (Alpine) skiing, including simulated cross-country skiing using treadmill roller skiing. Such events reportedly create high intramuscular pressures. Successful performance in these sports requires an optimal balance between the biomechanical and physiological properties of the muscle. Thus, this research group examined the effects of changing the knee and hip joint angle on muscle oxygenation and tHb, and its consequence for anaerobic metabolism to investigate the “tug-of-war” between biomechanics and physiology in relation to body posture and subsequent performance.

Since NIRS can measure regional tHb changes, and can thus be used as an indirect measure of blood flow (Boushel et al., 2000; DeBlasi et al., 1994), Rundell et al. (1997) and Foster et al. (1999) hypothesized that the metabolic information garnered could assist in the design of training programs for these groups of athletes. Their results showed that there was a reduced tHb during low posture positions in comparison to the high posture position during both speed skating and downhill skiing (giant slalom). This suggests that O₂ delivery can be compromised, and thus can lead to an increased onset and acceleration of anaerobic metabolism. This will facilitate the unloading of O₂ from Hb.

In fact, Rundell et al. (1997) reported a 59% greater change in muscle deoxygenation in the quadriceps of speed skaters in the low skating position, and Foster et al. (1999) showed lower peak VO₂, cardiac output, and greater deoxygenation changes in elite long-track speed skaters in the same (low) position. Muscle deoxygenation was related to knee and hip joint angle, blood lactate concentration, and heart rate, but not to whole-body O₂ uptake. Furthermore, the increased muscle deoxygenation was associated with the increased blood lactate, high intramuscular forces, and long duty cycle in skating. They concluded that NIRS provided a reliable method for evaluating the metabolic aspects of postural positions during speed skating and downhill skiing, and that intramuscular pressure exceeded perfusion pressure in some positions which limited blood flow to exercising muscle, thus confirming their proposed “reduce blood flow hypothesis” (Foster et al., 1999; Rundell et al., 1997; Szmedra et al., 2001).

In contrast to these results, Im et al. (2001) did not show a greater deoxygenation at a higher incline level during treadmill roller skiing in a group of endurance trained cross-country skiers. This may be partly related to the shorter duty cycle and increased upper body muscle mass utilized during polling. Instead they documented a strong relationship between percent deoxygenation and whole-body VO₂ (r = 0.83), illustrating that oxidative metabolism in the muscle can be successfully monitored using noninvasive NIRS. This is supported by the work of Miura et al. (2003).
Szmedra et al. (2001) also explored the relationship between muscle deoxygenation and cross-sectional area of the quadriceps muscle by using slalom (SL) and giant slalom (GS) skiers ages 9–18 years. Confirming the results stated above, i.e., increased muscle deoxygenation during the GS is consistent with an increase in anaerobic energy consumption (i.e., higher blood lactate), all skiers showed a greater absolute deoxygenation during the GS (low-posture) position. This study was therefore the first applied field research during Alpine skiing to confirm a restricted blood-flow hypothesis using NIRS. Invasive techniques (indocyanide green intravascular tracer) have been used simultaneously with NIRS to reliably measure blood flow in cerebral tissue (Elwell et al., 1994; Roberts et al., 1993) and skeletal muscle tissue (Boushel et al., 2000).

PROLONGED ENDURANCE EXERCISE USING NIRS

Although Chance et al. (1992) were the first to use NIRS during simulated rowing competition (6 minutes), Neary et al. (2001) were the first to examine muscle deoxygenation changes during prolonged (23–32 min) high intensity (85–90% VO2max) endurance exercise. Using trained male cyclists (VO2max = 61 ml·kg–1·min–1; n = 10) during a race-simulated 20-km cycling time trial competition on a set of wind-loaded rollers, and during incremental exercise to volitional fatigue (VO2max), muscle deoxygenation—as reflected by a qualitative change in tissue absorbency, mV—was recorded continuously from the right vastus medialis muscle. The results showed an initial rise and then a gradual steady decline in tissue absorbency until termination of the incremental test.

