Muscle Oxygen Saturation as a Marker of Internal Load in Elite Soccer: A Case Series

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Abstract

Herzog, S, Philippi, M, Feldmann, A, Asian, J, Filter, A, Requena, B, Batterson, PM, and Bogdanis, GC. Muscle oxygen saturation as a marker of internal load in elite soccer: A case series. *J Strength Cond Res* XX(X): 000–000, 2026—Accurate monitoring of internal and external load during training is essential for optimizing performance and managing fatigue. In soccer, heart rate (HR) is commonly used to assess internal load. This study examined the use of muscle near-infrared spectroscopy, which measures muscle oxygen saturation (SmO_2), as a potential alternative to HR by providing real-time insights into local muscular effort. Seventeen elite male professional soccer players (21.2 ± 4.01 years) performed an incremental treadmill test to exhaustion, of whom 14 had complete data sets suitable for threshold analyses. During the test, HR, expired gases, and SmO_2 of the vastus lateralis were continuously measured to identify ventilatory, lactate, and SmO_2 breakpoints. On a separate day, HR and SmO_2 were recorded in a subset of five players during small- and large-sided games (SSG and LSG). A repeated-measures analyses of variance comparing HR corresponding to the three different thresholds indicated that HR at BP2 (178 ± 5 beats·minute^{-1}) was similar with HR at LT2 and VT2 (177 ± 7 beats·minute^{-1} and 181 ± 6 $p = 1.000$ and $p = 0.0920$, respectively). Bland–Altman analysis indicated acceptable agreement between HR thresholds, while SmO_2 thresholds showed wider limits of agreement and greater individual variability. During small-sided game and LSG, players spent significantly more time above SmO_2-based thresholds compared with HR-based thresholds ($p < 0.05$), with the largest differences observed during LSG. These findings suggest that SmO_2 is more responsive to high-intensity, intermittent activity and may better reflect local muscular demand than HR. Incorporating SmO_2 into training and match monitoring may enhance internal load assessment and support more individualized performance and recovery strategies.

Key Words: muscle near-infrared spectroscopy, small-sided games, large-sided games, football, elite soccer

Introduction

Accurately assessing exercise intensity is a fundamental aspect of athletic training, particularly when managing training load to ensure optimal performance and avoid overtraining. Exercise intensity is often assessed using external load metrics such as running velocity and acceleration. However, these measures do not always reflect the physiological load imposed on the player, as internal load responses to a given external load can vary substantially depending on physical fitness (1,10,16). Internal load parameters, such as heart rate (HR) and respiratory gas exchange, provide a more accurate reflection of the body's actual exertion and recovery capacity than external load parameters alone (21,29). In particular, fluctuations in these physiological responses reflect the efficiency with which homeostasis is reestablished after exertion, making them valuable markers of recovery status and cumulative load. Monitoring and control of training load is particularly relevant in team sports such as soccer, where load management has become increasingly important (27). A considerable body of research has focused on external load parameters, often referring to match demands (11). The scientific literature shows a notable increase in high-speed running and overall intensity in soccer over the past two decades, based on external metrics (7,18). However, internal load has received comparatively less attention regarding the physiological responses associated with this rise in game intensity. Internal load monitoring has largely revolved around biochemical markers such as creatine kinase measured before or after training sessions, as well as HR and session-rate of perceived exertion during training (22).

While HR is the most commonly used internal metric during soccer training, it often lags behind real-time effort, fails to capture rapid changes in intensity, and can be influenced by nonphysiological factors such as temperature or emotional state, making it a poor standalone indicator of exertion in stop-and-go sports (2,9,26). An emerging alternative is muscle near-infrared spectroscopy (mNIRS), a noninvasive method that provides real-time measurements of muscle oxygen saturation (SmO_2). SmO_2 represents the percentage of oxygenated hemoglobin and myoglobin within the volume of tissue assessed by the sensor, with specific relevance to skeletal muscle. SmO_2 reflects the balance between oxygen supply and demand at the muscle level during physical activity (3). Because creatine phosphate resynthesis is dependent on oxygen availability (16), measures of muscle oxygenation are directly relevant to high-intensity exercise and recovery. Consistent with this physiological relationship, multiple studies have demonstrated a close association between SmO_2 and

