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RESTING HEART RATE VARIABILITY VALUES REFLECT SOME PERFORMANCE PARAMETERS IN PROFESSIONAL MALE SOCCER PLAYERS

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Abstract:

Background: Heart rate variability (HRV) is increasingly used in sports science as a non-invasive marker of autonomic nervous system function and training adaptation. In soccer, where players engage in mixed high-intensity efforts, HRV may provide insight into both aerobic and anaerobic capacities. This study aimed to evaluate the relationship between resting HRV and key physiological performance parameters in professional soccer players.

Methods: Seventeen professional male soccer players (age: 24.55 ± 4.71 years) from the Turkish second league participated. HRV data were collected using the Omegawave system alongside measures of aerobic and anaerobic power, sprinting, jumping, reaction time, lactate levels, and GPS-based match performance. Assessments were conducted over four visits, and standard time- and frequency-domain HRV indices were analyzed.

Results: Velocity at anaerobic threshold was positively correlated with several time-domain and frequency-domain HRV parameters, and negatively with LF:HF and LFnu ratios. VO_{2max} was positively associated with HFnu and negatively with LF-related parameters. GPS-derived performance metrics and lactate tolerance were also linked to HRV indicators, suggesting vagal activity reflects multiple aspects of performance.

Conclusions: Resting HRV parameters, particularly those reflecting parasympathetic activity, are associated with both aerobic and anaerobic performance indicators in professional soccer players. Suggesting that HRV monitoring can serve as a practical, non-invasive tool for tracking aerobic power and for planning and adjusting daily training loads.

1. Introduction

Soccer has a structure that requires the simultaneous use of different types of activities such as sprinting, jumping, jogging etc (1, 2), and therefore, many physiological parameters must be measured in order to create a more effective training program. It is seen that the most used of these tests are sprint tests, jumping and anaerobic power tests, aerobic power tests, lactate tests, global positioning system (GPS) measurements and recently heart rate variability (HRV) measurements (3, 4).

Considered a non-invasive indicator of the autonomic nervous system, HRV is defined as the fluctuation of time intervals between successive heartbeats (5), and is an indicator of neurocardiac functions of heart-brain interactions (6). Since HRV parameters reflect information about health and performance, they are also frequently used in the field of sports sciences. It has been stated that it is useful in examining the acute and chronic effects of training, and even the training load is adjusted according to HRV values (7). For instance, Da Siva et al. (2019) found it more effective when the training load was individually guided by HRV for endurance running in untrained women (8). Flatt and Esco (2016) accepted the HRV measurements a useful method to monitor the adaptation in training in female soccer players (9). Similarly, Rave and Fortrat (2016) found that HRV reflects the adaptation level in professional male soccer players (10). In another study, Sánchez-Sánchez et al. (2021) concluded that some resting HRV parameters measured before a soccer game can be used to determine the load that can be covered by soccer players. It was also stated that 12-week of recreational soccer program improved HRV by enhancing the parasympathetic activity in obese adolescents (11, 12). All these changes support that the increase in parasympathetic activity of HRV is related to the increase in health and performance, while the deterioration in HRV is related to the decrease in health and performance values (5, 6). Furthermore, it has been stated that an injury in the musculoskeletal structure or other peripheral anatomical structures increases autonomic nervous system activity. Therefore, HRV can be also used to determine the cumulative load created by training loads and fatigue, and the training loads could be adjusted in accordance with the HRV changes in order to prevent these negative situations (13). The study of Botelho et al. (2022), showing the correlation they found between cortisol level and HRV as the season continues, proved that this is also acceptable in soccer (14).

The optimal level of variability, flexibility and adaptability observed in the basic regulatory systems of the human organism can be measured by the autonomic nervous system activity (6), and this is important not only for the general health status, but also for sports activities that include intermittent and high-intensity loads, where different loading intensities are seen, such as soccer. Due to the fact that the variety of physiological requirements in the game, soccer has been a subject of thousands of scientific researches. Unlike the previous ones, in the current study, the relationship between physiological parameters, which are frequently measured in soccer players, and especially with the resting HRV values, was examined, and whether HRV could be instantaneously reflective for some parameters was examined.