This trend was identical to that observed by others during incremental maximal exercise (Belardinelli et al., 1995; Bhambhani et al., 1997; Costes et al., 1996). However, during the simulated 20TT race, muscle oxygenation rapidly decreased at the onset of exercise (0–2 km) and continued to decline gradually until the end of the race to a level 59% lower (i.e., greater deoxygenation) than the incremental VO2max test (–699 vs. –439 mV). This was a consistent pattern or trend in the data (Figures 1 and 2). In addition, during both active (2 min) and passive (4 min) recovery, muscle oxygenation remained below resting baseline levels following the 20-km time trial. This research revealed two important observations: (a) the deoxygenation of the vastus medialis muscle during the 20-km time trial exceeded that observed during the incremental VO2max test, despite the fact that whole-body VO2 was significantly greater during the latter test; and (b) the recovery in muscle oxygenation was significantly delayed and did not reach preexercise conditions during the 6-min recovery period following the 20-km time trial race.

Neary et al. (2001) concluded that despite a similar trend in the muscle deoxygenation profile between the two tests, the longer duration simulated race condition elicited a greater deoxygenation probably as a result of a higher intramuscular temperature, longer sustained lactic acidosis, lower pH, and possibly changes in motor unit recruitment.

In addition to the muscle oxygenation differences between the incremental VO2max and 20TT tests, another observation from this study was that O2 pulse, an indication of O2 utilization per heart beat, was significantly higher at the termination of the 20-km time trial vs. the incremental test (23.8 ± 1.8 vs. 22.1 ± 3.1 mL O2·beat–1, respectively). It has been reported that O2 pulse is a strong predictor of...
Figure 1. Group mean ($n = 10$) tissue absorbency (Hb/Mb-O$_2$; mV) during incremental VO$_2$max test and 20-km time trial with time to exhaustion normalised to 100%. AR = active recovery; PR = passive recovery. (Reprinted with permission from European Journal of Applied Physiology: “Vastus medialis muscle oxygenation trends during a simulated 20 km cycle time trial,” by J.P. Neary, K. Hall, and Y.N. Bhamhani, Vol. 85, pp. 427-433. © 2001 by Springer-Verlag.)

Figure 2. Tissue absorbency (Hb/Mb-O$_2$; mV) vs. actual time (seconds) during incremental VO$_2$max test and simulated 20-km time trial for an individual subject (DN). AR = active recovery; PR = passive recovery. (Reprinted with permission from European Journal of Applied Physiology: “Vastus medialis muscle oxygenation trends during a simulated 20 km cycle time trial,” by J.P. Neary, K. Hall, and Y.N. Bhamhani, Vol. 85, pp. 427-433. © 2001 by Springer-Verlag.)
stroke volume (Bhambhani et al., 1994). Physiologically this indicates that there was a greater stroke volume and an overall greater extraction of O₂ during the simulated competition.

EXERCISE TRAINING STUDIES

To date, four studies have used NIRS to examine the effects of exercise training on muscle deoxygenation: Costes et al. (2001); Usaj (2001); Neary et al. (2002); and Puente-Maestu et al. (2003). These studies all showed that NIRS is a promising technique that could be used to examine the influence of exercise training on muscle oxygenation and reoxygenation following exercise (Table 2).

Costes et al. (2001) first examined the influence of submaximal exercise cycle training on muscle oxygenation of the quadriceps muscle group using a group of healthy untrained subjects (posttraining VO₂max = 47 ml·kg⁻¹·min⁻¹). They hypothesized that local adaptations (increased capillary density, decreased lactic acid) would increase oxygenation in the muscle (i.e., reduce deoxygenation effect). Before and after 4 weeks of endurance training (120 min × 6 days·week⁻¹ × 70–80% HRmax), all subjects performed a 15-min bout of steady-state cycling exercise at both 50% and 80% of their preprogram VO₂max. Exercise training did not influence the pattern of muscle O₂ saturation at the 50% workrate, but during exercise at the 80% workrate the muscle O₂ saturation was significantly greater after training, i.e., less deoxygenation occurred as a result of training at the same relative workrate. However, hemoglobin volume (tHb) was significantly increased after training at both the 50% and 80% workrates.