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creatine phosphate recovery, supporting its use when evaluating high-intensity efforts and subsequent recovery (20). Owing to advances in portable, wireless devices, mNIRS has become increasingly accessible and practical for on-field noncompetition uses. (23). It shares the on-field applicability of HR but offers potential advantages in capturing more precise intensity shifts and may serve as an indicator of metabolic recovery regarding oxidative capacity and phosphocreatine resynthesis (17). Studies have shown that mNIRS responses correlate strongly with sprint ability and fatigue in soccer players (8,31), and it has outperformed HR in environments with highly variable intensity, such as hill running (6). Moreover, the critical oxygenation threshold identified by mNIRS (14) seems more stable across environmental changes than HR (19), indicating its robustness for field applications. We hypothesize that, due to its ability to more reliably track physiological intensity in complex, intermittent conditions, mNIRS could serve as an alternative to HR monitoring.

Methods

Experimental Approach to the Problem

To provide physiological context for the on-field analyses, an incremental laboratory test was first conducted. We compared the second ventilatory threshold (VT2), the second blood lactate threshold (LT2), and the second breakpoint in SmO_2 (BP2) in 17 elite (FSV Mainz 05 seconds team) male professional soccer players during an incremental running test to exhaustion, conducted as part of their preseason testing program. The focal point of the study then was to present a small-n observational case series comparing an index of internal load—specifically, the time spent at intensities above VT2—as assessed by both HR and SmO_2 during soccer-specific small-sided games (SSG) and large-sided games (LSG). The aim was to evaluate which of the two measures more sensitively detects rapid changes in metabolic stress. The incremental test was part of the physical preseason testing. Data collection was performed as part of their regular training and testing program. Given the challenges of integrating data collection into team training environments, and the elite status of the subjects, this small-n observational case series provides valuable insights that can inform and support future larger-scale studies.

Laboratory Incremental Running Test

Subjects completed an incremental treadmill test (Woodway, 1% incline) with 4-minute stages, interspersed by 45 seconds of rest. The test began at 8.5 km/h, increasing by 1.5 km/h per stage, ending at 16 km/h (submaximal). During rest periods, blood lactate was sampled, and subjects remained standing. SmO_2, HR, and gas exchange were continuously recorded. The thresholds derived from this test were used to individualize the subsequent on-field analyses. Before the test, subjects conducted a series of jumping protocols and functional movement screens, but no specific warm-up was conducted.

On-Field Assessment

Athletes performed a SSG (3 × 4 minutes, 4v4 players plus goalkeepers, 24 × 32 m pitch) and a LSG (2 × 10 minutes, 11v11 players, 68 × 105 m pitch). Both formats replicated realistic match conditions. SmO_2 and HR were continuously recorded at 0.5 Hz and synchronized automatically in the WIMU PRO; RealTrack Systems, Spain (SVIVO and WIMU Cloud). Warm-up for SSG included 13 minutes session with athletic trainers and 6 minutes passing drill. LSG included 19 minutes session with athletic trainers and 6 minutes passing drill.

Subjects

Seventeen elite (FSV Mainz 05 seconds team) male professional soccer players (mean ± *SD*: age 21.2 ± 4.01 years; height 181.9 ± 5.8 cm; mass 78.0 ± 7.2 kg; including seven defenders, six midfielders, two strikers, and two keepers) completed an incremental running step test. Five players were selected for SSG and LSG analysis; however, one LSG data set was lost due to technical issues, leaving four usable LSG data sets. All subjects were competitively active, injury free, and unmedicated. All players identified themselves in a fully recovered state. Players and coaches were fully informed about the potential risks and benefits derived from participation in the study protocol and signed an informed consent document before participating in the investigation. All measurements were conducted during regular training sessions without interrupting or influencing the training process. HR data were collected using sensors routinely worn by the players, and SmO_2 data logging was integrated into the WIMU unit. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki, as revised in 2024, and received approval from the Institutional internal Board of FSV Mainz 05. This board includes representatives from team management, Human Resources, the Head of Medical and Coaching staff, and the team's legal advisors (Approval Number: 2025-MAINZ-0011-A1).

