

Research article

Associations between Internal Load, Respiratory Metabolism, and Neuromuscular Activation during 1v1 Small-Sided Soccer Games

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Abstract

Small-sided soccer games (SSGs) are widely used in football training to simultaneously improve players' technical skills and physical fitness. However, the mechanistic relationship among internal load, respiratory metabolism, and neuromuscular activation during SSGs remains unclear. To examine the relationship between internal load and lower-limb neuromuscular activation during 1v1 SSGs, and to determine whether respiratory-metabolism variables mediate this association. A repeated-measures design was adopted. 60 physical education students (age: 18.75 ± 0.45 years; training experience: 3.27 ± 3.3 years; body mass: 69.35 ± 8.17 kg) completed a standardized 1v1 SSG protocol (8×1 min bouts with 1 min passive recovery). Internal load was quantified using the Firstbeat system - training impulse per minute (TRIMP·min⁻¹), total energy expenditure (EE_{total}), and heart rate (HR; average and peak) - while oxygen uptake (VO₂, mL·kg⁻¹·min⁻¹), minute ventilation (VE, L·min⁻¹), and respiratory rate (RespR, breaths·min⁻¹) were continuously estimated. Surface electromyography (sEMG) was recorded bilaterally from the rectus femoris (RF) and biceps femoris (BF), normalized to maximal voluntary contraction (MVC), and analyzed for root-mean-square amplitude (RMS), averaged EMG amplitude (aEMG), integrated EMG (iEMG), and median frequency (MF). Mediation analyses were performed to assess whether respiratory metabolism parameters mediated the effect of internal load on neuromuscular activation. Internal load indices showed consistent positive correlations with respiratory-metabolic variables, ranging from $r = 0.436$ between EE Total and Average VO₂ to $r = 0.944$ between Peak HR and Average VE (all $p < 0.001$). For BF, average VO₂, VE, and RespR correlated strongly with HR ($r = 0.864 - 0.938$); for RF, TRIMP correlated significantly with Peak VO₂ ($r = 0.864$, $p < 0.001$). BF metabolic indices were moderately correlated with MF ($r = 0.268 - 0.340$, $p < 0.05$), and RF average VO₂ correlated with aEMG ($r = 0.28$, $p < 0.05$). Mediation analysis revealed that: (1) BF models: The direct effects of HR (average/peak) on BF_{MF} were nonsignificant. In contrast, indirect effects via RespR, VE, and VO₂ were significant ($p < 0.05$), indicating full mediation by respiratory metabolism. (2) RF models: TRIMP·min⁻¹ had a significant positive direct effect on RF EMG indices (RMS, aEMG, iEMG; $p < 0.05$) and a significant negative indirect effect via Peak VO₂ (95% CI excluding 0), showing a "positive direct + negative indirect" dual-path mechanism. (3) Energy model: The effect of EE Total on RF_{aEMG} was fully mediated by Average VO₂, with no direct effect. Internal load and respiratory-metabolic responses showed consistent positive coupling during SSGs, forming a physiological basis for exercise performance. The BF muscle appeared to rely largely on respiratory-metabolic mediation for EMG frequency modulation, reflecting sensitivity to metabolic state. In contrast, RF activation was influenced by both direct internal load and indirect metabolic pathways. Findings suggest that BF activity may depend more on metabolic

status, whereas RF activation may reflect combined influences of load intensity and metabolic mediation, providing insight for more precise assessment of load and muscle function in soccer contexts.

Key words: Football, sided-games, Surface electromyography, Respiratory Metabolism.

Introduction

Small-sided games (SSGs) are soccer formats played on reduced pitches with fewer players, simultaneously developing technical - tactical behaviors and physical conditioning within game-like contexts (Hill-Haas et al., 2011). By manipulating task constraints - such as player number, pitch size, and rule modifications - coaches can systematically tune internal load and decision-making demands to target specific training outcomes (Clemente et al., 2021). Reducing player numbers and adjusting rules typically elevates physiological stress, with consistent increases in heart-rate responses and blood lactate during smaller formats (Halouani et al., 2017). Compared with running-based high-intensity interval training, SSGs often elicit similar cardiovascular strain while producing higher ratings of enjoyment, which supports their use for sustained adherence in team-sport settings (Selmi et al., 2020).

High-intensity match actions rely on coordinated activation of the hamstrings and quadriceps to generate and control sprinting, cutting, and striking forces, aligning with the predominance of lower-limb muscle injuries in elite football (Ekstrand et al., 2011). Biomechanical analyses show that hamstring musculotendon loading rises markedly with sprint speed, with the late swing phase imposing substantial eccentric stress, particularly relevant to biceps femoris function (Chumanov et al., 2011). Long-term surveillance in European elite clubs indicates that hamstring injuries represent a substantial and growing proportion of all time-loss injuries, increasing from 12% to 24% across two decades (Ekstrand et al., 2022a). Because targeted eccentric training reduces hamstring injury incidence, monitoring muscle-specific functional demands during training is a logical complement to preventive programming (Rudisill et al., 2023). Understanding how neuromuscular activation responds to different internal loads during SSGs could help identify muscle-specific fatigue patterns and potentially inform injury-prevention strategies, particularly for the hamstrings, which are highly load-sensitive. However, current SSG research rarely quantifies how internal

physiological load translates into muscle-specific activation or fatigue patterns relevant to hamstring function (Madison et al., 2019).

Surface electromyography (sEMG) provides noninvasive indices of neuromuscular activation and fatigue, with root-mean-square amplitude and related metrics showing criterion validity against torque declines (Gerdle et al., 2000). Frequency-domain measures such as median frequency typically shift downward with fatigue and are mechanistically linked to reductions in muscle-fiber conduction velocity (Lower et al., 2002). Standardized normalization procedures - most commonly relative to maximal voluntary contractions - are essential to compare activation magnitudes across sessions, muscles, and individuals (Burden, 2010). In this context, the rectus femoris (RF) and biceps femoris (BF) are particularly relevant since they represent antagonistic muscle groups (Prilutsky et al., 1998) central to soccer-specific actions: the RF contributes to hip flexion and knee extension during acceleration (Hagio et al., 2012), while the BF provides hip extension and eccentric control of knee flexion during braking and sprinting (Suarez-Arrones et al., 2020). Assessing these paired muscles allows examination of complementary activation strategies relevant to both propulsion and injury-prone deceleration phases.

Internal training intensity in SSGs is commonly quantified from heart-rate - derived measures aggregated as training impulse (TRIMP) to integrate exercise duration and intensity within a single load metric (Desgorces et al., 2020). The TRIMP concept, originally introduced to model performance as the balance of fitness and fatigue, formalized how cardiovascular strain accumulates to influence adaptation over time (Banister and Calvert, 1980). During ball drills, TRIMP demonstrates meaningful associations with other internal-load markers, supporting its use alongside energetic estimates to profile session demands (Jin et al., 2022).