2. Materials and Methods

2.1. Study Design

In this study, resting heart rate variability (HRV), aerobic and anaerobic power, reaction time, sprint and jumping ability, lactate level and in-match global positioning system (GPS) data of professional soccer players were presented and their relationships with each other, especially with HRV, were examined. After obtaining ethical approval from Ondokuz Mayıs University Institutional Ethical Committee 2023-278, the participants visited the measurement site 4 times. In the first familiarization session, the measurement procedure was explained to the participants and they were asked to fill in the informed consent forms.

At the second visit, body composition and all Omegawave measurements were taken procedurally. Participants' sprint tests, and Yo-Yo IR Test Level 2, in which maximal lactate levels and $\text{VO}_{2\text{max}}$ were determined, were performed with a one-hour rest break at their third visit. As a final measurement, basic GPS data from three different official matches, in which 17 players played for 90 minutes, were recorded. A flow diagram of the study design and four distinct participant visits is provided in Figure 1.

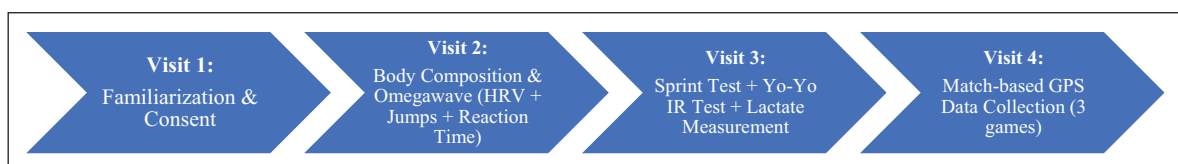


Figure 1. Flow diagram of participant recruitment, testing visits, and assessments

2.2. Participants

Seventeen professional male soccer players (mean age = 24.55 ± 4.71 years, height = 180.05 ± 6.24 cm, body weight = 76.79 ± 6.38 kg, BMI = 23.66 ± 1.08 kg/m²) voluntarily participated in this study.

Inclusion criteria were: (i) participating regularly in team training for at least the last three months, and (ii) appearing in professional league matches.

Exclusion criteria included: irregular training attendance, not playing in official matches, and the presence of chronic conditions such as diabetes mellitus, cardiovascular disease, arthritis, hypertension, or any musculoskeletal injuries involving muscles, ligaments, bones, cartilage, or tendons.

2.3. Procedures

Participants were instructed to refrain from vigorous physical activity and alcohol consumption within the 24 hours preceding each testing session. Caffeine intake was also restricted for at least 12 hours before all assessments. These pre-test instructions were standardized across all test days to minimize physiological variability.

2.3.1. Omegawave Measurements

Resting HRV, reaction time, and alactacid-lactacid power values were sequentially measured using the Omegawave 800 device (OmegaWave Sport Technology System, Oregon, USA), a system specifically developed for soccer players. In addition, values such as VO_2max , heart rate at anaerobic threshold, maximum aerobic velocity, velocity at anaerobic threshold, high intensity run ($> 15 \text{ km/hr.}$), and game total distance were obtained based on the estimation.

2.3.1.1 Heart Rate Variability Measurements: HRV measurements were initiated after participants rested in the supine position for five minutes. The measurement was carried out in a quiet room with only shorts on. Four Limb electrodes were placed on the wrists and ankles, and three Wilson electrodes were placed on the chest. During the five-minute measurement, the participants were asked not to move or talk. Time-domain parameters such as standard deviation of NN intervals (SDNN), standard deviation of the differences between successive NN intervals (SDSD), root mean square of successive RR interval differences (RMSSD), and frequency-domain parameters such as LF to HF ratio (LF:HF), total power (TP), high frequency (HF), high frequency in normal units (HFnu), low frequency (LF), low frequency in normal units (LFnu) and very low frequency (VLF) were recorded.

2.3.1.2. Reaction Time Tests: After the HRV measurements were completed and the participants put on their t-shirts, the subjects performed the sensory-motor skill measurement in the sitting position. The person grasped the handle with his dominant hand, with his hand on his knee and his thumb on the button, and was asked to press the button as soon as he heard each beep sound (52 beeps in total) coming from the computer at different intervals. During the measurement, values below 50 ms and above 400 ms were accepted as errors and were excluded from the evaluation by the device.