Procedures

Gas Exchange Measurements During the Laboratory Test. Respiratory data ($\dot{V}O_2$, $\dot{V}CO_2$, VE, RER) were measured breath-by-breath using a calibrated metabolic cart (Quark CPET, COSMED Srl, Rome, Italy) and analyzed in OMNIA software (Figure 1). $\dot{V}O_2$ and $\dot{V}CO_2$ were reported in STPD, and ventilatory variables in BTPS. HR was recorded through GARMIN HRM-Dual, and rate of perceived exertion was assessed using a modified Borg scale (0–10). Ventilatory thresholds (VT1, VT2) were determined using the V-slope method based on disproportionate increases in $\dot{V}CO_2$ relative to $\dot{V}O_2$ (4).

Muscle Oxygen Saturation (mNIRS). SmO_2 was recorded from the right and left vastus lateralis using wearable mNIRS sensors (Moxy Monitor, Fortiori Design LLC, Hutchinson, MN, USA), positioned at approximately two-thirds of the distance from the anterior superior iliac spine to the patella after palpating for the muscle belly (see Figure 1). Data were sampled at 1 Hz using the $\dot{V}O_2$ Master-Manager App. The Moxy Monitor uses four wavelengths (680–850 nm) and dual-detector spacing (12.5 and 25 mm) to achieve a tissue penetration depth of ~12.5 mm. Skinfold thickness was measured at each site to confirm adequate optical sensitivity and to reduce the influence of adipose tissue on light scattering. This device has demonstrated good to excellent test–retest reliability in controlled exercise settings, with intraclass correlation coefficients ranging from 0.79 to 0.92 (29) and 0.77–0.99 reported in earlier validation work (12). These values indicate acceptable-to-excellent reliability for repeated SmO_2 measurements, supporting its potential use as an internal load

Figure 1. Visual of eight-step process to place the mNIRS device (Moxy monitor), including light shield.

marker. SmO_2 breakpoints 1 and 2 (BP1, BP2) were determined as deflection points through expert rating (13).

Blood Lactate. Capillary blood (20 μL) was collected from the earlobe during treadmill rest intervals and analyzed using a Biosen C-Line analyzer (Biosen C-Line, EKF-diagnostic GmbH, Barleben, Germany). Lactate thresholds 1 and 2 (LT1, LT2) were determined using a modified Dmax method (24).

Statistical Analyses

All statistical analyses were performed using Python (version 3.12) with the Pandas, NumPy, SciPy, Statsmodels, Matplotlib, and Seaborn libraries. Descriptive statistics (mean ± *SD*) were calculated for HR and SmO_2 at each threshold: VT2, LT2, and BP2.

Outliers were identified separately for HR and SmO_2 using the interquartile range (IQR) method, defined as values lying below