Respiratory metabolism responds rapidly to workload fluctuations, and markers such as respiratory frequency, minute ventilation, and oxygen uptake provide sensitive indices of effort during intermittent and high-intensity exercise (Nicolò et al., 2017). During graded exercise, minute ventilation rises in concert with oxygen uptake, and their relationship underpins classic ventilatory-threshold and efficiency constructs used to interpret cardiorespiratory strain (Fairshair et al., 1987). In soccer - specific high-intensity shuttle-run protocols, respiratory frequency has been validated as a practical, sensitive marker of exercise intensity (Nicolò et al., 2020). At the muscle level, acidosis (H^+ accumulation) slows fiber conduction velocity and reduces sEMG median frequency, linking metabolic stressors to the electrophysiological signatures of fatigue (Brody et al., 1991). Therefore, based on this physiological relationship, it is theoretically expected that cardiorespiratory stress variables may mediate the association between internal load and muscle activation during SSGs (Perrey et al., 2003; Ertl et al., 2016).

While SSG research robustly characterizes physiological and locomotor demands, the mechanistic pathways that connect internal load to neuromuscular activation during ecologically valid game formats remain comparatively

underexplored (Clemente et al., 2022). Related physiology suggests that above-threshold exercise evokes progressive recruitment of fast-twitch motor units - contributing to the VO_2 slow component - implying bidirectional coupling between metabolic stress and muscle activation that warrants explicit modeling (Saunders et al., 2000). However, most previous SSG studies have primarily described external or internal load responses - such as heart-rate dynamics, lactate accumulation, or time - motion characteristics - without integrating these systemic indicators with muscle-specific neuromuscular measures (Bujalance-Moreno et al., 2019). To our knowledge, no prior research has quantitatively tested whether respiratory-metabolic responses mediate the relationship between cardiovascular load and muscle activation during soccer-specific play. Furthermore, existing evidence is dominated by team-based formats (3v3 - 6v6) (Clemente et al., 2021), whereas the 1v1 configuration imposes maximal individual and physiological demands, providing an opportunity to isolate player-specific responses. Given that SSG outcomes also vary with playing standard and training status, examining this mechanism in sub-elite collegiate athletes extends current SSG physiology literature beyond descriptive characterization toward a more integrative understanding of metabolic - neuromuscular coupling.

Accordingly, the present study investigated whether internal load during 1v1 SSGs relates to maximal lower-limb muscle activation and whether respiratory metabolism (oxygen uptake, respiratory frequency, and minute ventilation) mediates that association using validated sEMG and cardiopulmonary measures (Yamada et al., 2008). By clarifying this pathway in trained college physical-education students performing standardized 1v1 bouts, our objective is to refine evidence-based load prescription strategies that support performance development while informing injury-risk management in soccer practice. Among SSG formats, the 1v1 configuration was deliberately selected as an experimental model because it elicits the most intense and individualized physiological load (Bujalance-Moreno et al., 2019; Clemente et al., 2025) while minimizing external influences from teammates or tactical variability. Given the muscle-specific mechanical functions described above, we anticipated that BF activation - being more sensitive to metabolic stress - would exhibit full mediation through respiratory - metabolic variables, whereas RF activation would demonstrate partial mediation, reflecting both direct load effects and indirect metabolic influences (Salzman et al., 1993; Bergstrom et al., 2020).

Therefore, given the gaps in understanding how internal load translates into neuromuscular responses during ecologically valid soccer contexts, and the potential mediating role of respiratory metabolism in this process, this study aimed to: (i) examine the associations between

internal training load (quantified via TRIMP) and maximal lower-limb muscle activation during 1v1 small-sided games; and (ii) determine whether respiratory-metabolic variables (oxygen uptake, respiratory frequency, and minute ventilation) mediate this relationship. We hypothesized that higher internal load would be positively

associated with greater neuromuscular activation, and that respiratory metabolism would act as a significant mediator of this association.

Methods

Experimental approach

This study adopted a single-group repeated-measures experimental design to examine the associations among internal load, respiratory metabolism, and neuromuscular activation during 1v1 SSGs. Sixty male physical-education students completed a standardized 1v1 SSG protocol (8 × 1-min bouts interspersed with 1-min passive recovery) under controlled indoor conditions. Internal load indicators (TRIMP·min⁻¹, total energy expenditure, average and peak heart rate) and respiratory–metabolic variables (oxygen uptake, respiratory rate, and minute ventilation) were continuously obtained using the Firstbeat system. Surface electromyography (sEMG) of the rectus femoris (RF) and biceps femoris (BF) was recorded and normalized to maximal voluntary contraction (MVC) to derive RMS, aEMG, iEMG, and MF indices. All measurements were synchronized to capture concurrent cardiovascular, respiratory, and neuromuscular responses, and mediation analyses were performed to determine whether respiratory–metabolic factors mediated the relationship between internal load and muscle-specific activation patterns.

Setting

All sessions were conducted in an indoor venue under controlled environmental conditions (temperature: 20 - 24°C; relative humidity: 45 - 55%). Although this setting reduced ecological validity compared with outdoor play, it ensured standardized environmental and surface conditions necessary for physiological and neuromuscular measurements. Testing was performed at the same time of day to minimize circadian variation. This study was approved by the Research Ethics Committee of Chaohu University (Approval No.: CH20240011; Date: October 7, 2024), and all participants provided written informed consent in accordance with the Declaration of Helsinki.

Participants

An a priori sample size was determined for the primary mediation analysis (internal load, Respiratory Metabolism, neuromuscular activation). We assumed medium path coefficients for the X and Y paths (Note: In the mediation model, the X path refers to the effect of the independent variable on the mediating variable, while the Y path refers to the effect of the mediating variable on the dependent variable) ($r \approx 0.35 - 0.40$), consistent with prior work showing moderate-to-large associations between heart-rate - derived internal load and respiratory/physiological responses during small-sided play and intermittent match-like exercise (Dellal et al., 2011b), and is comparable to previous mediation studies employing within-subject or repeated-measures designs in the field of exercise physiology (Vickery-Howe et al., 2024). Power planning followed recommendations for bias-corrected bootstrap tests of the indirect effect: with $a = b \approx 0.39$, Fritz and MacKinnon (Fritz and MacKinnon, 2007) report $N \approx 71$ (participants) to achieve 80% power at $\alpha = 0.05$ for simple mediation with continu-

ous variables, whereas smaller paths (a or $b \approx 0.26$) require substantially larger samples. To corroborate this, we consulted simulation-based guidance indicating comparable or slightly higher requirements when sampling variability, residual correlations, or small direct effects are considered (Pan et al., 2018).

To improve the reliability of individual measurement indices, each participant completed 5 testing sessions, and the averaged values across sessions were used in the mediation analysis. This repeated-measures design substantially reduced measurement error, enhanced the stability of parameter estimates, and effectively increased the statistical power of the model. Therefore, we set the target sample size at 60 participants (≈ 300 session-level observations), which was deemed sufficient to detect moderate-sized indirect effects with ≥ 0.80 power under realistic intraclass correlations - consistent with recent summaries of sample size requirements for (simple) mediation and multilevel mediation analyses (Vickery-Howe et al., 2024). A total of 60 male college students majoring in physical education were recruited. Inclusion criteria were: (i) regular participation in exercise training (≥ 3 times per week); (ii) at least 2 years of exercise experience; (iii) no musculoskeletal injuries in the past 6 months. Exclusion criteria were: (i) history of cardiovascular or respiratory diseases; (ii) current use of medications affecting cardiopulmonary or neuromuscular function. The final sample had the following characteristics: age = 18.75 ± 0.45 years, training experience = 3.27 ± 3.30 years, and body mass = 69.35 ± 8.17 kg.