2.3.1.3. Three Stage Jump Tests: Subjects were finally subjected to a three-stage jumping test. The first test included five counter movement jumps. Repositioning and holding for a few seconds were allowed between jumps during the first stage, and their mean jump height and mean flight time were recorded. Five minutes later, the participant performed the same jumps, this time for 10 seconds, as many jumps as possible and as high. During this measurement the number of jumps, mean jump height and alactic power were calculated. After resting for ten minutes, he performed the same test, this time for 60 seconds. At the end of the measurement the number of jumps, mean jump height and lactic power were recorded.

2.3.2. Sprint Tests

Sprint tests were conducted over a 30-meter distance on a natural grass soccer field after a 10-minute standard warm-up of low-intensity jogging and a few acceleration runs. After the warm-up, Each participant completed two trials with 5-minute rest intervals. Time and speed were recorded at the 10 m, 20 m, and 30 m marks using the Fusion Smart Speed System (Fusion Sport, Coopers Plains, QLD, Australia) and individuals' best sprint values were included in the average.

2.3.3. Yo-Yo Intermittent Recovery Test Level 2 and Post-Test Lactate Assessment

Yo-Yo IR Test Level 2 was used in this study. The test began at a running speed of 13 km/h, progressively increasing until volitional exhaustion, and the participants did the 2 x 20 m runs at progressively increased speed until they were exhausted. Participants had a total active recovery time of 10 seconds between each running bout, during which they jog a distance of 2 x 5 meters. All soccer players were familiar with the Yo-Yo IR Test Level 2. Therefore, no extra trial was made. Each participant tried to reach the finishing line before the beep sound. The test of the person who could not reach this line twice in succession was terminated and the distance reached was recorded. VO_2max was determined using the following equation.

$$\text{VO}_2\text{max (mL}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}) = \text{distance (m)} \times 0.0136 + 45.3 \text{ [5].}$$

The lactate levels of the participants were determined by finger measurements using the Lactate pro analyzer (Arkray Inc, Kyoto, Japan) right at the end of the test.

2.3.4. GPS Recording

All GPS data of 17 soccer players were collected by using 10-Hz Catapult OptimEye X4 (Catapult Optimeye X4, Catapult Innovations, Melbourne, Australia) during three different official games. The following GPS parameters were recorded and analyzed: total distance covered (m), mean running speed (m/min and km/hr), and top running speed (km/hr).

2.4. Statistical Analyses

All analyses were performed using SPSS v.22 software (SPSS Inc., Chicago, IL, USA). After calculating the descriptive statistics, the distribution and homogeneity of the data were tested. Since the sample size was below 50, the Shapiro-Wilk test was conducted to evaluate the normality. Means of the same parameters obtained from different tests were analyzed by Paired Sample t-test or Wilcoxon test according to distribution. Since some parameters did not show normal distribution, correlation analysis was performed with Spearman's rank correlation coefficient. An alpha value of 0.05 was accepted for all statistical analyses.

3. Results

The sprint time and speed performances of the participants over 10, 20, and 30 meters are presented in **Table 1**. The mean 10-meter sprint time was 1628.00 ± 52.45 ms with a mean speed of 6.15 ± 0.20 m.s⁻¹. Over 20 meters, players reached a speed of 7.80 ± 0.21 m.s⁻¹ in 2911.10 ± 78.33 ms. The 30-meter sprint time averaged 4065.80 ± 114.03 ms, with a corresponding speed of 8.67 ± 0.36 m.s⁻¹.

Table 1. Sprint time and speed performance of the participants over 10, 20, and 30 meters.

10 m	1628.00 ± 52.45 ms
	6.15 ± 0.20 m.s ⁻¹
20 m	2911.10 ± 78.33 ms
	7.80 ± 0.21 m.s ⁻¹
30 m	4065.80 ± 114.03 ms
	8.67 ± 0.36 m.s ⁻¹

Values are presented as mean $\pm$ standard deviation, ms: milliseconds; m.s⁻¹: meters per second; m: meters.