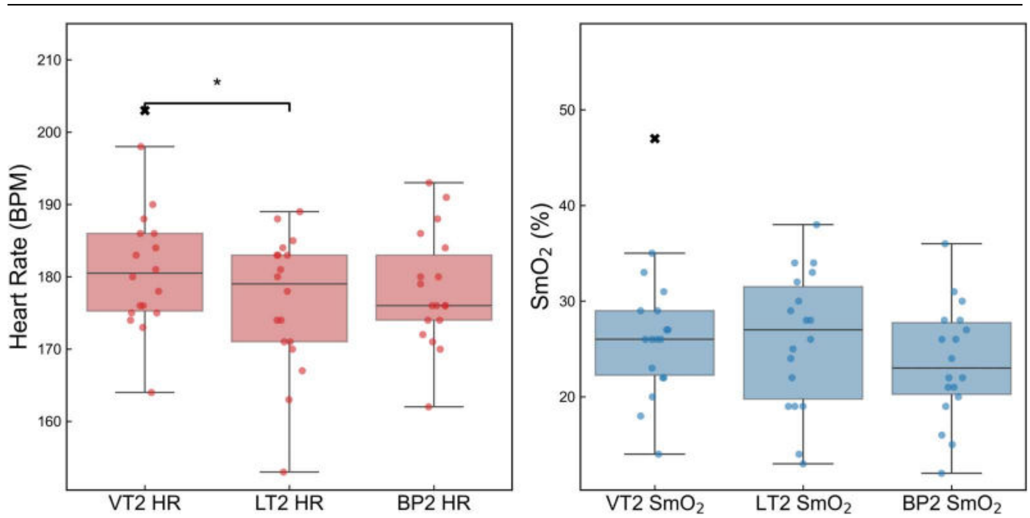

Figure 2. Heart rate (HR) and muscle oxygen saturation (SmO_2) across physiological thresholds. Box plots display the distribution of HR (left) and SmO_2 (right) measured at the second ventilatory threshold (VT2), second lactate threshold (LT2), and breakpoint (BP2) in 14 trained subjects. Data points represent individual observations, with outliers (**x**; previously identified using the IQR method) removed from the analysis. Horizontal lines within boxes represent the median; box edges denote the interquartile range (IQR), and whiskers extend to 1.5 × IQR. Asterisks indicate statistically significant differences between thresholds based on Bonferroni-corrected paired t-tests (*$p < 0.05$). HR increased significantly from VT2 to LT2, while no significant differences were observed in SmO_2 across thresholds.