Overview of experimental procedures

All participants attended a familiarization session and practice before the formal tests. Each test began with a standardized 10-minute warm-up, which included jogging, dynamic stretching, and ball familiarity drills. This was followed by maximal voluntary contraction (MVC) tests for surface electromyography (sEMG) signal normalization; the participants then completed the small-sided soccer game (SSG) protocol, and finally performed the MVC tests again. The overview of the study can be observed in Figure 1.

Maximal voluntary contractions

Assessment of maximal voluntary contraction (MVC) was performed on the bilateral rectus femoris and biceps femoris muscles. When testing the rectus femoris, participants adopted a seated position, with their knee joints flexed over 90 degrees, and performed isometric knee extension against manual resistance. For testing the biceps femoris, participants lay in a prone position, with their knee joints flexed over 135 degrees, and performed isometric knee flexion. Each MVC lasted for 5 seconds, was repeated twice, and a 30-second interval was allowed between repetitions. MVC protocols of isometric lower - limb testing have demonstrated good to excellent reliability in prior literature (ICCs ~ 0.76 to 0.95 , typical errors $< \sim 7\%$) in similar testing contexts (Redden et al., 2018; Nuzzo et al., 2019; Gam et al., 2024). Therefore, we considered the reproducibility of MVCs in the current protocol sufficient for sEMG normalization, while acknowledging that precise repeatability may differ across samples and machines.

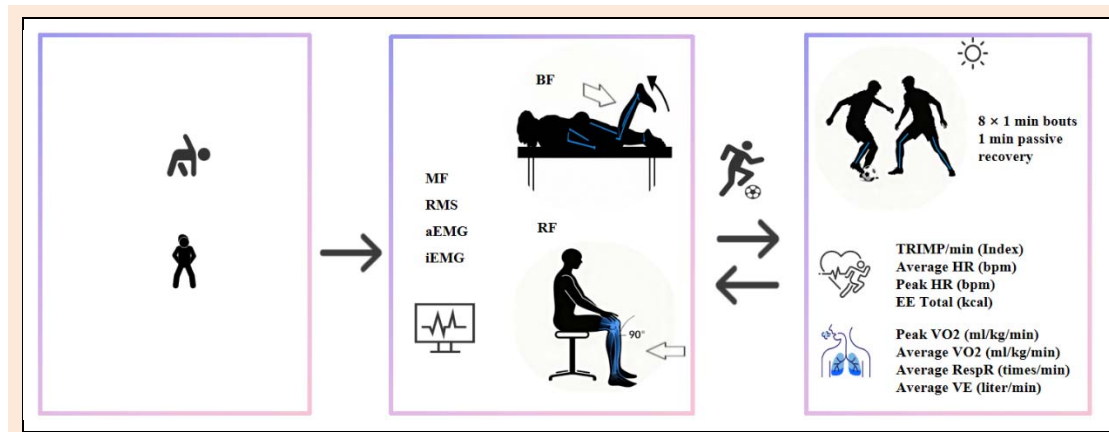


Figure 1. Experimental protocol and measurement overview. Participants first completed a standardized warm-up followed by a muscle activation assessment. Surface electromyography (sEMG) signals were recorded from the biceps femoris (BF) and rectus femoris (RF) muscles during isometric contractions to determine mean frequency (MF), root mean square (RMS), averaged EMG (aEMG), and integrated EMG (iEMG). Afterward, participants performed an 8 × 1-min small-sided game (SSG) protocol with 1-min passive recovery between bouts. Internal load and respiratory responses were continuously monitored, including training impulse per minute (TRIMP/min), average and peak heart rate (HR_avg, HR_peak), total energy expenditure (EE_total), peak and average oxygen uptake (VO₂), average respiratory rate (RespR), and ventilation (VE).

Small-sided game protocol

The SSG consisted of eight 1-minute 1v1 bouts separated by 1-minute passive rest. Games were played on a 20 × 10 m indoor pitch with futsal-size goals. (18.4 °C, 55% relative humidity), using futsal goals. The attacking player attempted to dribble or pass the ball past the opponent's end line to score, while the defending player sought to steal the ball or block the attack. If the ball went out of bounds, the coach returned the ball immediately to ensure game continuity. Assessment of maximal voluntary contraction (MVC) was performed on the bilateral rectus femoris and biceps femoris muscles.

Measurements

Internal training load

Heart-rate data were captured with the Firstbeat Team System (Firstbeat Technologies, Jyväskylä, Finland). Data were acquired and processed in the Firstbeat Sports platform (cloud application) during the study period. Beat-to-beat intervals are detected from the chest-strap ECG signal; Firstbeat's processing pipelines include artifact detection, R - R interval editing, and HRV-derived modeling that enable stable intensity zoning and load estimation in dynamic exercise. Independent work (Schneider et al., 2018) shows that HR from chest-strap/ECG systems is accurate and reliable for load monitoring in sport and that HR-based TRIMP behaves with acceptable test - retest characteristics in team settings, supporting its use as a primary internal-load indicator (Ulmer et al., 2019). Internal load was quantified as TRIMP·min⁻¹ (Banister-type TRIMP; duration and intensity weighting relative to individual HR_{max}). We also report Average HR, Peak HR, and total energy expenditure (EE) from device algorithms; consistent with prior reviews, EE should be interpreted as an estimate rather than a criterion measure (Selmi et al., 2020).

Respiratory – metabolic variables

Estimates of oxygen uptake (VO₂, mL·kg⁻¹·min⁻¹), respiratory frequency (RespR, breaths·min⁻¹), and minute ventilation (VE, L·min⁻¹) were obtained continuously using Firstbeat's cardiopulmonary model, which derives RespR

and VE from HRV (R - R) features and models VO₂ dynamics accordingly. Thus, Respiratory–metabolic variables refers to the modeled estimates of VO₂, VE, and RespR derived from heart-rate/HRV processing in the Firstbeat platform. The Firstbeat VO₂ method and related algorithms have shown validity for estimating VO₂/VO_{2max} without individual calibration in controlled and free-living tasks (Smolander et al., 2011; Gao et al., 2021). Nevertheless, we interpret VO₂/VE/RespR as modeled approximations rather than direct gas-exchange measures. Independent studies also support HRV/ECG-derived RespR during exercise with good agreement to reference signals (Rogers et al., 2022).

Surface Electromyography

Surface EMG was recorded with a Delsys Trigno wireless system (Delsys Inc., Natick, MA, USA) using EMGworks software during the study period, following previous procedures recommendations (Feng et al., 2025). Bipolar electrodes with a 10-mm interelectrode distance were placed longitudinally along the muscle fibers according to SENIAM recommendations. For the rectus femoris (RF), electrodes were positioned at 50% of the line between the anterior superior iliac spine and the superior border of the patella; for the biceps femoris (BF), placement was at 50% of the line between the ischial tuberosity and the lateral epicondyle of the tibia. The skin was shaved, lightly abraded, and cleaned with 70% isopropyl alcohol to maintain low impedance (<5 kΩ), and electrode sites were marked with semi-permanent ink to ensure consistent pre - post placement. All sEMG indices used the signals of the target muscles during MVC as the standardized reference: for BF, MVC during isometric knee flexion; and for RF, MVC during isometric knee extension. MVC signals were processed by taking the midpoint of the sEMG time series as the starting point and sliding bidirectionally along the time axis to both ends for subsequent index standardization. The amplitude-related indices included root mean square (RMS, reflecting instantaneous activation intensity), average electromyographic amplitude (aEMG, reflecting time-averaged activation level), and integrated electromyography

(iEMG, reflecting cumulative activation load over time). The frequency-domain index was median frequency (MF), calculated via Fast Fourier Transform (FFT) and used to characterize neuromuscular fatigue, as a decrease in MF indicates reduced muscle-fiber conduction velocity and increased fatigue severity.