Table 2 displays the resting HRV indices obtained using the Omegawave system, along with reaction time measures. Time-domain HRV metrics such as SDNN, SDSD, and RMSSD were 75.73 ± 24.30 ms, 82.20 ± 37.02 ms, and 65.13 ± 30.12 ms, respectively. Frequency-domain parameters including LF, HF, TP, LFnu, and HFnu were also reported, as well as a mean LF:HF ratio of 2.05 ± 1.57 . The mean reaction time was 0.168 ± 0.030 seconds.

Table 2. Omegawave-based resting HRV indices, jump test results, VO₂max estimates, and reaction time data.

Time-domain HRV parameters	
SDNN (ms)	75.73 ± 24.30
SDSD (ms)	82.20 ± 37.02
RMSSD (ms)	65.13 ± 30.12
Frequency-domain HRV parameters	
LF:HF	2.05 ± 1.57
TP (ms ²)	1991.67 ± 1839.16
HF (ms ²)	701.73 ± 610.15
HFnu (%)	39.99 ± 16.44

LF (ms ²)	1096.87±1278.20
LFnu (%)	60.01±16.44
VLF (ms ²)	193.07±111.79
Sensory-motor skill	
Reaction time (s)	0.168±0.030

SDNN, standard deviation of NN intervals; SDDSD, standard deviation of the differences between successive NN intervals; RMSSD, root mean square of successive RR interval differences; LF:HF, LF to HF ratio; TP, total power; HF, high frequency; HFnu, high frequency in normal units, LF, low frequency, LFnu, low frequency in normal units; VLF very low frequency s: seconds, ms: milliseconds; ms²: milliseconds squared; %: percent.

Table 3 summarizes the results of jump-based power tests, VO₂max estimations, and match-derived running parameters. Mean countermovement jump height was 44.61±3.65 cm, and flight time averaged 514.90±29.23 ms. Participants performed an average of 11.90±2.81 jumps in the 10-second alactic test and 77.00±22.70 jumps in the 60-second lactic test, with corresponding alactic and lactic power values of 3.59±0.97 W/kg and 3.13±1.07 W/kg. The estimated VO₂max was 55.81±3.24 mL·kg⁻¹·min⁻¹, while velocity at anaerobic threshold and maximal aerobic velocity were 14.31±0.71 km/h and 17.73±1.57 km/h, respectively. Game total distance was estimated at 11.30±0.76 km.

Table 3. Jump Tests, Estimated VO₂max, and Match Parameters

Alactic and lactic power results	
Mean jump height (cm)	44.61 ± 3.65
Mean flight time (ms)	514.90 ± 29.23
10-sec alactic test results	
Number of jumps	11.90 ± 2.81
Mean jump height (cm)	31.75 ± 3.07
Alactic power (W/kg)	3.59 ± 0.97
60-sec lactic test results	
Number of jumps	77.00 ± 22.70
Mean jump height (cm)	24.88 ± 3.78
Lactic power (W/kg)	3.13 ± 1.07
Estimated parameters	
max (mL·kg ⁻¹ ·min ⁻¹)	55.81 ± 3.24
Heart rate at anaerobic threshold (beat/min)	172.60 ± 2.85
Maximum aerobic velocity (km/h)	17.73 ± 1.57
Velocity at anaerobic threshold (km/h)	14.31 ± 0.71
High intensity run (> 15 km/h)	2.43 ± 0.68
Game total distance (km)	11.30 ± 0.76

Values are presented as mean ± standard deviation. Jump parameters include mean jump height (cm) and flight time (ms) derived from countermovement and fatigue-based protocols. Alactic and lactic power values are expressed in watts per kilogram (W/kg). Estimated VO₂max is presented in milliliters per kilogram per minute (mL·kg⁻¹·min⁻¹). Heart rate is given in beats per minute (bpm). High-intensity runs refer to distances covered at speeds > 15 km/h. Game total distance is based on Omegawave estimations; cm: centimeters; ms: milliseconds; W/kg: watts per kilogram; mL·kg⁻¹·min⁻¹: milliliters per kilogram per minute; bpm: beats per minute; km/h: kilometers per hour; km: kilometers.

The physiological results derived from the Yo-Yo Intermittent Recovery Test Level 2 are reported in Table 4. Maximal heart rate averaged 194.68±6.36 bpm, and post-test lactate concentration reached 11.38±2.90 mmol/L. Players covered an average of 829.09±142.99 m during the test. The VO₂max calculated from the Yo-Yo test was 56.58±1.94 mL·kg⁻¹·min⁻¹.