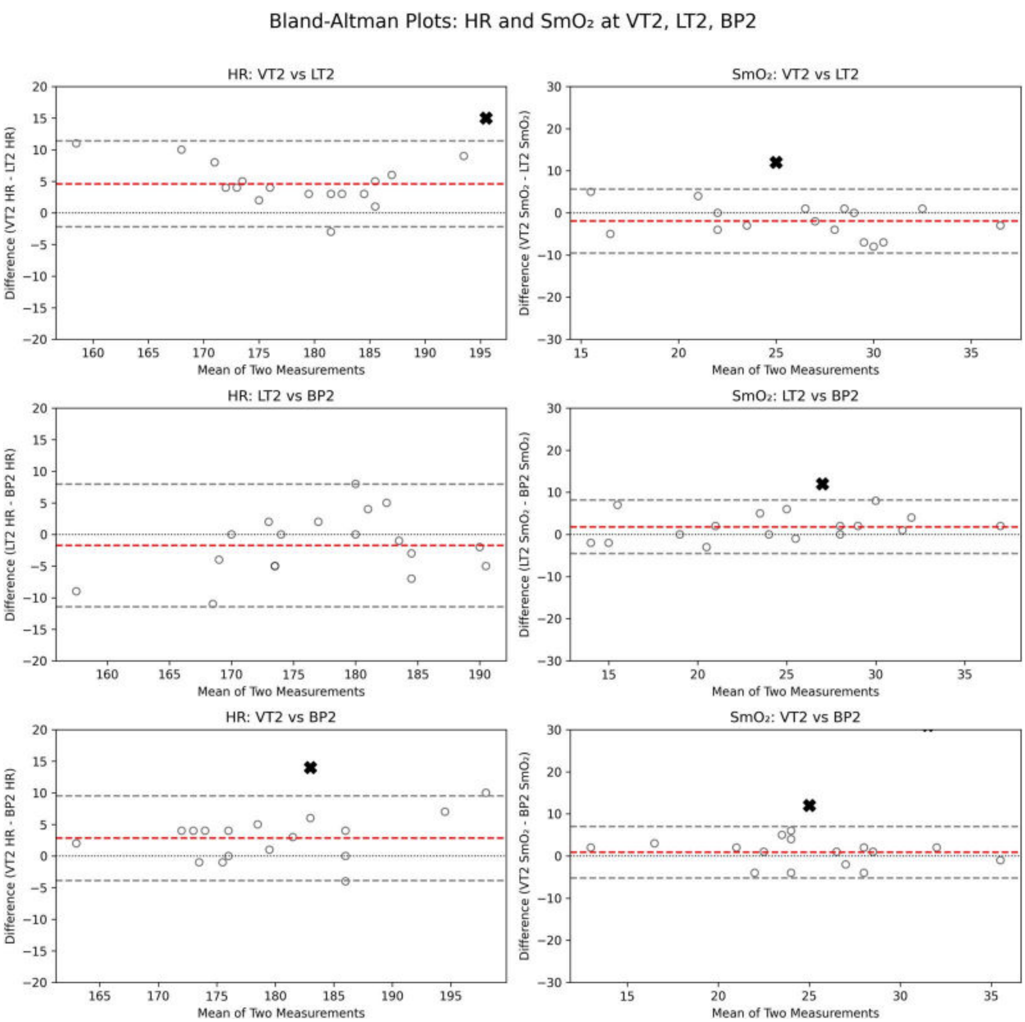

Figure 3. Bland–Altman plots comparing heart rate (HR) and muscle oxygen saturation (SmO_2) measurements at three physiological thresholds: VT2, LT2, and BP2. Each plot shows the mean of two threshold measurements (*x*-axis) against their difference (*y*-axis). The dashed red line represents the mean difference (bias), while the gray dashed lines indicate the upper and lower limits of agreement (±1.96 SD), calculated after excluding statistical outliers (based on the interquartile range method). Outliers were not included in the calculation of bias or limits of agreement but are visualized on the plots as black asterisks (**x**; previously identified using the IQR method). The dotted black line represents perfect agreement.

Q1 − 1.5 × IQR or above Q3 + 1.5 × IQR (31). Only subjects with complete, nonoutlier data across all three thresholds were included in the final analyses, yielding a sample size of 14 for both HR and SmO_2.

To assess the effect of threshold on HR and SmO_2, separate one-way repeated-measures analyses of variance (ANOVA) were conducted. Where a significant main effect was detected ($p < 0.05$), pairwise comparisons between thresholds (VT2 vs LT2, LT2 vs BP2, VT2 vs BP2) were conducted using paired-sample t-tests. Bonferroni correction was applied to adjust for multiple comparisons and control the family-wise error rate at $\alpha = 0.05$. Results were visualized using boxplots, with significance indicated where appropriate. Outliers were excluded from statistical testing but retained in plots as bold black "X" markers for transparency.

Agreement between threshold-based measurements was further assessed using Bland–Altman analysis (5). For each threshold comparison, the mean of paired measurements was plotted against their difference. Bias (mean difference) and 95% limits of agreement (LOA) (±1.96 *SD*) were calculated after excluding statistical outliers.

Results

The laboratory analyses are presented first to provide the physiological context from which on-field internal-load comparisons were interpreted. The repeated-measures ANOVA for HR corresponding to the three different thresholds revealed a statistically significant main effect ($F_{(2, 26)} = 6.61$, $p = 0.0048$). Bonferroni-adjusted post hoc comparisons indicated a small (2%), but statistically significant difference in HR between VT2 and LT2 (181 ± 6 vs. 177 ± 7 beats·minute^{-1}, respectively, $p = 0.0008$), while HR corresponding to BP2 (178 ± 5 beats·minute^{-1}) was similar with that at LT2 and VT2 ($p = 1.000$ and $p = 0.0920$, respectively, see Figure 2). By contrast, the repeated-measures ANOVA comparing SmO_2 showed no main effect ($F_{(2, 26)} = 2.07$, $p = 0.1464$), indicating no significant differences in SmO_2 across thresholds (BP2: 25 ± 6%, LT2: 25 ± 6%, VT2: 25 ± 6%, see Figure 2).

Bland–Altman analysis (see Figure 3) revealed small bias given standard error of measurement observed in other studies (26), between threshold stages for both HR and SmO_2. For HR, the

