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Commentary

Best practices for simultaneous measurement of NIRS-based cerebral and muscle oximetry during exercise

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It is a pleasure to contribute a commentary on the very interesting review by Dr. Orcioli-Silva and colleagues[1] on the simultaneous measurements of cerebral cortex and muscle tissue oxygenation during exercise in healthy adults using near-infrared spectroscopy (NIRS). The first NIRS measurements of the cerebral cortex and muscle were performed on humans in 1977[2] and 1982,[3] respectively. Although the first application of NIRS to measure exercising human muscle dates back to 1987,[4] the first simultaneous cerebral and muscle measurements during exercise were published 21 years later in 2008.[5] The simultaneous measurement of an increase in oxygenation of the prefrontal cortex and a decrease in oxygenation of the vastus lateralis muscle was conducted by NIRS oximetry in trained adults during progressive maximal exercise to exhaustion on a cycling ergometer. A total of 19 other studies published over the last 16 years were carefully reviewed by Orcioli-Silva et al.[1] This relatively limited number of studies (performed on 290 adults in total) can be attributed to a number of factors, including (a) the technical difficulties of performing such simultaneous measurements in realistic exercise settings by using the available NIRS devices of varying performance, and (b) the increased complexity of data interpretation, as briefly suggested by Perrey[6] in his commentary on the review article by Orcioli-Silva et al.[1]

Muscle NIRS measurements, even during dynamic exercise, present fewer difficulties than cerebral ones; in fact, we very recently summarized 191 muscle NIRS oxygenation studies published in the last 5 years, including 3435 adult participants in 37 domains of sports activities.[7] A total of 130 studies (68%) employed wearable (i.e., portable) continuous-wave devices with wireless data transmission. These easy-to-use single-point NIRS oximeters were introduced in 2018.[8] Only 6 out of 20 simultaneous brain and muscle studies[9–14] included in the review by Orcioli-Silva et al.[1] used these more suitable wireless continuous-wave NIRS oximeters. One study used a time-domain NIRS oximeter,[15] and another study employed a frequency-domain NIRS oximeter.[16] Notwithstanding the higher cost of these latter 2 oximeters, which is attributable to their technology, they offer the advantage of being less sensitive to the subcutaneous adipose tissue layer and to skin pigmentation. Consequently, their use improves the accuracy of the muscle oxygenation measurements.[17,18] It is of interest to note that the first commercial dual-channel frequency-domain NIRS brain/muscle oximeter has recently received approval from the U.S. Food and Drug Administration.

It is also important to note that in the field of exercise physiology, it is necessary to measure not only muscle and cerebral microvascular oxygenation but also electrophysiological activity and primarily systemic physiological signals related to the state of the cardiorespiratory and autonomic nervous system, such as heart rate, respiratory rate, mean arterial pressure, peripheral arterial oxygenation, and electrodermal activity.[19,20] This approach allows for a comprehensive understanding of the perfusion and consumption of oxygen in active tissue during exercise.[21] In order to achieve this, it is necessary to synchronize different physiological and behavioral data, which can present a challenge. Consequently, dedicated systems such as Lab Stream Layer (LSL) or equivalent are required. LSL offers a convenient means of synchronizing disparate multimodal data streams with heterogeneous sampling rates.

It is important to note that changes in vascular hemodynamics and oxygenation that are not induced by neurovascular coupling (and thus brain activity) can interfere with

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NIRS measurements. These influences can affect both the cerebral and the extracerebral tissue compartments. With regard to the influence of changes in the extracerebral tissue on continuous-wave NIRS devices and the relevance of this for clinical NIRS applications, a recent review concluded that "extracerebral tissue indeed influences NIRS measurement, although the evidence (i.e., correlation) for this influence varies considerably across the assessed studies" and that the "current uncertainty regarding the influence of extracerebral tissue remains a hurdle in the clinical implementation of NIRS for intraoperative monitoring".[22]