Data processing and outcomes

For data processing, the average of five measurements was used as the calculation data, and all values were expressed as the ratio of (post-exercise value - pre-exercise value) to pre-exercise value; the independent variables were internal load indicators (TRIMP·min⁻¹, average heart rate, peak heart rate, energy expenditure), the mediating variables were respiratory indicators, and the dependent variables were the maximum contractile electromyographic (EMG) indices (RMS, iEMG, aEMG, MF) obtained during the maximal voluntary contraction (MVC) of the BF and RF; in the mediation model, the median frequency of the BF and the RMS, iEMG, aEMG, and MF of the RF were specified as dependent variables.

Statistical analysis

Data were analyzed using IBM SPSS Statistics (v30.0, IBM Corp., Armonk, NY, USA). Preprocessing of surface electromyographic (sEMG) signals included the removal of DC components, Butterworth band-pass filtering (10 - 500 Hz), and adaptive 50 Hz power-line notch filtering. Missing values and outliers were all handled using median imputation. Data normality was assessed via the Shapiro-Wilk test, while multicollinearity was detected based on tolerance and variance inflation factor (VIF). Associations between internal load and surface electromyographic (sEMG) indicators were examined using Spearman correlation analysis and linear regression models. Mediation effect analysis was implemented using the PROCESS macro (Model 4; Hayes, 2022), with 5000 bootstrap samples used to generate 95% bias-corrected confidence intervals (CIs). The indirect effect was considered statistically significant if the 95% CI did not include zero. The statistical significance level was set at $p < 0.05$.

Results

Descriptive statistics for all measured variables are presented in Table 1. Overall, the 1v1 SSG protocol elicited high cardiovascular and respiratory responses alongside consistent muscle activation across participants. Internal training load, expressed as TRIMP·min⁻¹, averaged 1.90 ± 0.50 . Heart-rate and metabolic values reflected vigorous exercise intensity, with an average HR of 155.2 ± 12.5 bpm and peak HR of 178.2 ± 10.7 bpm. Total energy expenditure across the 8×1 -min bouts was 197.3 ± 26.3 kcal. Respiratory-metabolism data showed elevated ventilatory responses: average $\text{VO}_2 = 39.3 \pm 4.3$ mL·kg⁻¹·min⁻¹, peak $\text{VO}_2 = 48.1 \pm 3.3$ mL·kg⁻¹·min⁻¹, mean respiratory frequency = 36.7 breaths·min⁻¹ (IQR 34.7 - 38.6), and average $\text{VE} = 71.8$ L·min⁻¹ (IQR 64.5 - 77.4). These descriptive values suggest that players performed at high physiological intensity. Neuromuscular outcomes obtained from MVCs of BF and RF are also displayed in Table 1. For both

muscles, indices of maximal activation were consistently high, confirming effective effort in pre- and post-testing. RMS, iEMG, aEMG, and MF values provided complementary perspectives on the amplitude and spectral properties of activation.

Table 1. Subject characteristics.

Parameters	Mean	SD/IQR	P-value
Age (years)	18.75	18.00-19.00	<0.001
Height (cm)	179.18	5.54	0.072
Body mass (kg)	69.35	8.17	0.258
Experience (years)	3.27	3.00-3.00	<0.001
TRIMP·min ⁻¹ (Index)	1.90	0.50	0.060
Average HR (bpm)	155.17	12.49	0.529
Peak HR (bpm)	178.15	10.66	0.326
EE Total (kcal)	197.31	26.27	0.489
BF_RMS _{MVC}	0.32	0.03-0.26	<0.001
BF_MF _{MVC}	0.09	0.02-0.15	0.018
BF_iEMG _{MVC}	0.26	0.03-0.27	<0.001
BF_aEMG _{MVC}	0.26	0.03-0.27	<0.001
RF_RMS _{MVC}	0.05	0.15	0.058
RF_MF _{MVC}	0.09	0.06	0.098
RF_iEMG _{MVC}	0.05	-0.08-0.15	0.001
RF_aEMG _{MVC}	0.05	-0.08-0.15	0.001
Peak VO_2 (mL·kg ⁻¹ ·min ⁻¹)	48.07	3.31	0.141
Average VO_2 (mL·kg ⁻¹ ·min ⁻¹)	39.27	4.33	0.290
Average RespR (breaths·min ⁻¹)	36.67	34.66-38.58	0.013
Average VE (L·min ⁻¹)	71.77	64.45-77.37	0.021

SD, standard deviation; IQR, interquartile range; TRIMP·min⁻¹, training impulse per minute; HR, heart rate; EE total, total energy expenditure; BF, biceps femoris; RF, rectus femoris; EMG, electromyography; RMS, root-mean-square amplitude; MF, median frequency; iEMG, integrated EMG; aEMG, averaged EMG amplitude; MVC, maximal voluntary contraction; VO_2 , oxygen uptake; RespR, respiratory rate; VE, minute ventilation. bpm = beats·min⁻¹; VO_2 in mL·kg⁻¹·min⁻¹; RespR in breaths·min⁻¹; VE in L·min⁻¹; EE_total in kcal.

Collinearity

Multicollinearity diagnostics showed that most variable combinations (e.g., TRIMP·min⁻¹ and Peak VO_2 , Average HR and Average RespR, EE Total and Average VO_2) had low variance inflation factors ($\text{VIF} < 5$), indicating generally independent variability among predictors. However, several pairings demonstrated moderate collinearity, including TRIMP·min⁻¹ and Average VO_2 ($\text{VIF} = 7.17$), Average HR and Average VO_2 ($\text{VIF} = 9.15$), and Peak HR and Peak VO_2 ($\text{VIF} = 5.51$) (Table 2). These values exceed the conventional $\text{VIF} < 5$ threshold, suggesting partial overlap between cardiovascular and metabolic indicators. To minimize nonessential multicollinearity, all continuous predictors were mean-centered prior to mediation analysis. As all VIFs remained below 10 and tolerance values exceeded 0.15, no variable reduction was required, and the models were retained for analysis.

Associations between internal load and muscle activation

BF correlation analysis results indicated that most internal load indicators exhibited highly significant positive correlations with the respiratory-related variable. For instance, TRIMP·min⁻¹ showed strong positive correlations with average Ave VO_2 ($r = 0.938$, $p < 0.001$), AveRespR ($r = 0.864$, $p < 0.001$), and AveVE ($r = 0.893$, $p < 0.001$); meanwhile, AveH and PeakHR also maintained strong positive correlations with the aforementioned respiratory-metabolic

variables (r range: 0.757 - 0.944, all $p < 0.001$). Although the overall correlation between respiratory-related variables and EMG indicators was relatively low, significant associations were still observed between some variables. Specifically, AveVO₂ showed a significant positive corre-

lation with EMG median frequency (MF, $r = 0.268$, $p < 0.05$), as did AveRespR with MF ($r = 0.34$, $p < 0.01$) and AveVE with MF ($r = 0.29$, $p < 0.05$). This finding suggests that the respiratory metabolic level may exert a certain influence on the maximal muscle activation level (Figure 2).