Costes et al. (2001) concluded that changes in muscle tHb may reflect the recruitment of unperfused capillaries during exercise and provide a better matching of capillary flow to the metabolic demand. Additionally, the influence of blood lactate on muscle O₂ saturation was reduced with training (i.e., diminished Bohr effect), and the increased oxidative metabolism (elevated citrate synthase and β-hydroxyacyl CoA dehydrogenase enzymes) would suggest an increased O₂ extraction. In summary, they concluded that NIRS was able to assess the overall adaptation as a result of endurance training in these healthy untrained individuals.

In the study by Usaj (2001), the use of NIRS in a group of 6 male subjects showed that a 4-week endurance-training program of the forearm musculature increased submaximal isometric contraction duration. Although maximal isometric force development with training was not significantly affected, the increased duration of submaximal contraction was likely related to changes in muscle characteristics with training, and this resulted in part in an observed greater deoxygenation before termination of muscular contraction.

Research by Puente-Maestu et al. (2003) showed that 6 weeks of endurance exercise training improved muscle oxidative capacity (citrate synthase) and endurance time in patients with chronic obstructive pulmonary disease. As well, the time constant of the deoxygenation recovery signal (tHbO₂) was significantly reduced at workrates below and above the lactate threshold. This indicates that there was an improvement in reoxygenation after training, and would support the work of Chance et al. (1992) showing that highly trained athletes recover faster than less trained individuals. Furthermore, these changes in muscle tHbO₂ correlated (r = 0.76) with changes in citrate synthase enzyme activity in muscle biopsy samples.
Table 2 Exercise Training Studies That Have Used NIRS to Examine Changes in Oxidation in Skeletal Muscle

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<th>Duration/ Intensity</th>
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| Costes et al.   | College-age males ($n = 5$)     | 4 weeks                                  | Steady state submax cycling (15 min) @50% and 80% VO$_2$max | 1. Increased blood volume after training.  
                              | College-age females ($n = 2$)    | (120 min × 6d/wk; 70–80% HRmax)          |                                                       | 2. Oxygenation change influenced by training, and NIRS signal may provide insight in physical fitness of subject. |
|                 |                                 |                                          | Isometric forearm grip strength         |                                                       |                                                      |
| Usaj (2001)     | Untrained/healthy males ($N = 6$) | 4 weeks (2×/day, 5d/wk; 30s; progressing by 15s/ wk × 5 contractions) | 20-km time trial VO$_2$max test         | 1. Oxygen saturation was related to improvement in isometric strength.               |
| Neary et al.    | Cyclists (well-trained) males ($N = 10$) | 3 weeks (60 min × 5d/wk; 85–90% VO$_2$max) |                                                        | 1. Individual variability exists.                                                       |
|                 |                                 |                                          |                                        | 2. Mean muscle deoxygenation during 20-kmTT was significantly lower at posttraining. |
|                 |                                 |                                          |                                        | 3. NIRS pattern was not changed with training and not different at same workrate during VO$_2$max. |
|                 |                                 |                                          |                                        | 4. Enhanced VO$_2$max due primarily to central adaptations; improved cycling performance due to local changes in muscle oxygenation. |
|                 |                                 |                                          |                                        | 2. Citrate synthase correlated with deoxygenation recovery signal.                     |
Puente-Maestu et al. (2003) concluded that “NIRS may be a useful non-invasive tool for detecting the adaptations of skeletal muscle to training” (p. 585).

The only study to date that has used well-trained athletes (VO\textsubscript{2max} = 66.1 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}) was conducted by Neary et al. (2002), who investigated the effects of high intensity short-term endurance training (3 weeks) on muscle deoxygenation in experienced competitive cyclists. This was the first study reported in which muscle deoxygenation was significantly greater during a 20-km cycling time trial (simulated criterion performance) after endurance training. Mean muscle deoxygenation (tissue absorbency [mV] measurements were used to reflect muscle deoxygenation) after training (–707 ± 227 mV) was significantly greater than before training (–550 ± 292 mV; Figure 3) despite the large individual differences. Performance time was also significantly faster ($p \leq 0.05$) after training. Furthermore, the use of NIRS to monitor muscle deoxygenation revealed individual differences between cyclists. Individual data plots revealed that 5 of the 8 cyclists had significantly greater muscle deoxygenation at posttraining.