Apart from descriptive information, mean comparisons of similar parameters derived from different tests were also performed in this study. Accordingly, there was no significant difference in $\text{VO}_{2\text{max}}$ obtained from Omegawave and Yo-Yo IR Test Level 2 ($p=0.316$). However, game total distance that was estimated from Omegawave was significantly higher than total distance covered parameter which was derived from GPS measurement ($p=0.006$).

Table 4. The lactate, heart rate and $\text{VO}_{2\text{max}}$ test results derived from Yo-Yo IR Test Level 2.

Maximal heart rate (beat/min)	194.68 $\pm$ 6.36
Maximal lactate level (mmol)	11.38 $\pm$ 2.90
Total distance (m)	829.09 $\pm$ 142.99
max ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	56.58 $\pm$ 1.94

Values are presented as mean $\pm$ standard deviation. Maximal heart rate is expressed in beats per minute (bpm), and maximal lactate levels in millimoles per liter (mmol). Total distance covered during the test is reported in meters (m). $\text{VO}_{2\text{max}}$ is estimated in milliliters per kilogram per minute ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$); bpm – beats per minute; mmol – millimoles per liter; m – meters; $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ – milliliters per kilogram per minute.

The correlations between sprint metrics, jump parameters, reaction time, and selected cardiorespiratory measures are presented in Table 5. Significant negative correlations were observed between 10 m sprint time and both total distance ($r=-0.732$, $p<0.05$) and $\text{VO}_{2\text{max}}$ ($r=-0.732$, $p<0.05$). Positive correlations were reported between 10 m sprint speed and the same two variables ($r=0.732$, $p<0.05$). Several jump metrics (e.g., mean jump height, number of jumps) were also significantly associated with GPS-derived top speed values (e.g., $r=0.857$, $p<0.05$). Reaction time showed moderate negative correlations with total distance and mean speed ($r=-0.762$, $p<0.05$). A range of statistically significant associations was also observed between other test-derived variables.

Table 5. Correlations between sprint, jump, reaction time, and cardiorespiratory measures.

10 m sprint time	Yo-Yo IR 2 total distance	-0.73*
10 m sprint time	Yo-Yo IR 2 max	-0.73*
10 m sprint speed	Yo-Yo IR 2 total distance	0.73*
10 m sprint speed	Yo-Yo IR Test Level 2 max	0.73*
30 m sprint speed	Number of jumps (10 sec test)	-0.78*
30 m sprint speed	Number of jumps (60 sec test)	-0.79*
30 m sprint speed	Yo-Yo IR 2 maximal heart rate	-0.72*
Heart rate at anaerobic threshold	High-intensity running distance	0.79**
Heart rate at anaerobic threshold	Game Total Distance	0.7**
max (rest-based)	Velocity at anaerobic threshold	0.77**
max (rest-based)	Maximal Aerobic Velocity	0.52*
max (rest-based)	Yo-Yo IR 2 maximal lactate level	0.59*
maximum aerobic velocity	alactic power in 10 sec test	0.73*
maximum aerobic velocity	lactic power in 60 sec test	0.78**
maximum aerobic velocity	number of jumps in 10 sec test	0.70*
mean jump height	GPS top speed	0.86*
mean jump flight	GPS top speed	0.86*
number of jumps (10 sec test)	GPS top speed	0.78*
mean jump height (10 sec test)	Reaction time	-0.66*
Omegawave alactic power in 10 sec test	Yo-Yo IR Test Level 2 maximal heart rate	0.69*
Omegawave number of jumps in 60 sec test	GPS top speed	0.83*
Omegawave mean jump height in 60 sec test	Yo-Yo IR Test Level 2 maximal lactate level	0.68*

Omegawave lactic power in 60 sec test	Yo-Yo IR Test Level 2 maximal heart rate	0.78**
Omegawave reaction time	Yo-Yo IR Test Level 2 maximal lactate level	-0.56*
Omegawave reaction time	GPS total distance covered	-0.76*
Omegawave reaction time	GPS mean speed	-0.76*
Yo-Yo IR Test Level 2 maximal lactate level	GPS total distance covered	0.77*

Values are presented as Spearman correlation coefficients (r). Significant associations are indicated as *p < 0.05 and **p < 0.01. Sprint performance includes 10 m and 30 m times and speeds. Jump metrics include number of jumps, jump height, and flight time derived from 10-second and 60-second jump tests. Cardiorespiratory indicators include VO₂max, heart rate, and lactate levels derived from the Omegawave system and Yo-Yo IR Test Level 2. GPS metrics include total distance, mean speed, and top speed. AT: anaerobic threshold; VO₂max: maximal oxygen uptake; bpm: beats per minute; W/kg: watts per kilogram; m: meters; km/h: kilometers per hour; sec: seconds.