Table 2. Collinearity results of variable indicators.

Parameters X	Parameters M	Tolerance	VIF
TRIMP·min ⁻¹ (Index)	Peak VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.283	3.540
TRIMP·min ⁻¹ (Index)	Average VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.139	7.174
TRIMP·min ⁻¹ (Index)	Average RespR (breaths·min ⁻¹)	0.383	2.612
TRIMP·min ⁻¹ (Index)	Average VE (L·min ⁻¹)	0.234	4.269
Average HR (bpm)	Peak VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.351	2.849
Average HR (bpm)	Average VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.109	9.150
Average HR (bpm)	Average RespR (breaths·min ⁻¹)	0.334	2.992
Average HR (bpm)	Average VE (L·min ⁻¹)	0.227	4.398
Peak HR (bpm)	Peak VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.181	5.514
Peak HR (bpm)	Average VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.404	2.478
Peak HR (bpm)	Average RespR (breaths·min ⁻¹)	0.549	1.822
Peak HR (bpm)	Average VE (L·min ⁻¹)	0.429	2.330
EE Total (kcal)	Peak VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.774	1.292
EE Total (kcal)	Average VO ₂ (mL·kg ⁻¹ ·min ⁻¹)	0.824	1.214
EE Total (kcal)	Average RespR (breaths·min ⁻¹)	0.828	1.208
EE Total (kcal)	Average VE (L·min ⁻¹)	0.553	1.807

TRIMP·min⁻¹, training impulse per minute; VO₂, oxygen uptake; RespR, respiratory rate; VE, minute ventilation; HR, heart rate; EE_total, total energy expenditure; bpm, beats·min⁻¹; mL·kg⁻¹·min⁻¹, milliliters per kilogram per minute; L·min⁻¹, liters per minute; VIF, variance inflation factor; bpm = beats·min⁻¹; VO₂ in mL·kg⁻¹·min⁻¹; RespR in breaths·min⁻¹; VE in L·min⁻¹; EE_total in kcal. Notes: Parameters X = predictor; Parameters M = mediator.



Figure 2. Pairwise correlations among internal load indicators, respiratory-metabolic variables, and biceps femoris (BF) electromyographic (EMG) parameters. The upper triangle displays Spearman's correlation coefficients, where color intensity indicates the strength of correlation, with (***) $p < 0.001$, (**) $p < 0.01$, and (*) $p < 0.05$ denoting statistical significance. The lower triangle presents scatter plots with overlaid linear regression lines, visualizing pairwise linear trends. Diagonal panels show kernel density plots, representing the distribution of each variable. Variables include training impulse per minute (TRIMP), average and peak heart rate (AveHR, PeakHR), total energy expenditure (EE), rectus femoris EMG indices [root mean square (RMS), mean frequency (MF), integrated EMG (iEMG), and average EMG amplitude (aEMG)], and respiratory parameters [peak oxygen uptake (PeakVO₂), average oxygen uptake (AveVO₂), average respiratory exchange ratio (AveRespR), and average ventilation (AveVE)].



Figure 3. RF correlation matrix illustrating bivariate associations among internal load, surface rectus femoris electromyography (sEMG), and respiratory-metabolic variables. The upper triangle displays Spearman's correlation coefficients, where color intensity indicates the strength of correlation, with (***) $p < 0.001$, (**) $p < 0.01$, and (*) $p < 0.05$ denoting statistical significance. The lower triangle presents scatter plots with overlaid linear regression lines, visualizing pairwise linear trends. Diagonal panels show kernel density plots, representing the distribution of each variable. Variables include training impulse per minute (TRIMP·min⁻¹), average and peak heart rate (AveHR, PeakHR), total energy expenditure (EE), rectus femoris EMG indices [root mean square (RMS), mean frequency (MF), integrated EMG (iEMG), and average EMG amplitude (aEMG)], and respiratory parameters [peak oxygen uptake (PeakVO₂), average oxygen uptake (AveVO₂), average respiratory exchange ratio (AveRespR), and average ventilation (AveVE)].

RF correlation analysis (Figure 3) results showed that there were highly significant positive correlations between internal load indicators and respiratory-related variables. Specifically, the TRIMP·min⁻¹ exhibited a strong positive correlation with PeakVO₂ ($r = 0.864$, $p < 0.001$), and EE Total maintained a significant positive correlation with AveVO₂ ($r = 0.436$, $p < 0.001$). Although the overall correlation between respiratory-related variables (M) and electromyographic (EMG) indicators was relatively low, average oxygen uptake (AveVO₂) showed a significant positive correlation with average electromyographic amplitude (aEMG) ($r = 0.28$, $p < 0.05$). Moreover, significant correlations were observed between internal load indicators and EMG indicators: TRIMP·min⁻¹ demonstrated significant positive correlations with integrated electromyography (iEMG), average electromyographic amplitude (aEMG), and root mean square (RMS) ($r = 0.325$, $p < 0.05$; $r = 0.325$, $p < 0.05$; $r = 0.292$, $p < 0.05$).

To investigate the mediating role of respiratory-metabolic variables, separate mediation models were built to test their effects on the relationships between internal load and maximal muscle activation of the BF (Figure 4) and RF (Figure 5).

Mediation analyses

A: Peak HR → Average RespR → BF_MF. Results revealed that Peak HR significantly and positively predicted Average RespR ($a = 0.2141$, $p < 0.05$), and Average RespR also exerted a significant positive effect on BF_MF ($b = 0.0107$, $p < 0.05$). However, the direct effect of Peak HR on BF_MF was not significant ($c' = -0.0013$). Mediation analysis demonstrated that the indirect effect was significant ($\beta = 0.0023$, 95% confidence interval [95%CI]: 0.0007 - 0.0058), while the total effect was non-significant ($\beta = 0.0009$, 95%CI: -0.0013 - 0.0032). These findings indicated that Average RespR played a full positive mediating role in the relationship between Peak HR and BF_MF.

B: Peak HR → Average VE → BF_MF. As shown in the results, Peak HR significantly and positively predicted Average VE ($a = 0.0972$, $p < 0.05$), whereas the effect of Average VE on BF_MF was not significant ($b = 0.0025$, [n.s.]). Meanwhile, the direct effect of Peak HR on BF_MF was also non-significant ($c' = -0.0015$). Nevertheless, the indirect effect reached a significant level ($\beta = 0.0025$, 95% CI: 0.0001 - 0.0048), while the total effect remained non-significant ($\beta = 0.0009$, 95% CI: -0.0013 - 0.0032). Collectively, Average VE exhibited a full mediating effect in the association between Peak HR and BF_MF, albeit with a relatively weak effect magnitude.