This significant muscle deoxygenation correlated highly with training changes in peak power output ($r = –0.73$), VO\textsubscript{2max} ($r = –0.78$), and 20-km time trial ($r = –0.93$). These data strongly suggest that NIRS can therefore be used to evaluate individual fitness differences in cyclists, and thus indirectly corroborates the findings of the studies of Bae et al. (1996) and Costes et al. (2001) discussed above.

![Figure 3](image-url)

**Figure 3.** Tissue deoxygenation (Hb/Mb-O\textsubscript{2}; Ab, mV) vs. distance (km) during simulated 20-km time trial test before and after endurance training. Values are mean ± SE. #Significance at $p = 0.08$; *Significance at $p < 0.05$. AR = active recovery; PR = passive recovery. (Reprinted with permission from *Medicine and Science in Sports and Exercise*, “Effects of short-term endurance training on muscle de-oxygenation trends using NIRS,” by J.P. Neary, D.C. McKenzie, and Y.N. Bhamhahi, Vol. 34, pp. 1725-1732. © 2002 by Lippincott Williams & Wilkins.)
further illustrate this point, Neary et al. (2002) showed that in one particular subject the trend in tissue deoxygenation matched the submaximal VO\(_2\) changes during the simulated performance ride. For example, this subject recorded his highest VO\(_2\) (4.29 L·min\(^{-1}\)) and greatest deoxygenation (−870 mV) at the 6-km interval. However, he terminated the test with an \(\text{O}_2\) consumption of 3.95 L·min\(^{-1}\) and a tissue deoxygenation of −755 mV.

It was also shown during the incremental (VO\(_2\)max) tests that muscle deoxygenation at identical workrates was not different between pre- and posttraining. This finding differs from that of Costes et al. (2001) as cited above. However, there is no physiological reason why there would be a difference in the oxygen cost at a given power output regardless of whether it was before or after a period of training. Thus, it is likely that the difference between these two studies could be related to a number of factors including: (a) the fact that during the posttraining test in the study by Costes et al. (2001) the subjects exercised at a lower mean percentage (i.e., 80% vs. 73%) of VO\(_2\)max; (b) a difference in the exercise protocol between studies, i.e., 1-min incremental protocol vs. 15-min steady state; and (c) subject population, i.e., trained vs. untrained.

Alternatively, it could indicate a unique finding on the part of Costes et al. (2001) that the reduced deoxygenation after training was related to an increased arterial venous oxygen (a-vO\(_2\)) difference. Although this is speculative, it would support their finding of a significant increase in the oxidative enzymatic activity of citrate synthase. However, this warrants further research. Regardless of the exact reason for these differences at this time, both studies provided their support in the use of NIRS as a noninvasive method for evaluating changes in skeletal muscle deoxygenation resulting from endurance training.

**TAPER STUDIES**

To date, no published study has used NIRS to monitor tissue oxygenation during a taper period. However, we recently completed a pilot study to test the hypothesis that muscle oxygenation changes, as measured by NIRS, do occur in competitive cyclists during a period of tapering (Neary et al., in press). In this pilot study, training intensity was maintained at 85–90% VO\(_2\)max, but training volume was reduced systematically employing either a 30% (T30), 50% (T50), or 80% (T80) reduction in training volume over a 7-day period. An incremental VO\(_2\)max test and a 20-km time trial were performed pre- and posttaper. Although a limitation of this study was the small number of subjects, the results showed that the T50 protocol elicited a 52% greater muscle deoxygenation (−749 ± 324 to −1140 ± 465 mV) with a concomitant increase in VO\(_2\) (0.18 L·min\(^{-1}\)) during the posttaper 20-km time trial. The 20-km time trial performance time was also improved in the T50 group (4.53 %, \(p = 0.057\)).