Several methods have been developed for the removal of these artifacts and physiological components.[20,21,23,24] For example, short-channel regression algorithms can remove physiological "noise" from the extracerebral tissue layers by subtracting the signal measured at a short source-detector separation (mainly scalp hemodynamics) from that of a long separation (brain and scalp hemodynamics).[25,26] The utilization of a general linear model (GLM) in conjunction with temporally embedded canonical correlation analysis has also been demonstrated to be a valuable method for the regression of physiological noise in NIRS signals.[27]

Unfortunately, only 3 out of the 20 studies reviewed details (alas, insufficient) on NIRS data processing.[11,28,29] The interpretation of NIRS data regarding cerebral oxygenation is complicated by the influence of systemic physiological changes in the cerebral and extracerebral tissue layers, such as those observed during strenuous exercise. In such instances, the observed changes in cerebral oxygenation appear to reflect primarily extracerebral blood flow (mainly extracranial) rather than cerebral cortical oxygenation.[30,31] It is also important to note that NIRS measurement of the head can be influenced by the activity of the temporal muscle, which can lead to misinterpretation of the data.[32–34]

We agree with Perrey's commentary[6] on the review by Orcioli-Silva et al.[1] that NIRS is an exceptional tool in our understanding of the cerebral and muscle microvascular oxygen demand during exercise. However, we strongly recommend that specific signal processing techniques are required for the validity of the NIRS data and for the interpretation of future measurements, which are necessary to confirm the results identified by the review's authors.[1] Furthermore, it is advisable to conduct additional measurements of systemic physiological activity concurrently with NIRS measurements to facilitate accurate interpretation of NIRS measurements, particularly in situations where a change in systemic activity is anticipated.[21] It is recommended that future studies utilize the latest portable/mobile whole-brain continuous-wave NIRS systems with an ultra-low profile, a lightweight design, a high channel count, a large dynamic range, good subject comfort, robust contact with the (haired) scalp, precise timing synchronization, minimal crosstalk, stable data transmission, and long battery life.[35] In order to obtain accurate muscle measurements, it is recommended that lightweight (approximately 20 g), compact, smartphone-controllable, and wearable multi-distance continuous-wave muscle NIRS oximeters with Bluetooth connection up to 150 m and on-board data collection (up to 50 h) are utilized.[7] Furthermore, it is essential to adhere to the recently proposed best practices for muscle and brain NIRS studies. In this context, we also refer to the guidelines for muscle measurements published as a table on "pressing issues to improve the quality in muscle oximetry for sports science" in 2018.[8] As part of the Cores of Reproducibility in Physiology (CORP) initiative of the American Physiological Society, Barstow[17] published a CORP article about the use of NIRS for skeletal muscle research. In that article recommendations were included to reduce variability and errors in data collection, analysis, and interpretation, and best practices were included to improve the reproducibility of muscle oximetry measurements; further guidelines were included in the 2024 review by Perrey et al.[7] In 2018, Herold et al.[36] published recommendations for the application as well as data processing and analysis of NIRS-based cerebral oximetry in exercise−cognition science. More recently, in 2021, a representative group of leaders in the field, members of the Society for Functional Near-Infrared Spectroscopy, published more detailed guidelines.[24] This consensus article delineates the optimal methodologies for describing the techniques employed in brain NIRS studies. It also furnishes guidelines to enhance the reliability, repeatability, and traceability of reported brain NIRS studies and to encourage best practices. A recent review by Klein[37] enumerates several options that could enhance spatial specificity and all preprocessing steps that might improve signal quality in real-time applications.

Authors' contributions

VQ, MF, and FS drafted the manuscript. All authors contributed to the improvement of the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

