34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Integrated device for the measurement of systemic and local oxygen transport during physical exercise

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Abstract— **Current methods for monitoring exercise exertion rely upon heart rate monitors, which represent a crude and lagging indicator of conditioning. The rationale for the present study is that both systemic and local metabolic mechanisms are responsible for physical performance, and therefore they should be simultaneously quantified to achieve an objective assessment of human conditioning. We propose a compact, wearable near-infrared spectroscopy (NIRS) device integrated with electrocardiography (ECG) and photoplethysmography (PPG) to simultaneously assess the cardiovascular and local response to exercise. The system was tested on subjects performing a graded maximal exercise by comparing our readings with metabolic variables measured with respiratory gas analysis. We found strong correlations between local deoxyhemoglobin concentration [HHb], heart rate and oxygen uptake, as well as between oxyhemoglobin concentration [HbO$_2$] and stroke volume. This study shows that combined NIRS, ECG and PPG measurements yield useful information to understand the interplay between systemic and local muscular responses to exercise.**

I. INTRODUCTION

While monitoring exertion via heart rate monitor has long been a centerpiece of exercise and rehabilitation training, heart rate is a crude and lagging indicator of conditioning and training thresholds [1]. In order to remediate the inadequacies of heart rate monitoring as a score of exercise, novel biosensing methods that are able to assess not only the cardiac response to exercise, but also the ability of the peripheral muscle to utilize oxygen, have been proposed [2]. By coupling a peripheral muscle assessment with a systemic cardiac assessment, a complete picture of the effect of exercise and performance thresholds could be calculated and presented in real time to the user and trainer or coach. Such personalized, real-time monitoring would help advance training thresholds while avoiding overtraining. Unfortunately, no currently available technology provides this critical training information in real time.

To accomplish this, we exploit the ability of near-infrared spectroscopy to measure the levels of oxygenated and deoxygenated hemoglobin while the muscle is working. We use the relationship between the electrical measure of the heart and its resulting pulse to infer a specific feature of the cardiac output; that is, the ability of the heart to eject blood. As a byproduct, we are also able to measure heart rate. We hypothesize that these measures, taken together, can be leading indicators of training thresholds by accurately describing the interplay between cardiac performance and muscle activity. In this work, we propose an integrated prototype for continuous ambulatory use that is able to non-invasively assess both systemic and local response to physical exercise.

II. MATERIAL AND METHODS

The proposed system integrates electrocardiography, photoplethysmography and near-infrared spectroscopy sensing techniques to assess physiological variables at systemic and local level in a synchronous fashion.

A. Near-infrared spectroscopy (NIRS)

This optical technique uses multiple near-infrared (650-1000 nm) sources projected into the metabolizing muscle in which the main absorbers are oxyhemoglobin (HbO$_2$) and deoxyhemoglobin (HHb, or HbR) contained in the blood, and myoglobin present in muscle fibers and water [2]. By measuring the optical absorption at several wavelengths and solving a linear system derived from photon diffusion theory, it is possible to determine the relative concentrations (changes of concentration against a zero-baseline) of both oxyhemoglobin and deoxyhemoglobin. Although the relative concentrations of oxy- and deoxyhemoglobin provide an indication of oxygen metabolism during exercise, it is highly desirable to measure the absolute concentrations of these absorbers. In fact, knowing the absolute concentrations allows personalization of the readings and thus enables adequate follow-up training and long-term monitoring. In addition, absolute readings embed information that is useful for studying local oxygen metabolism in terms of oxygen demand-supply balance, arteriovenous difference, oxygen consumption and blood flow [3].

Continuous-wave NIRS (CW-NIRS) has been used to detect variations in absorption coefficients, primarily because of its native inability to separate the effects of absorption and scattering. This problem is a direct consequence of the solution of the diffusion equation that governs the migration of NIR photons in highly scattering media, which requires the measurement of at least two parameters to be converted into the two unknown absorption and scattering coefficients. In our NIRS system, we perform

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978-1-4577-1787-1/12/$26.00 ©2012 IEEE

attenuation measurements at 980nm where peak absorption of water exists and is dominant compared to the contribution of hemoglobin. Using the solution of the photon diffusion equation, we evaluate the reduced scattering coefficient at this wavelength which then allows us to calculate the spectrum of the reduced scattering coefficient at other NIR wavelengths (680nm, 830nm). As a result, this measuring technique allows the quantitative evaluation of molar concentration of oxygenated and deoxygenated hemoglobin in human tissues using continuous-wave lasers [4].