The general trend for a lower skeletal muscle deoxygenation after tapering supports previous invasive research that peripheral metabolic alteration can occur following a taper (Neary et al., 1992; 2003; Shepley et al., 1992; Trappe et al., 2001). Further research is warranted in this area of exercise sport science to determine the utility of NIRS for detecting changes in local muscle oxygenation during tapering in both well-trained endurance athletes and strength athletes.
RESISTANCE TRAINING STUDIES

Although the application of NIRS to sports and exercise have increased exponentially over the past 15 years, only a few studies have examined the effects of resistance (weight) training exercises on muscle oxygenation. Most recently, Hoffman et al. (2003) examined the relationship between two resistance-training protocols on muscle oxygenation, postexercise reoxygenation, and their relationship to the anabolic hormonal response (Table 1). These researchers used a group (n = 11) of resistance-trained males with 6–8 years experience who performed both a light-intensity, high-volume (15 reps at 60% 1-RM) and a high-intensity, low-volume (4 reps at 90% 1-RM) protocol in a random order separated by a minimum of 72 hours. Hoffman et al. found no significant differences in muscle deoxygenation between protocols despite a tendency for greater tissue deoxygenation (7%) after the high-intensity protocol. However, postexercise reoxygenation, an index of muscle oxygen recovery kinetics, was significantly different. There was a 44% longer delay in the start of reoxygenation after the light-intensity high-volume exercise. Hoffman et al. speculated that the higher lactate accumulation might have accounted for the differences.

A secondary purpose of the study by Hoffman et al. (2003) was to examine the relationship between muscle ischemia (imposed by the high intramuscular pressure during resistance training) and the growth hormone response to the different exercise protocols. The results showed that growth hormone concentrations were influenced by tissue ischemia. The prolonged ischemia after the light-intensity high-volume protocol, reflected by a greater delay in muscle reoxygenation, resulted in a greater growth hormone response compared to the high-intensity low-volume protocol.

The only other published study on resistance training and NIRS was that by Tamaki et al. (1994). Using three groups of subjects—experienced weight-lifters, novice weight-lifters, and a control group of non-weight-lifters—they showed that the quadriceps muscle could become anoxic following a 3-set protocol of 10-repetition maximum. At the beginning of the 10-RM exercise, deoxygenated Hb increased rapidly, oxygenated-Hb decreased rapidly, and tHb (an indirect measure of blood volume) gradually increased to the end of exercise. However, with each set, tHb increased without returning to the resting baseline level. Tamaki et al. concluded that (a) the weight-lifting exercises produced a restriction of arm blood flow, similar to the application of a tourniquet; and (b) this state of ischemia resulted in a relative lack of O₂ supply, i.e., progressive reduction of blood volume and oxygenation in the muscle with an increase in the number of sets.

This relative lack of O₂ supply to the working muscles may be one possible cause for the unexpected high proportion of slow-twitch fibres found in bodybuilders (MacDougall et al., 1982). Therefore, the preliminary results from these studies appear to support the use of NIRS to investigate the relative changes in muscle oxygenation and blood volume during resistance training exercises. Further studies in this area are needed to expand our knowledge regarding the effects of different types of resistance training programs on muscle metabolism, and to determine whether NIRS measurements are consistent with the metabolic adaptations found in the resistance training literature.
Summary

The use of NIRS in sports and exercise science has increased exponentially during the past several years. Based on the available literature, there is sufficient data to show that NIRS can be used as an objective measurement tool for evaluating localized muscle oxidative metabolism and hemodynamics during both acute exercise and following chronic training programs. Data is available to show that NIRS can be used to differentiate physical fitness level, indirectly reflect blood flow changes during acute exercise, and monitor changes in endurance exercise training and during resistance workout exercises. More research is warranted to examine the effects of differing training strategies such as tapering on muscle oxygenation and tHb changes, the contribution of myoglobin to the NIRS signal, and more precisely define the local region of interrogation by the NIRS probe.

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