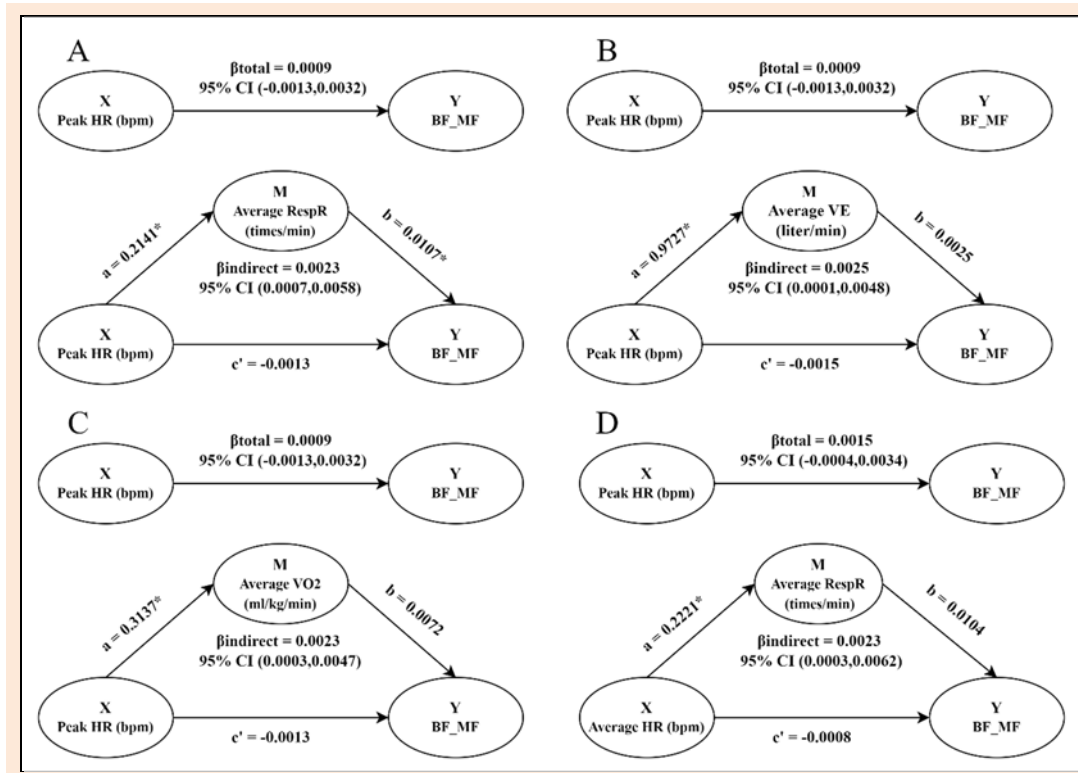


Figure 4. Mediation models showing indirect effects of heart rate (HR) indices (X) on biceps femoris (BF) electromyography median frequency (MF) (BF_MF, Y) via respiratory-metabolic variables (M). (A-C) Peak HR (beats·min⁻¹) as X with Average respiratory rate (RespR), minute ventilation (VE), or oxygen uptake (VO₂) as M. (D) Average HR as X and Average RespR as M. Path coefficients (a, b, c'), bootstrapped 95% confidence intervals (CIs), and indirect effects (a×b) are reported. $p < 0.05$.

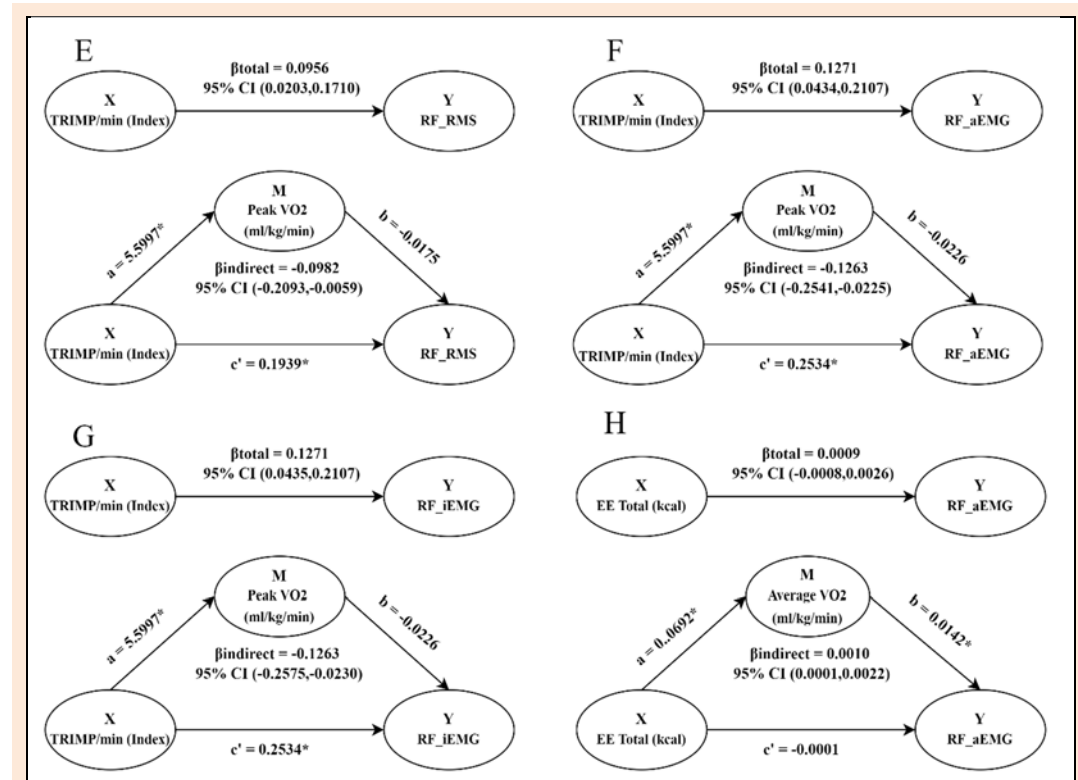


Figure 5. Mediation models showing indirect effects of internal-load indicators (X) on rectus femoris (RF) electromyography (EMG) outcomes (Y) via respiratory-metabolic variables (M). (E-G) Training impulse per minute (TRIMP·min⁻¹) as X with peak oxygen uptake (VO₂, mL·kg⁻¹·min⁻¹) as M and RF root-mean-square amplitude (RF_RMS), RF averaged EMG amplitude (RF_aEMG), or RF integrated EMG (RF_iEMG) as Y. (H) total energy expenditure (EE_{total}, kcal) as X, average VO₂ (mL·kg⁻¹·min⁻¹) as M, and RF_aEMG as Y. Path coefficients (a, b, c'), bootstrapped 95% confidence intervals (CIs), and indirect effects (a×b) are shown. $p < 0.05$.

C: Peak HR $\rightarrow$ Average VO₂ $\rightarrow$ BF_MF, Results indicated that Peak HR significantly and positively predicted Average VO₂ ($a = 0.3137$, $p < 0.05$), but the effect of Average VO₂ on BF_MF was non-significant ($b = 0.0072$, n.s.), and the direct effect of Peak HR on BF_MF was also non-significant ($c' = -0.0013$). The indirect effect was significant ($\beta = 0.0023$, 95%CI: 0.0003 - 0.0047), while the total effect was non-significant ($\beta = 0.0009$, 95%CI: -0.0013 - 0.0032). These data suggested that Average VO₂ exerted a full mediating role in the relationship between Peak HR and BF_MF, with its effect transmitted indirectly through respiratory and metabolic indicators.

D: Average HR $\rightarrow$ Average RespR $\rightarrow$ BF_MF, Results showed that Average HR significantly and positively predicted Average RespR ($a = 0.2221$, $p < 0.05$), while the effect of Average RespR on BF_MF was non-significant ($b = 0.0104$, n.s.); the direct effect of Average HR on BF_MF was also non-significant ($c' = -0.0008$). Mediation analysis revealed a significant indirect effect ($\beta = 0.0023$, 95%CI: 0.0003 - 0.0062), whereas the total effect was non-significant ($\beta = 0.0015$, 95%CI: -0.0004 - 0.0034). Thus, Average RespR served as a full mediator in the relationship between Average HR and BF_MF.