References

1. Orcioli-Silva D, Beretta VS, Santos PCR, et al. Cerebral and muscle tissue oxygenation during exercise in healthy adults: A systematic review. *J Sport Health Sci* 2024;**13**:459–71.
2. Jöbsis FF. Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *Science* 1977;**198**:1264–7.
3. Giannini I, Ferrari M, Carpi A, Fasella P. Rat brain monitoring by near-infrared spectroscopy: An assessment of possible clinical significance. *Physiol Chem Phys* 1982;**14**:295–305.
4. Takada M, Tamura T, Tamura M. Non-invasive near-infrared measurements of human arm tissues *in vivo*. *Adv Exp Med Biol* 1987;**215**:301–4.
5. Rupp T, Perrey S. Prefrontal cortex oxygenation and neuromuscular responses to exhaustive exercise. *Eur J Appl Physiol* 2008;**102**:153–63.
6. Perrey S. Could near infrared spectroscopy be the new weapon in our understanding of the cerebral and muscle microvascular oxygen demand during exercise? *J Sport Health Sci* 2024;**13**:457–8.
7. Perrey S, Quaresima V, Ferrari M. Muscle oximetry in sports science: An updated systematic review. *Sports Med* 2024;**54**:975–96.
8. Perrey S, Ferrari M. Muscle oximetry in sports science: A systematic review. *Sports Med* 2018;**48**:597–616.