The reduced complexity of CW-NIRS hardware allows the implementation of a small-size apparatus. Our current NIRS probe has a skin-contact footprint of 2x3 cm (Figure 1) and an approximate weight of 60 grams. To guarantee stable placement during vigorous exercise, the optical probe is secured to the skin using biocompatible double-sided tape. The NIRS system measures molar concentrations of HbO_2 (hereby indicated with $[HbO_2]$) and HHb ([HHb]), the total volume of hemoglobin ($[tHb]=[HbO_2]+[HHb]$) and the tissue percent saturation index ($TOI=[HbO_2]/[tHb]$) with a sampling period of 20ms.

B. *Electrocardiography*

Electrocardiography (ECG) is the gold standard for the measurement of the electrical activity of the heart. In this system, we use an integrated 3-lead ECG module (EG01010, Medlab, Germany) with adhesive stress electrodes (Blue Sensor SP, Ambu A/P, Denmark). Several clinical studies have shown that 3-lead/4-lead ECG systems are, in most cases, as reliable as conventional 12-lead configurations in evaluating cardiac pathology [5].

Measurement of the ECG Lead I (left arm-right arm), Lead II (right arm-left leg) and Lead III (left arm-left leg) are simultaneously and continuously recorded with 50Hz sampling frequency and 8-bit analog-to-digital conversion. The heart rate is calculated as the inverse of the average time interval between two consecutive R waves (R-R interval).

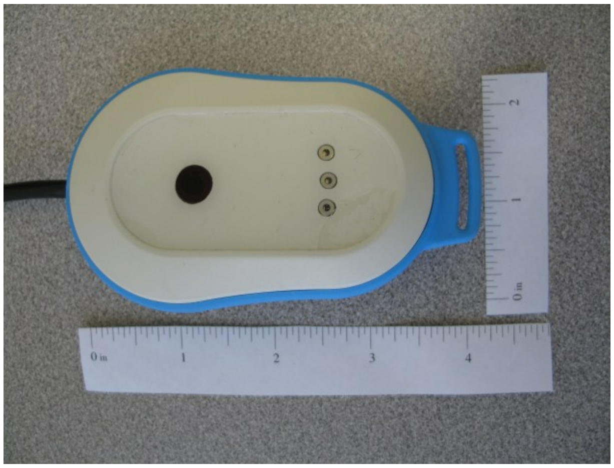

Figure 1: CW-NIRS probe using 3 laser diodes (680nm, 830nm, 980nm) and one photodetector with NIR optical filter. The distance between sources and detector is 30mm.

C. *Photoplethysmography*

Photoplethysmography (PPG) is an optical measurement technique for detecting blood volume changes in microvasculature sites (e.g., fingertip) [6]. This technique relies on the relative optical transparency of human tissues to near-infrared light, and it quantifies the changes in blood perfusion in the catchment volume. We used a fingertip OEM PPG sensor (EG00532, Medlab, Germany) with a sampling rate of 50Hz. When paired with electrocardiography, PPG allows the measurement of time-related cardiovascular parameters such as pulse transit time and pulse wave velocity. Pulse transit time (PTT) is calculated as the time interval between the peak of the ECG R-wave and the peak amplitude of the synchronized PPG waveform. PPG is consensually accepted as a surrogate of arterial compliance as arterial stiffness decreases PTT. PTT has been shown to be linearly correlated with blood pressure, but without the level of accuracy needed to represent beat to beat blood pressure [7].

D. *Integrated device*

To achieve a combined measurement of systemic (ECG, PPG) and local (NIRS) measures of oxygen transport, we integrated all three subsystems into a small, belt-worn device. A digital signal processor (dsPIC series) governs the synchronized acquisition of data and it interfaces with a low-power 900MHz RF chipset (Texas Instruments CC1110) for the wireless transmission of data packets to a remote receiver. A lithium-ion rechargeable battery provides continuous operation for more than 4 hours. Custom-designed software installed on a remote laptop collects data from the wearable sensor using a CC1111 900 MHz RF USB dongle paired with the transmitter.

E. *Exercise protocol*

For this preliminary study, we recruited 3 healthy subjects (age 26±2) from the student population of the University of Houston. The volunteers performed a cycling exercise protocol consisting of 5 minutes of warm-up at a constant workload of 50W, followed by a graded increment of 15W/min until volitional exhaustion, while maintaining a pedaling cadence of 60 ± 3rpm throughout the experiment. The termination of the exercise was determined by the inability of the subject to maintain the imposed cadence. The exercise equipment consisted of a stationary road bike linked to an electronic load generator (CompuTrainer Lab, RacerMate Inc., Seattle, WA) calibrated to the weight of each individual before the experiment. Respiratory gases were collected and analyzed using a breath-to-breath metabolic cart (Cosmed, Italy), which provides measurements of oxygen uptake, stroke volume and cardiac output [8]. All subjects were asked to sign an informed consent approved by the Institutional Review Board of the University of Houston.

The workload was normalized to perform a group analysis independent of the maximal workload elicited by the individuals; all variables were samples at 10% workload intervals, where 0% is intended as the baseline workload at 50W. All plots report mean values ± standard error.