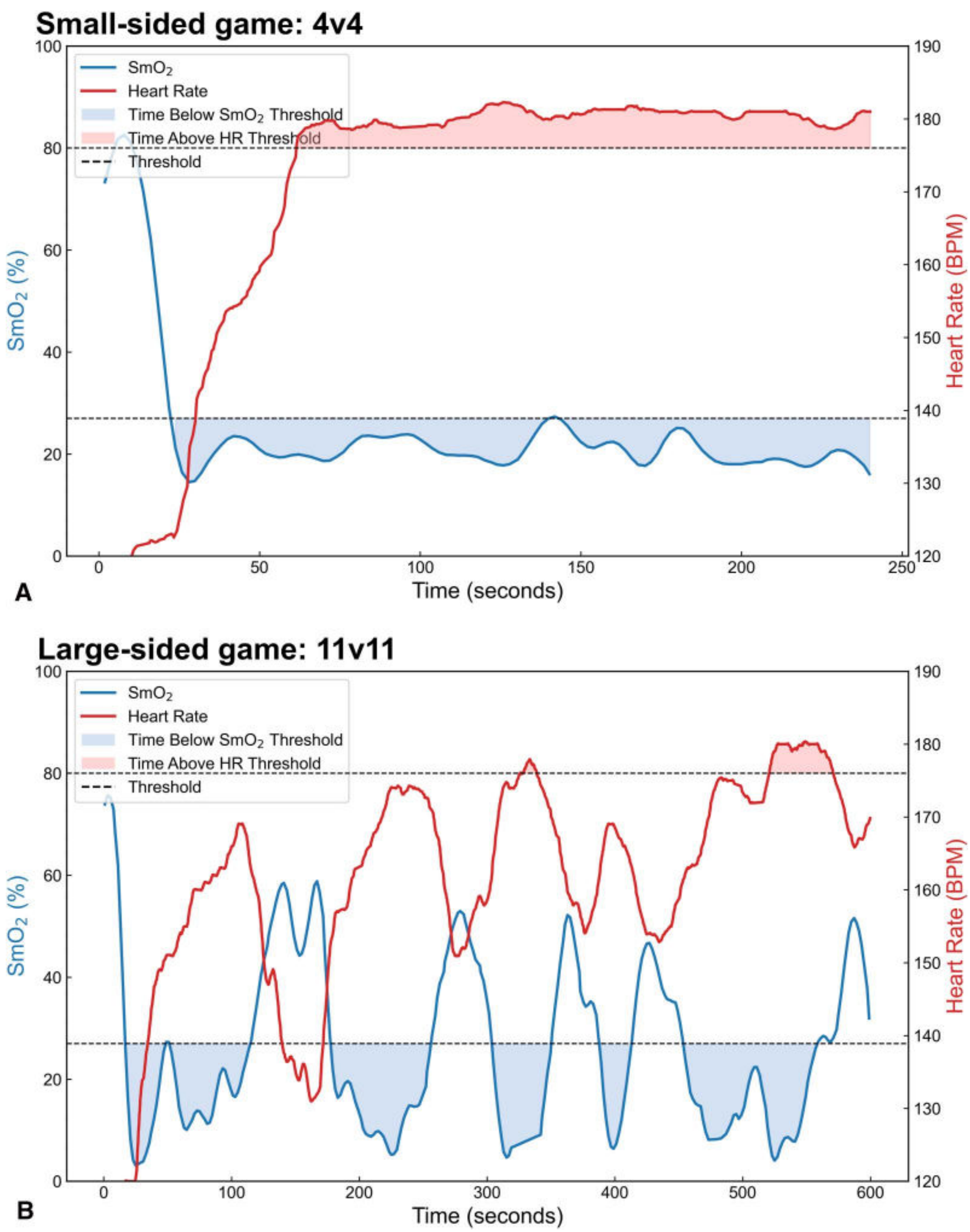

Figure 4. Example time series data from one subject for both (A) small-sided game (SSG) and (B) large-sided game (LSG). Black dashed lines represent the exercise test derived threshold for either muscle oxygen saturation (SmO_2) or heart rate (HR). SmO_2 trace is in blue; identified time spent below the ventilatory threshold 2 (VT2) SmO_2 is shaded blue. HR trace is in red; identified time spent below the VT2 HR is shaded red.

mean bias ranged from −1.8 to 2.1 beats·minute^{-1} across comparisons, with LOA between approximately ±10 and ±14 beats·minute^{-1}. SmO_2 comparisons demonstrated greater variability, with biases ranging from −1.7 to 3.2% and LOA ranging from ±9% to ±15%. Outliers were observed in all comparisons and are indicated in the corresponding plots (Figures 2 and 3). Overall, agreement was stronger for HR than for SmO_2, suggesting greater consistency in HR measurements across thresholds. While HR biases were small (within ±2 beats·minute^{-1}), the presence of individual outliers exceeding the 95% LOA indicates that, for some athletes, HR values differed more substantially between thresholds—particularly between VT2 and LT2. This may reflect individual physiological variability, day-to-day fluctuations in cardiovascular status, or technical inconsistencies in measurement.