9. Buzza G, Lovell GP, Askew CD, et al. The effect of short and long term endurance training on systemic, and muscle and prefrontal cortex tissue oxygen utilisation in 40 − 60 year old women. *PLoS One* 2016;**11**:e0165433. doi:10.1371/journal.pone.0165433.
10. Buzza G, Lovell GP, Askew CD, Solomon C. The effect of short- and long-term aerobic training years on systemic O_2 utilization, and muscle and prefrontal cortex tissue oxygen extraction in young women. *J Strength Cond Res* 2019;**33**:2128–37.
11. Buzza G, Lovell GP, Askew CD, Solomon C. A comparison of $\dot{V}$ O 2, and muscle and prefrontal cortex tissue oxygen extraction between short and long-term aerobically trained men aged 40 − 60 years. *Int J Exerc Sci* 2020;**13**:964–78.
12. Cherouveim ED, Margaritelis NV, Koulouvaris P, et al. Skeletal muscle and cerebral oxygenation levels during and after submaximal concentric and eccentric isokinetic exercise. *J Sports Sci* 2022;**40**:195–202.
13. Jones B, Cooper CE. Near infrared spectroscopy (NIRS) observation of vastus lateralis (muscle) and prefrontal cortex (brain) tissue oxygenation during synchronised swimming routines in elite athletes. *Adv Exp Med Biol* 2018;**1072**:111–7.
14. Perentis PA, Cherouveim ED, Malliou VJ, et al. The Effects of high-intensity interval exercise on skeletal muscle and cerebral oxygenation during cycling and isokinetic concentric and eccentric exercise. *J Funct Morphol Kinesiol* 2021;**6**:62. doi:10.3390/jfmk6030062.
15. Ganesan G, Cotter J, Reuland W, et al. Use of diffuse optical spectroscopy to monitor muscle and brain oxygenation dynamics during isometric and isokinetic exercise. *Proc SPIE* 2013;**8578**:857803. doi:10.1117/12.2007459.
16. Formenti D, Perpetuini D, Iodice P, et al. Effects of knee extension with different speeds of movement on muscle and cerebral oxygenation. *PeerJ* 2018;**6**:e5704. doi:10.7717/peerj.5704.
17. Barstow TJ. Understanding near infrared spectroscopy and its application to skeletal muscle research. *J Appl Physiol (1985)* 2019;**126**:1360–76.
18. Tuesta M, Yáñez-Sepúlveda R, Verdugo-Marchese H, et al. Near-infrared spectroscopy used to assess physiological muscle adaptations in exercise clinical trials: A systematic review. *Biology (Basel)* 2022;**11**:1073. doi:10.3390/biology11071073.
19. Scholkmann F, Kleiser S, Metz AJ, et al. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *Neuroimage* 2014;**85**:6–27.
20. Tachtsidis I, Scholkmann F. False positives and false negatives in functional near-infrared spectroscopy: Issues, challenges, and the way forward. *Neurophotonics* 2016;**3**:031405. doi:10.1117/1.NPh.3.3.031405.
21. Scholkmann F, Tachtsidis I, Wolf M, Wolf U. Systemic physiology augmented functional near-infrared spectroscopy: A powerful approach to study the embodied human brain. *Neurophotonics* 2022;**9**:030801. doi:10.1117/1.NPh.9.3.030801.
22. Eleveld N, Esquivel-Franco DC, Drost G, et al. The influence of extracerebral tissue on continuous wave near-infrared spectroscopy in adults: A systematic review of *in vivo* studies. *J Clin Med* 2023;**12**:2776. doi:10.3390/jcm12082776.
23. Pinti P, Scholkmann F, Hamilton A, et al. Current status and issues regarding pre-processing of fNIRS neuroimaging data: An investigation of diverse signal filtering methods within a general linear model framework. *Front Hum Neurosci* 2019;**12**:505. doi:10.3389/fnhum.2018.00505.
24. Yücel MA, Lühmann AV, Scholkmann F, et al. Best practices for fNIRS publications. *Neurophotonics* 2021;**8**:012101. doi:10.1117/1.NPh.8.1.012101.
25. Gagnon L, Cooper RJ, Yücel MA, et al. Short separation channel location impacts the performance of short channel regression in NIRS. *Neuroimage* 2012;**59**:2518–28.
26. Wyser DG, Kanzler CM, Salzmann L, et al. Characterizing reproducibility of cerebral hemodynamic responses when applying short-channel regression in functional near-infrared spectroscopy. *Neurophotonics* 2022;**9**:015004. doi:10.1117/1.NPh.9.1.015004.
27. von Lühmann A, Li X, Müller KR, et al. Improved physiological noise regression in fNIRS: A multimodal extension of the general linear model using temporally embedded canonical correlation analysis. *Neuroimage* 2020;**208**:116472. doi:10.1016/j.neuroimage.2019.116472.
28. Caen K, Vermeire K, Pogliaghi S, et al. Aerobic interval training impacts muscle and brain oxygenation responses to incremental exercise. *Front Physiol* 2019;**10**:1195. doi:10.3389/fphys.2019.01195.
29. Cherouveim ED, Margaritelis NV, Koulouvaris P, et al. Skeletal muscle and cerebral oxygenation levels during and after submaximal concentric and eccentric isokinetic exercise. *J Sports Sci* 2022;**40**:195–202.
30. Iwasaki W, Nogami H, Takeuchi S, et al. Detection of site-specific blood flow variation in humans during running by a wearable laser Doppler flowmeter. *Sensors (Basel)* 2015;**15**:25507–19.
31. Miyazawa T, Horiuchi M, Komine H, et al. Skin blood flow influences cerebral oxygenation measured by near-infrared spectroscopy during dynamic exercise. *Eur J Appl Physiol* 2013;**113**:2841–8.
32. Schecklmann M, Mann A, Langguth B, et al. The temporal muscle of the head can cause artifacts in optical imaging studies with functional near-infrared spectroscopy. *Front Hum Neurosci* 2017;**11**:456. doi:10.3389/fnhum.2017.00456.
33. Rashid A, Roatta S. Hemodynamic monitoring in the human temporalis muscle using near-infrared spectroscopy. *Physiol Meas* 2023;**44**:065001. doi:10.1088/1361-6579/acd6d5.
34. Volkening N, Unni A, Löffler BS, et al. Characterizing the influence of muscle activity in fNIRS brain activation measurements. *IFAC-PapersOnLine* 2016;**49**:84–8.
35. Uchitel J, Vidal-Rosas EE, Cooper RJ, Zhao H. Wearable, integrated EEG-fNIRS technologies: A review. *Sensors (Basel)* 2021;**21**:6106. doi:10.3390/s21186106.
36. Herold F, Wiegel P, Scholkmann F, et al. Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise-cognition science: A systematic, methodology-focused review. *J Clin Med* 2018;**7**:466. doi:10.3390/jcm7120466.
37. Klein F. Optimizing spatial specificity and signal quality in fNIRS: An overview of potential challenges and possible options for improving the reliability of real-time applications. *Front Neuroergonomics* 2024;**5**:1286586. doi:10.3389/fnrgo.2024.1286586.