III. RESULTS

A. Systemic measures

Both R-R interval and pulse transit time (PTT) of the subjects decreased throughout the duration of the exercise (Figure 2). The spread between R-R and PTT is as wide as 140ms at the beginning of the exercise, but it gradually decreases until they assume similar values at maximum workload (300-320ms). Heart rate (HR), calculated as the inverse of R-R interval, linearly increases (R^2=0.98) as a function of workload, as is widely reported in the literature [9]. The decreasing trend of PTT means a quicker delivery of arterial blood to the periphery, which indicates a progressive vasodilation of the major vessels. To further investigate the interplay between cardiac rate and vasodilation, we calculated the percent ratio between PTT and R-R interval (Figure 3).

The initial linear increase implies that the major contribution to augmented blood supply to the periphery comes from the increased heart rate; between 70% workload and exhaustion, the R-R interval increases at the same rate as the pulse transit time.

Cardiac output (CO) and stroke volume (SV) estimated with respiratory gas analysis are shown in Figure 4.

CO linearly increases during the phase of moderate exercise, followed by a moderate increase when the workload intensity becomes higher. The progressive diminution of stroke volume during vigorous exercise, in contrast with increased heart rate, is responsible for the final plateau of cardiac output (CO=HR·SV).

B. Local measures

The molar concentration of HbO_2 remained constant during light and moderate exercise, and it abruptly decreased after 40% of normalized workload, with a maximum negative slope at 70%WL. The reduced standard error bars indicate a consistent desaturation pattern in all three subjects, with a baseline value at 53.3 ±1.4μM and desaturation range between baseline and exhaustion in the order of 30μM. In turn, [HHb] showed a linear increase (R^2=0.996) throughout the exercise protocol, with the total excursion being 7.8μM (Figure 5). In addition, [HHb] closely tracks oxygen uptake and carbon dioxide trends (R^2=0.96, not reported here). Since the variation of [HbO_2] during maximal exercise was threefold, the correspondent change in [HHb] the total volume of hemoglobin [tHb] (not reported)

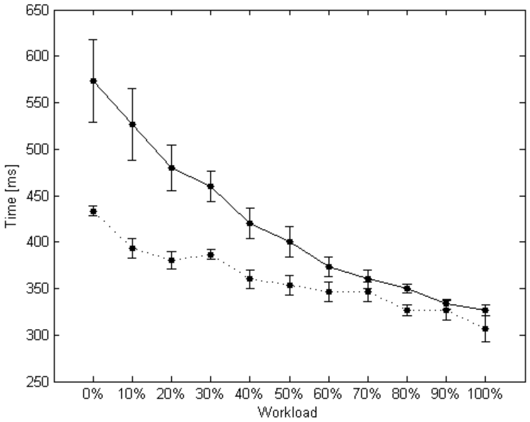

Figure 2: R-R interval (solid line) and pulse transit time (dashed line) as a function of normalized workload.

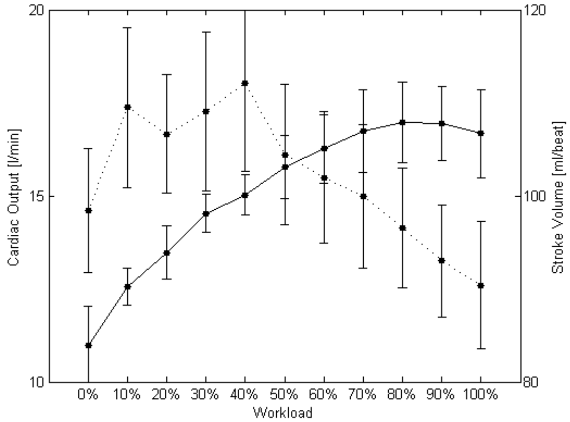

Figure 4: Cardiac output (solid line) and stroke volume (dashed line) as function of normalized workload.

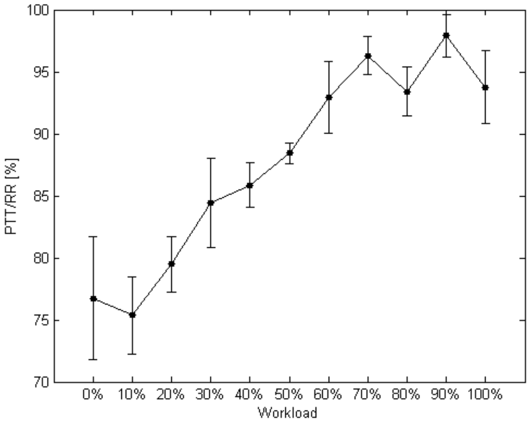

Figure 3: Percent ratio between pulse transit time (PTT) and R-R interval.