SmO_2 data showed broader LOA and greater dispersion, especially between VT2 and BP2. Several outliers exceeded ±15%, suggesting more heterogeneous local muscle oxygenation responses to increasing exercise intensity. This may be due to differences in muscular oxygen extraction, local perfusion, or the inherent sensitivity of mNIRS during exercise testing.

In the gameplay analysis (see Figure 4 example), athletes consistently spent more time above VT2 when thresholds were defined using SmO_2 compared with HR (Figure 5). During 4v4

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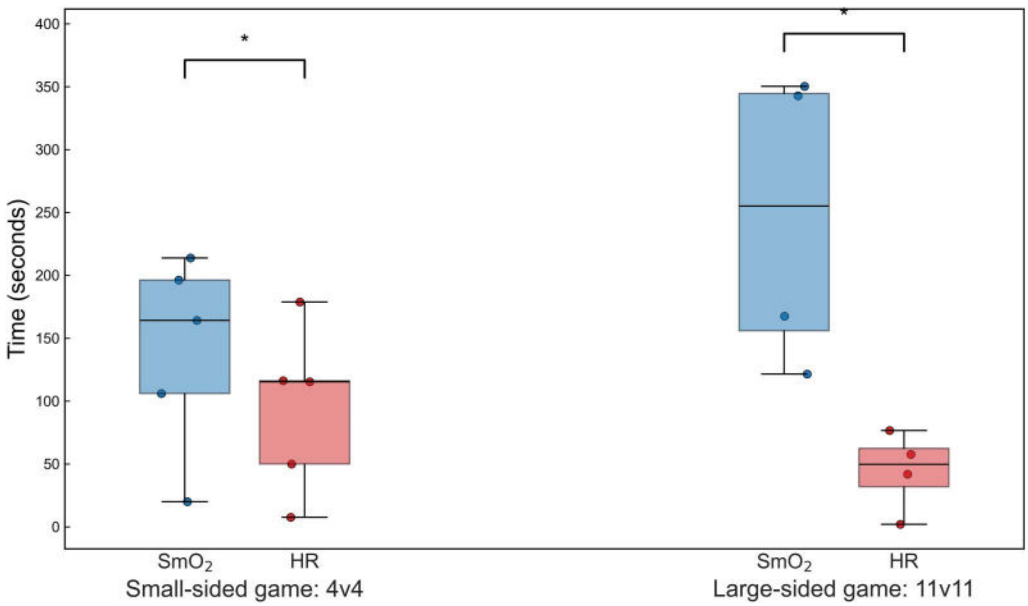

Figure 5. Comparison of time spent above ventilatory threshold 2 (VT2), for muscle oxygen saturation (SmO_2) and heart rate (HR) during small-sided (4v4) and large-sided (11v11) soccer games. Each box represents the distribution of time across players, with individual data points overlaid. Significant differences between SmO_2 and HR within each game format are indicated by asterisks ($p < 0.05$).*

games, the average time spent above VT2 was 136.4 ± 59.9 seconds based on SmO_2 and 93.6 ± 71.5 seconds based on HR ($p < 0.05$). In 11v11 games, this difference was more pronounced: 245.5 ± 107.9 seconds for SmO_2 and 44.5 ± 32.3 seconds for HR ($p < 0.05$). Across both formats, SmO_2-derived thresholds consistently classified greater portions of gameplay as exceeding VT2, highlighting clear differences between the two internal-load metrics. This pattern indicates that SmO_2-based thresholds capture high-intensity, intermittent activity differently than HR-based thresholds and may reflect aspects of local muscular demand not detected by HR alone.

Discussion

The primary aim of this analysis was to explore differences in internal training load metrics derived from mNIRS and HR, rather than to evaluate the efficacy of mNIRS in determining exercise thresholds. While mNIRS successfully identified physiological breakpoints in this study, this application has been extensively validated in previous research, including recent meta-analyses (26).