The relationships between resting heart rate variability (HRV) parameters and selected performance indicators are presented in Table 6. LF:HF ratio showed significant negative correlations with multiple performance measures such as jump height (r=-0.697, p<0.05), flight time (r=-0.697, p<0.05), and VO₂max (r=-0.536, p<0.05). Conversely, HFnu was positively correlated with the same variables (e.g., VO₂max: r=0.536, p<0.05). Additional significant associations were observed between time-domain HRV parameters (e.g., SDNN, SDSD, RMSSD) and velocity at anaerobic threshold, with r values ranging from 0.605 to 0.711 (p<0.05 or p<0.01).

Table 6. Correlations between heart rate variability parameters and selected performance indicators.

Parameters		r values
LF:HF	mean jump height	-0.70*
	mean flight time	-0.70*
	Yo-Yo IR Test Level 2 maximal lactate level	-0.53*
	max	-0.54*
	velocity at anaerobic threshold	-0.62*
HFnu	mean jump height	0.70*
	mean flight time	0.70*
	Yo-Yo IR Test Level 2 maximal lactate level	0.53*
	max	0.54*
	velocity at anaerobic threshold	0.62*
LFnu	mean jump height	-0.70*
	mean flight time	-0.70*
	Yo-Yo IR Test Level 2 maximal lactate level	-0.53*
	max	-0.54*
	velocity at anaerobic threshold	-0.62*
SDNN	velocity at anaerobic threshold	0.60*
SDSD	velocity at anaerobic threshold	0.71**
RMSSD	velocity at anaerobic threshold	0.71**
TP	velocity at anaerobic threshold	0.55*
HF	velocity at anaerobic threshold	0.75**

Values represent Spearman correlation coefficients (r). Significant associations are marked as *: p<0.05; *: p<0.01. HRV parameters were recorded using a resting-state Omegawave system. SDNN: standard deviation of NN intervals; SDSD: standard deviation of the differences between successive NN intervals; RMSSD: root mean square of successive RR interval differences; TP: total power; LF: low-frequency power; HF: high-frequency power; LF:HF: low-to-high frequency power ratio; HFnu / LFnu: high-/low-frequency power in normalized units; AT: anaerobic threshold.

4. Discussion

This study examined the associations between resting-state heart rate variability (HRV) and a broad range of physiological and performance parameters in professional male soccer players. By integrating laboratory-based assessments (aerobic and anaerobic power, sprinting, jumping and reaction time) with field-derived measures (GPS metrics and Yo-Yo IR2 outcomes), the primary aim was to determine whether resting HRV reflects multidimensional physical readiness. The main finding was that indices associated with parasympathetic modulation were consistently related to aerobic performance, anaerobic power, lactate tolerance, and match-play demands, supporting the utility of HRV as a non-invasive monitoring tool in elite soccer.

Sprint Performance and Anaerobic Power Metrics: Sprint performance, particularly over short distances (10 m and 30 m), demonstrated meaningful associations with both aerobic and anaerobic indicators. The relationships observed between 10 m sprint performance and Yo-Yo IR2-derived $\text{VO}_{2\text{max}}$ and total distance suggest that acceleration ability may reflect an athlete's ability to repeatedly perform high-intensity efforts during intermittent exercise. Furthermore, the negative association between 30 m sprint speed and maximal heart rate during the Yo-Yo IR2, alongside its relationship with jump repetition capacity in both alactic and lactic protocols, indicates that sprint speed may serve as an integrated marker of neuromuscular and metabolic efficiency. Collectively, these findings highlight sprint performance as not only an anaerobic quality but also a contributor to intermittent endurance performance in soccer.