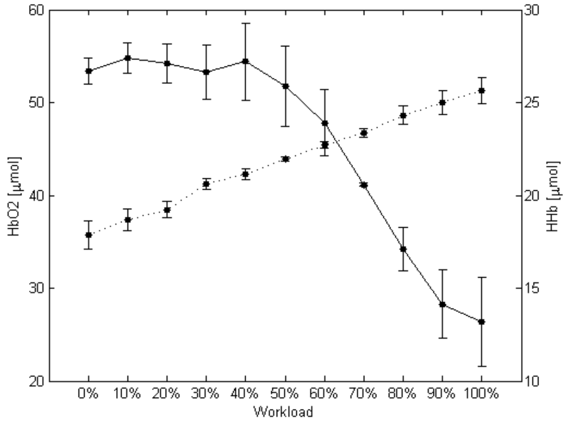

Figure 5: Oxyhemoglobin [HbO_2] (solid line) and deoxyhemoglobin [HHb] (dashed line) as a function of normalized workload.

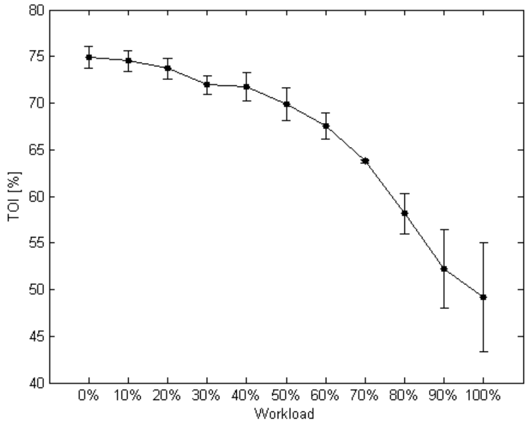

Figure 6: Tissue oxygenation index [%] as function of normalized workload.

followed a very similar decreasing trend of [HbO_2], with an average baseline-exhaustion difference of 23μM. The muscle desaturation pattern described by tissue percent saturation index (TOI) is shown in Figure 6. Unlike [HbO_2], the TOI curve did not exhibit a well-defined deflection point at moderate workload. Instead, the muscle desaturation decay becomes more accentuated as the workload increases. All subjects showed consistent TOI values between 0% and 70%WL, whereas individual differences were noted during vigorous exercise. On average, the desaturation range from baseline to exhaustion was 25%. Since NIRS measures oxygenation mostly in the venous capillary compartment, the overall TOI drop indicates that about one-fourth of oxyhemoglobin in the venous return has been depleted of oxygen and utilized by muscular tissues.

IV. DISCUSSION

Numerous devices based on frequency-domain, time-domain and continuous-wave NIRS techniques have been proposed for non-invasively assessing oxygen use in skeletal muscles. However, cost, size, and lack of standardization have limited use of these devices primarily to research. In addition, the interplay between cardiovascular response to exercise at the systemic level and local delivery and utilization of oxygen has not been well investigated. Several studies have explored correlations between skeletal muscle oxygenation with respiratory gas analysis [10] and blood lactate concentration [11] during exercise; others have investigated changes in cardiac output and stroke volume and vasodilation, with little attention to muscle utilization. Therefore, our understanding of cardiovascular and muscle response to vigorous exercise is limited.

This aim of this work is: 1) to propose a compact, wearable NIRS device capable of accurately measuring molar concentrations of hemoglobin and 2) to integrate non-invasive sensing techniques to simultaneously assess the cardiovascular and local response to vigorous exercise.

Our preliminary results show that the molar hemoglobin concentrations measured by NIRS were consistent amongst healthy subjects. [HbO_2] exhibited a steady start followed by a steep desaturation from 40% workload onward, similar to what was observed for stroke volume. Deoxyhemoglobin [HHb] is strongly correlated to heart rate (R^2=0.98), oxygen uptake and carbon dioxide linear trends. The ratio between PTT and HR correlates with cardiac output (R^2=0.90); therefore, a combined measurement of ECG and PPG could potentially represent a novel method to assess cardiac output non-invasively. The relationship between CO and TOI is well modeled by a piece-wise linear trend with deflection at 40%-50%WL.

The results indicate that oxygen consumption at the skeletal muscle level initiates well before systemic variables, primarily cardiac output and RR/PTT, reach their plateau. The strong correlation between stroke volume and [HbO_2] also suggests that the stabilization of the cardiac pumping capacity after a moderate level of workload could be responsible for reduced oxygen supply to the periphery, and thus to the gradual transition from aerobic to anaerobic muscle metabolism. In conclusion, this study shows that a combination of non-invasive methods such as NIRS, ECG and PPG delivers important information on the interplay between systemic and local muscular responses to exercise.

ACKNOWLEDGMENT

The authors thank Karishma Prasad and Patrick Howell for their help in collecting data.

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