A noteworthy observation was that the HR corresponding to BP2 was similar to that observed at LT2 and VT2, which confirms previous findings that SmO_2 breakpoints are practically useful to identify exercise intensity thresholds (26). In addition, SmO_2 values exhibited minimal variation across thresholds lending further support to the use of BP2 to identify metabolic thresholds. These findings suggest that although threshold identification methods may differ, the resulting HR and SmO_2 values display overlapping physiological profiles. However, While HR biases were small (within ±2 beats·minute^{-1}), the presence of individual outliers exceeding the 95% LOA indicates that, for some athletes, HR values differed more substantially between thresholds—particularly between VT2 and LT2. This may reflect individual physiological variability, day-to-day fluctuations in cardiovascular status, or technical inconsistencies in measurement.

When looking at the on-pitch data, a clear discrepancy emerges in the time spent at high intensity as determined by HR vs. SmO_2. Athletes consistently spent more time above SmO_2-based thresholds compared with HR-based thresholds during both SSG and LSG gameplay formats. Without making an immediate value judgment, these findings prompt a deeper examination—ideally one that can inform future real-world applications. Given the scope of this study as a case series, the small sample size and limited number of trials are the first aspects to consider. For example, in the study by Bujalance-Moreno et al. (8), SSG resulted in more than 60% of the time spent above what could be considered the second ventilatory threshold, compared with 40% in this study. While methodological differences exist—such as HRmax zones used by Bujalance-Moreno et al. (8) vs. gas exchange–based HR zones used here—it is possible that with a larger data set, the gap between findings in SSGs may narrow. Notably, Bujalance-Moreno et al. (8) also used mNIRS and found consistent SmO_2 nadirs and peaks aligned with HR during 4v4 bouts, reinforcing the reliability of SmO_2. However, the divergence becomes more pronounced when examining LSG, which are more representative of real match physiology. Here, the discrepancy in time spent above threshold when comparing HR and SmO_2 cannot be attributed to sample size or method alone, but may reflect the larger sensitivity of SmO_2 to detect changes in metabolic stress compared with HR. A closer look at the physiological mechanisms behind each metric helps to explain this divergence.

SmO_2 and HR differ fundamentally in how they track physiological responses. SmO_2 responds rapidly to changes in local muscular activity, offering real-time feedback on oxygen supply and utilization during intense efforts (34). By contrast, HR exhibits a slower response and may not adequately reflect short-term or intermittent fluctuations in workload, an issue particularly relevant in the context of soccer's stop-and-go nature (25). While HR captures overall cardiovascular load, SmO_2 reflects local muscle oxygen dynamics, highlighting their complementary, rather than interchangeable, roles in monitoring internal load. Furthermore, SmO_2 values can offer insights into performance limitations in soccer (31). That study (31) observed a decline in repeated-sprint ability in elite women football players, attributed to a reduced desaturation and resaturation slope—indicating impaired oxygen delivery or utilization. This has practical relevance for sprint-intensive roles such as fullbacks, attacking midfielders, and strikers, particularly in LSG contexts. Given the persistent gap between laboratory-based gas exchange analysis and on-field running performance, live SmO_2 monitoring may provide a valuable means of detecting performance constraints in real time, especially those related to local muscular oxygen dynamics.

These findings suggest that SmO_2 may offer a more sensitive and context-specific tool for monitoring internal load and identifying physiological limits during soccer-specific tasks. The integration of SmO_2 in training and performance analysis could therefore enhance individual load management.

Practical Applications

The differences between HR and SmO_2 responses highlight SmO_2's potential value in soccer internal load monitoring. While HR provides useful cardiorespiratory stress data, SmO_2 offers faster, localized insights into muscle effort—particularly during high-intensity, intermittent actions typical of match play. In LSG formats, SmO_2 may be more sensitive to physiological load, capturing exertion that HR may underestimate. Integrating SmO_2 into training and competition monitoring may enhance the accuracy of intensity tracking and support more individualized, responsive load management. Beyond real-time tracking of oxygen demands during LSG, SmO_2 can also be beneficial for fatigue and recovery monitoring during training (33,34) and for identifying specific energy system training needs—distinguishing between limitations in oxygen utilization vs. oxygen delivery. This added layer of physiological insights would allow coaches and practitioners to tailor conditioning programs with greater precision. SmO_2 may therefore offer a highly practical approach and completer picture of player demands on the pitch, supporting more effective training load monitoring, performance optimization, and recovery strategies.

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