Reaction Time and Energy System Efficiency: Reaction time was associated with variables spanning multiple energy systems. Faster reaction times were linked to greater jump height in short-duration explosive tests and to superior match-play outputs such as total distance and mean running speed. These findings suggest that neuromuscular efficiency and sensorimotor processing may contribute to both explosive performance and sustained match activity. Additionally, the association between reaction time and higher lactate tolerance during the Yo-Yo IR2 implies that central nervous system efficiency may influence the ability to sustain high-intensity efforts under metabolic stress.

GPS Metrics and Explosive Power: Match-play GPS variables demonstrated strong associations with laboratory-based power measures. In particular, top running speed during competition was closely related to jump height, flight time, and repeated jump capacity, reinforcing the link between explosive lower-limb power and high-speed match actions. The relationship between total distance covered and maximal lactate accumulation further supports the notion that metabolic tolerance contributes to sustained external load during competition. These findings emphasize the value of integrating laboratory and match-derived data when interpreting player performance profiles.

Omegawave-Derived Metrics and Physiological Performance: Estimated physiological variables obtained from the Omegawave system showed robust associations with both laboratory and match-performance outcomes. Heart rate at the anaerobic threshold was positively related to high-intensity running distance and total match distance, underscoring its relevance to competitive demands. Higher $\text{VO}_{2\text{max}}$ values were associated with greater velocity at the anaerobic threshold, maximal aerobic velocity, and lactate tolerance, reflecting superior aerobic conditioning. The observed relationship between maximal aerobic velocity and jump-derived power outputs further indicate an interaction between aerobic fitness and anaerobic performance capacities in professional soccer players.

HRV and Aerobic Performance: The primary focus of this study was the association between HRV and performance. Resting-state HRV was examined to determine its ability to reflect athletes' real-time physical readiness. Parameters included SDNN, SDSD, RMSSD, TP, LF:HF, HF, HFnu, LF, LFnu, and VLF.

Previous studies support this link. One study reported that 27% of $\text{VO}_{2\text{max}}$ improvements following aerobic training in sedentary individuals were explained by vagally mediated HRV (16). Botek et al. (2014) showed that even when $\text{VO}_{2\text{max}}$ did not improve post-training, changes in HF and RMSSD reflected training-induced vagal modulation (17). In Portuguese First Division female players, preseason fitness training improved vagal-related HRV parameters in line with aerobic fitness gains (18, 19). Similarly, in the present study, velocity at the anaerobic threshold was positively associated with all HRV parameters except LF and VLF. Increases in velocity at anaerobic threshold corresponded with higher SDNN, SDSD, RMSSD ($p=0.017$, $p=0.003$, $p=0.003$), as well as TP, HF, and HFnu ($p=0.033$, $p=0.001$, $p=0.013$), while LF:HF and LFnu decreased ($p=0.013$), indicating greater parasympathetic modulation.

$\text{VO}_{2\text{max}}$ was also associated with frequency-domain HRV indices, with higher aerobic capacity corresponding to increased HFnu and reduced LF:HF and LFnu ($p=0.039$). These findings highlight that improved parasympathetic activity is linked with superior aerobic performance. Given that $\text{VO}_{2\text{max}}$ values derived from the Yo-Yo IR2 and Omegawave were not significantly different, the practical utility of HRV-based estimation is further supported. Similarly, Yo-Yo IR2 maximal lactate levels correlated negatively with LF:HF and LFnu, and positively with HFnu ($p=0.043$), suggesting that greater lactate tolerance coincides with increased vagal tone.

HRV and Anaerobic Power: Beyond aerobic fitness, HRV parameters were also related to anaerobic power characteristics. Jump height and flight time during maximal jumping tasks were positively associated with HFnu and negatively associated with LF:HF and LFnu, indicating that parasympathetic dominance may support explosive neuromuscular performance. These findings suggest that resting HRV reflects not only endurance-related qualities but also the capacity to produce and sustain high-power outputs.