Across all four models, the direct effects of heart rate-related indices (Peak HR or Average HR) on BF_MF were non-significant. Instead, their influences on BF_MF were primarily transmitted through respiratory and metabolic parameters - RespR, VE, and VO₂ - which demonstrated significant indirect effects. Although the magnitude of these mediations was small and total effects were non-significant, the consistent pattern suggests that increases in ventilatory and metabolic strain are associated with shifts in BF median frequency, reflecting progressive neuromuscular fatigue. These results indicate that modulation of BF_MF is more closely associated with variations in respiratory - metabolic load than with direct cardiovascular responses, suggesting a physiological linkage between metabolic demand and muscle frequency characteristics rather than a definitive causal relationship.

Model E (TRIMP·min⁻¹ $\rightarrow$ Peak VO₂ $\rightarrow$ RF_RMS). Results showed that TRIMP·min⁻¹ significantly and positively predicted Peak VO₂ ($a = 5.599$, $p < 0.05$), while Peak VO₂ exerted a marginally negative effect on RF_RMS ($b = -0.0175$). The direct effect of TRIMP·min⁻¹ on RF_RMS was significant ($c' = 0.1939$, $p < 0.05$), as was the indirect effect ($\beta = -0.0982$, 95%CI [-0.2093, -0.0059]), with a significant total effect ($\beta = 0.0956$, 95%CI [0.0203, 0.1710]). These findings indicate that Peak VO₂ plays a significant negative mediating role between TRIMP·min⁻¹ and RF_RMS: TRIMP·min⁻¹ directly promotes increased RF_RMS, while indirectly inhibiting it through elevated Peak VO₂.

Model F (TRIMP·min⁻¹/min $\rightarrow$ Peak VO₂ $\rightarrow$ RF_aEMG). TRIMP·min⁻¹ significantly and positively predicted Peak VO₂ ($a = 5.599$, $p < 0.01$), and Peak VO₂ showed a marginally negative effect on RF_aEMG ($b = -0.0226$). The direct effect of TRIMP·min⁻¹ on RF_aEMG was significant ($c' = 0.2534$, $p < 0.05$), alongside a significant indirect effect ($\beta = -0.1263$, 95%CI [-0.2541, -0.0225]) and a significant total effect ($\beta = 0.1271$, 95%CI [0.0434, 0.2107]). This demonstrates that Peak VO₂ exerts

a significant negative mediating role in the relationship between TRIMP·min⁻¹ and RF_aEMG, forming a dual pathway of "direct positive promotion + indirect negative inhibition," with the direct effect being more prominent.

Model G (TRIMP·min⁻¹ $\rightarrow$ Peak VO₂ $\rightarrow$ RF_iEMG). Path coefficients were consistent with those in Model F, indicating that the mediation pattern of TRIMP·min⁻¹ on RF_iEMG was identical to that on RF_aEMG. This further validates the consistency and robustness of results across different EMG indicators (RF_aEMG vs. RF_iEMG).

Model H (EE Total $\rightarrow$ Average VO₂ $\rightarrow$ RF_aEMG). EE Total significantly and positively predicted Average VO₂ ($a = 0.0692$, $p < 0.05$), and Average VO₂ predicted RF_aEMG ($b = 0.0142$, $p < 0.05$), whereas the direct effect of EE Total on RF_aEMG was non-significant ($c' = -0.0001$). The indirect effect was significant ($\beta = 0.0010$, 95%CI [0.0001, 0.0022]), but the total effect was non-significant ($\beta = 0.0009$, 95%CI [-0.0008, 0.0026]). These results suggest that Average VO₂ exerts a full positive mediating role between EE Total and RF_aEMG, meaning the effect of EE Total on RF_aEMG is entirely transmitted through Average VO₂.

Models E - G all exhibited a pattern of negative partial mediation: TRIMP·min⁻¹ directly promoted increased EMG indicators (RF_RMS, RF_aEMG, RF_iEMG) while indirectly inhibiting them through increased Peak VO₂. Consistent results between Models F and G validate the reliability of measurements and conclusions across different EMG indicators. In contrast, Model H showed a pattern of full positive mediation, indicating that the effect of EE Total on RF_aEMG is entirely dependent on transmission through Average VO₂.

Discussion

This study examined the cardiopulmonary, metabolic, and neuromuscular demands of 1v1 SSGs and whether respiratory - metabolic variables mediate the relationship between training intensity and muscle activation. Internal-load and respiratory-metabolic parameters showed strong positive associations, suggesting physiological coupling between cardiovascular stress and oxygen demand. However, several predictors were statistically inter-correlated (e.g., HR and VO₂, VIF $\approx 5 - 9$), indicating that complete statistical independence was limited despite mean-centering. Partial correlations and tolerance values confirmed acceptable but non-negligible overlap among predictors, which should be considered when interpreting model coefficients. These findings extend prior SSG research by linking systemic metabolic strain to muscle-specific activation responses, rather than restating known HR - VO₂ relationships.

TRIMP·min⁻¹ tracked HR and energy cost, consistent with football studies showing individualized TRIMP relates more closely to physiological adaptation (e.g., velocity at lactate threshold) than alternative load measures and displays good day-to-day reliability (Akubat et al., 2012). In line with our data, SSGs with fewer players and/or larger relative pitch areas elicit higher HR and VO₂, highlighting substantial internal loads in 1v1 - 2v2 formats (Hill-Haas et al., 2011; Dellal et al., 2011a). Because EMG

median frequency (MF) indexes recruitment/conduction-velocity shifts that scale with task intensity, whereas amplitude measures are more susceptible to non-physiological variance (e.g., placement, cross-talk), the slightly stronger MF - RespR/VO₂ associations we observed ($r \approx 0.27 - 0.34$ vs. $r \approx 0.20 - 0.26$ for amplitude) provide convergent evidence that the higher systemic strain in these formats is reflected at the neuromuscular level; nonetheless, these effects are small, and differences between correlations should be interpreted cautiously if confidence intervals overlap.

The stronger coupling observed between MF and physiological load is physiologically coherent. During fatiguing contractions, muscle-fiber conduction velocity slows; the sEMG power spectrum shifts to lower frequencies and MF declines - an effect repeatedly demonstrated with simultaneous conduction-velocity and spectral measurements (Eberstein and Beattie, 1985). This phenomenon has been linked to the VO₂ slow component during heavy exercise - for example, a study (Borroni et al., 2001) found that the time course of EMG mean power frequency in several muscles paralleled the slow rise in VO₂, supporting a model in which progressive recruitment of higher-order motor units contributes to spectral decline. MF, therefore, captures efficiency-related aspects of activation that amplitude measures can miss, whereas RMS/iEMG/aEMG (valuable for activation magnitude) are more susceptible to non-neural and methodological factors (electrode placement, normalization strategy, amplitude cancellation) (Burden, 2010). Within this context, the present study's high concordance among amplitude indices and the comparatively tighter relationships for MF with systemic physiology are expected outcomes and support using MF alongside amplitude metrics when profiling neuromuscular status around SSGs.

The mediation findings suggest a possible mediating role of respiratory-metabolic stress between internal load and neuromuscular activation. Work above lactate/ventilatory threshold expresses a VO₂ slow component and heightened ventilatory drive that are classically interpreted as a progressive loss of contractile efficiency - conditions known to influence motor-unit recruitment and EMG spectral features (Whipp, 1994; Jones et al., 2011). The observed paths - HR → RespR (or VE) → BF MF and EE → VO₂ → RF aEMG - are therefore consistent with established bioenergetics linking respiratory-metabolic stress to neuromuscular efficiency. While prior soccer and exercise studies typically report associations between respiratory or load variables and metabolic or external indices (Montini and Rocchi, 2022; Ashcroft et al., 2023) identifying their mediating influence on EMG-derived activation in a soccer-specific, repeated-bout design represents a novel contribution that may help explain why athletes display disproportionate neuromuscular 'cost' at comparable external loads.

Muscle-specific responses further contextualize these mechanisms. The BF exhibited significant post-exercise decrements (MVC: $p < 0.001$; MF: $p = 0.018$), consistent with the high eccentric and lengthening demands imposed during braking, change-of-direction, and the late swing phase of sprinting - actions that lengthen and load

the hamstrings near their vulnerable range. Biomechanical and modeling work shows marked hamstring force and strain peaking in late swing, particularly in the biceps femoris long head, supporting the greater fatigue signature observed here (Schache et al., 2012; Liu et al., 2017). Epidemiologically, hamstring injuries remain the most prevalent time-loss diagnosis in elite men's football and have increased in relative burden over the last two decades, highlighting the practical importance of monitoring and managing hamstring load in high-intensity microcycles that feature 1v1 work (Ekstrand et al., 2022b).

The biceps femoris long head (BF) experiences high eccentric braking demands in late swing, when the hamstrings are lengthened and active to decelerate the shank (Chumanov et al., 2007; Liu et al., 2017). By contrast, the rectus femoris (RF) contributes more to hip flexion during swing and also to knee-extension torque generation across stance, consistent with its biarticular role in propulsion tasks (Salzman et al., 1993; Kakehata et al., 2021). Such task differences likely imply greater recruitment of higher-threshold motor units and conduction-velocity shifts in BF under braking demand - changes that are captured by EMG spectral metrics (mean/median frequency) because these frequencies track muscle-fiber conduction velocity (Arendt-Nielsen and Mills, 1985; McManus et al., 2020). Phenotype/architecture may further contribute: BF shows adaptability to eccentric loading (e.g., fascicle-length increases after eccentric training), consistent with its exposure to high late-swing strain (Pincheira et al., 2022). Meanwhile, quadriceps (including RF) generally exhibit a mixed fiber-type profile under intense knee-extensor work rather than a uniformly "fast" signature (Krustrup et al., 2004). However, because fiber-type distributions vary regionally within human muscles, inter-muscle spectral differences (BF vs RF) should be interpreted cautiously.

Several limitations should be acknowledged. Participants were male physical-education majors, which may limit generalizability to elite or female players. Sex-based differences in muscle composition, hormonal milieu, and fatigue resistance have been shown to influence neuromuscular and metabolic responses to high-intensity exercise (Hicks et al., 2001; Hunter, 2014; 2016), suggesting that the mediation mechanisms observed here should be interpreted cautiously when extrapolating to broader athletic populations. Future research should include female and mixed-sex cohorts across different competitive levels and implement in-play EMG acquisition to validate whether similar mediation pathways persist under diverse physiological and contextual conditions. Additionally, all testing was performed indoors under controlled temperature, which enhanced standardization and data quality but reduced ecological validity relative to outdoor soccer environments. Differences in surface traction, ball dynamics, and ambient conditions can influence physiological and neuromuscular responses; therefore, generalization to outdoor match play should be made cautiously. Moreover, only acute responses were examined without a recovery time-course, and EMG was collected pre/post rather than in-play, leaving in-bout neuromuscular dynamics inferred from systemic physiology. In addition, respiratory and energetic parameters were estimated using HR/HRV-based

proprietary algorithms; although such methods show good group-level validity for estimating $\text{VO}_2/\text{VO}_{2\text{max}}$ and deriving respiratory frequency (Smolander et al., 2011; Rogers et al., 2022), individual-level error and magnitude-dependent bias can occur - especially at very high intensities and for energy-expenditure estimates - relative to criterion gas-exchange or gold-standard methods.

Some potential practical applications may be drawn from our findings. $\text{TRIMP} \cdot \text{min}^{-1}$ can anchor daily internal-load monitoring during 1v1 microcycles, corroborated by brief snapshots of RespR or VE to infer metabolic strain; in practice, coaches can track % time spent in upper respiratory zones and note within-session respiratory drift (a rising RespR/VE for the same drill) to flag “costly” exposures. Incorporating MF (BF, RF) alongside amplitude indices can help detect efficiency-related fatigue that HR alone may miss; a simple workflow is two standardized 5–10 s isometric checks (knee flexion for BF, knee extension for RF) pre- and ~3–5 min post-SSG, comparing MF to each athlete’s rolling baseline to judge meaningful change. For hamstring risk management when emphasizing 1v1 work, pairing sessions with eccentric posterior-chain strengthening and sprint-mechanics exposure could represent a potential strategy given the biomechanical and epidemiological evidence for late-swing vulnerability and rising burden in elite football. In an applied scenario, coaches may use 1v1 bouts as high-load stimuli within a weekly microcycle, manipulating bout duration, recovery ratio, and pitch constraints to adjust intensity without excessive fatigue; when respiratory strain is high and MF falls (especially BF), follow the session with low-eccentric or technical work, whereas high respiratory strain with stable MF suggests primarily aerobic stress and allows cautious maintenance of lower-limb eccentric content. Progressive integration of 1v1 formats across the preseason can enhance conditioning and specific hamstring robustness if balanced with recovery and strength work, and continuous monitoring of EMG-based indices - especially BF MF - can provide early feedback on neuromuscular efficiency to guide timely load adjustments and reduce overreaching or injury risk.

Conclusion

This study identified evidence of a mediating mechanism among internal load, respiratory metabolism, and neuromuscular parameters during 1v1 small-sided soccer games (SSGs), with training impulse per minute ($\text{TRIMP} \cdot \text{min}^{-1}$) serving as a sensitive index of internal load. In the biceps femoris (BF), frequency-domain sEMG metrics - particularly median frequency (MF) - correlated more strongly with physiological and respiratory-metabolic variables than amplitude-based indices. Moreover, the hamstrings, especially BF, exhibited a more pronounced functional decline post-exercise, reflecting the high eccentric demands imposed by sprinting and cutting actions and reaffirming their documented susceptibility to fatigue and injury. These findings provide preliminary findings into the relationship among internal load, respiratory metabolism, and neuromuscular function during soccer-specific high-intensity drills, while offering practical reference for load

monitoring and injury-prevention strategies.

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Key points

- Internal training load and respiratory metabolism (oxygen uptake, ventilation, respiratory rate) were strongly correlated, showing tight physiological coupling during 1-versus-1 small-sided soccer games.
- The relationship between heart rate and biceps femoris muscle activation was fully mediated by respiratory and metabolic factors.
- Rectus femoris muscle activation was influenced by both direct effects of internal load and indirect inhibition through elevated oxygen uptake, indicating a dual regulation mechanism.

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