HRV in Training Load Monitoring and Recovery: In elite soccer, HRV is widely used to assess training adaptation and recovery. Proietti et al. (2017) found HRV differentiated international- from national-level players during a competitive season, advocating its role in load monitoring (22). Sánchez-Sánchez et al. (2021) linked pre-match LF and RMSSD values to external load tolerance in youth players (11). Muñoz-López et al. (2021) reported that HRV takes 24–72 hours to normalize post-match, supporting its use in recovery management. This study's findings are consistent with these observations, suggesting HRV can serve as a readiness and recovery indicator.

HRV as a Fatigue Marker: HRV is also used to identify chronic fatigue and prevent maladaptation. Bricout et al. (2010) reported increased LF:HF ratios post-match in youth players, indicating heightened sympathetic activity (24). Botelho et al. (2022) linked mood, hormonal markers, and creatine kinase to HRV, particularly LF:HF, over a 7-week training period (14). Additional studies suggest that HRV alterations vary according to match outcomes and internal load. One cohort study in Spanish First Division players proposed that HRV can reflect chronic fatigue across a season (26). In summary, HRV is responsive to training and match stress, and its associations with performance may help guide strategies to optimize athlete management.

Limitations

This study should be interpreted in light of several limitations. First, the sample size was relatively small ($n=17$) and consisted exclusively of professional male players competing in the Turkish Second Division. Although access to elite athletes often constrains sample size, this limitation may reduce statistical power and restrict the generalizability of the findings to other competitive levels, age groups, or female players. Second, HRV measurements were obtained only at rest and at a single time point, preventing evaluation of longitudinal adaptations or day-to-day variability in response to training and match load. Third, $\text{VO}_{2\text{max}}$ and lactate-related variables were estimated rather than directly measured, which may introduce a degree of measurement error despite the use of validated field-based protocols. Future studies should incorporate larger and more diverse cohorts, longitudinal HRV monitoring, and direct physiological measurements to further clarify HRV-performance relationships across competitive contexts.

Future Directions

Future studies should examine HRV-performance relationships using larger and more diverse samples, including different competitive levels and female players, to improve generalizability. Longitudinal designs monitoring HRV alongside training load and match demands across a competitive season may clarify its sensitivity to adaptation and fatigue. Additionally, HRV-guided training interventions should be explored to determine whether individualized load prescription enhances performance and recovery in professional soccer.

Conclusions

Overall, this study supports the inclusion of HRV analysis as a multidimensional readiness tool, especially when used in conjunction with sport-specific performance tests and match-derived metrics.

Previous research has shown that HRV improves following various training interventions, including soccer-specific programs (8, 12, 27). The present study extends this evidence by demonstrating that resting-state HRV is significantly associated with multiple physiological and performance parameters reflecting both aerobic and anaerobic energy systems in professional soccer players. Anaerobic power metrics such as jump height and flight time were associated primarily with frequency-domain HRV parameters, particularly HFnu and LF:HF (6, 29). Meanwhile, aerobic performance indicators like $\text{VO}_{2\text{max}}$ and velocity at anaerobic threshold were related to both time-domain (SDNN, RMSSD) and frequency-domain indices (6, 17, 28). These results emphasize the validity of HRV as a non-invasive tool reflecting both parasympathetic modulation and physical capacity. Furthermore, HRV demonstrated meaningful associations with match-performance metrics, including sprint performance, lactate tolerance, and GPS-derived external load variables, supporting its relevance for real-world performance profiling. Given the consistency between $\text{VO}_{2\text{max}}$ values derived from Omegawave and Yo-Yo IR2 ($p>0.05$), HRV appears reliable as a surrogate indicator in applied settings. Lastly, considering the variation in physical demands across

different competitive levels, future studies may investigate HRV–performance relationships across leagues or demographic profiles (22), and generate normative data for individual tracking while accounting for age, gender, and training background (6, 17, 30, 31).

Practical Applications

Since HRV reflects autonomic nervous system activity and its responsiveness to training load and recovery (6, 28), its integration into daily athlete monitoring routines is strongly encouraged. In particular, frequency-domain HRV parameters provide sensitive feedback regarding anaerobic readiness, while combined interpretation of time- and frequency-domain indices may offer insight into aerobic conditioning. Resting HRV values can serve as a cost-effective, non-invasive indicator to inform training prescription, monitor fatigue, and guide tapering strategies across a competitive season. Recent literature also supports its role in load optimization (11, 22), fatigue detection (24, 26), and psychophysiological monitoring (14).

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