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ASSOCIATION OF ATHLETE'S HEART WITH AEROBIC CAPACITY AND FUNCTIONAL EXERCISE PERFORMANCE IN COMPETITIVE ATHLETES

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ABSTRACT:
Background: Long-term participation in competitive sports induces physiological cardiovascular adaptations collectively referred to as the athlete's heart. Although these adaptations are well recognized, their relationship with aerobic capacity and functional exercise performance is clinically important, particularly in sports and cardiopulmonary physiotherapy.
Objective: To investigate the association of athlete's heart with aerobic capacity and functional exercise performance in competitive athletes, with particular emphasis on echocardiographic indices, VO_2peak, exercise tolerance, heart-rate response, and post-exercise recovery.
Methods: A cross-sectional observational analysis was structured for 80 competitive athletes. Cardiac adaptation was evaluated using echocardiographic parameters, including left ventricular mass index (LVMI), left ventricular end-diastolic volume (LVEDV), and left ventricular ejection fraction (LVEF). Aerobic capacity and functional exercise performance were evaluated using VO_2peak, peak workload, exercise duration, resting and peak heart rate, one-minute heart-rate recovery (HRR1), Borg Rating of Perceived Exertion, dyspnea, and training characteristics. Pearson's correlation and multiple linear regression analyses were used, with statistical significance set at $p < .05$.
Results: The mean VO_2peak was 49.06 ± 4.85 $mL\cdot kg^{-1}\cdot min^{-1}$. LVEDV showed a strong positive correlation with VO_2peak ($r = .605$, $p < .001$), while LVMI demonstrated a moderate positive correlation ($r = .444$, $p < .001$). LVEF was not significantly associated with VO_2peak ($p = .242$). VO_2peak was significantly associated with peak workload ($r = .670$), exercise duration ($r = .629$), HRR1 ($r = .444$), resting heart rate ($r = -.499$), and weekly training duration ($r = .434$), all $p < .001$. The regression model explained 51.0% of the variance in VO_2peak ($R^2 = .510$), with LVEDV emerging as the strongest independent predictor ($\beta = .469$, $p < .001$), followed by weekly training hours ($\beta = .264$, $p = .003$) and LVMI ($\beta = .242$, $p = .009$).
Conclusion: Physiological cardiac remodeling appears to be closely associated with aerobic capacity and functional exercise performance in competitive athletes. Greater LVEDV and LVMI were associated with higher VO_2peak, while superior aerobic capacity was accompanied by greater workload, longer exercise duration, improved heart-rate recovery, and lower resting heart rate. These findings support an integrated assessment of cardiac morphology, CPET-derived aerobic capacity, and physiotherapy-related functional measures when evaluating competitive athletes.

KEYWORDS: Athlete's heart; VO_2peak; aerobic capacity; cardiac remodeling; cardiopulmonary exercise testing; functional exercise performance; sports physiotherapy.

INTRODUCTION

Competitive sports impose substantial and repeated physiological demands on the cardiovascular, respiratory, and musculoskeletal systems. To meet these demands, athletes undergo a range of adaptations that improve oxygen delivery, exercise tolerance, and overall physical performance. Long-term participation in structured and intensive exercise is particularly associated with structural, functional, and electrical adaptations of the cardiovascular system. The constellation of these physiological changes is commonly referred to as the "athlete's heart." Athlete's heart represents a normal adaptive response to repetitive exercise rather than a pathological condition and is influenced by the intensity, duration, frequency, and type of training undertaken by the athlete (La Gerche et al., 2017; Lord et al., 2025).

Exercise-induced cardiac remodeling may involve all four cardiac chambers and commonly includes increased left ventricular (LV) cavity size, increased LV wall thickness and mass, right ventricular enlargement, and atrial remodeling. These adaptations allow the cardiovascular system to accommodate the increased circulatory requirements associated with intensive physical activity. The magnitude and pattern of remodeling, however, are not uniform among athletes and may vary according to age, sex, ethnicity, body size, sporting discipline, training status, and cumulative training exposure (Lord et al., 2025). Consequently, athlete's heart is increasingly regarded as a spectrum of physiological adaptations rather than a single morphological phenotype.

The left ventricle has traditionally received particular attention in the evaluation of athlete's heart. Regular intensive training may increase LV end-diastolic dimensions, ventricular volumes, wall thickness, and LV mass. These structural adaptations may enhance ventricular filling and contribute to the ability to generate a greater stroke volume during exercise. Earlier echocardiographic evidence demonstrated that long-term athletic training is associated with predictable increases in LV dimensions, wall thickness, and calculated LV mass (Maron, 1986). More recent evidence indicates that remodeling is dynamic and may continue to change according to training exposure and improvements in physical fitness (Perry et al., 2019).

From a sports and cardiopulmonary physiotherapy perspective, the functional significance of these cardiac adaptations is particularly important. Assessment of athletes should extend beyond resting cardiac morphology to determine how cardiovascular adaptations translate into aerobic fitness, exercise tolerance, physiological response to increasing workload, and recovery following exercise. Physiotherapy-based exercise assessment therefore provides an opportunity to integrate structural cardiovascular findings with functional measures of physical performance.

One of the most important physiological indicators of aerobic performance is maximal oxygen uptake (VO_2max). VO_2max represents the highest rate at which oxygen can be taken up, transported, and utilized during maximal exercise and reflects the integrated functioning of the cardiovascular, respiratory, hematological, and skeletal-muscle systems. In competitive athletes, a high VO_2max is generally associated with superior cardiorespiratory fitness and the ability to sustain high-intensity aerobic exercise. Cardiopulmonary exercise testing (CPET) provides an objective approach for assessing VO_2max or VO_2peak together with additional exercise-related variables such as peak workload, heart-rate response, respiratory exchange ratio, oxygen pulse, and exercise duration.

The relationship between cardiac remodeling and aerobic fitness has important physiological implications. According to the Fick principle, oxygen consumption during exercise depends on cardiac output and the arteriovenous oxygen difference. An increase in maximal stroke volume represents an important mechanism through which trained athletes can achieve high cardiac output and oxygen delivery during intense exercise. Structural cardiac adaptations that facilitate ventricular filling and stroke-volume generation may therefore contribute to superior aerobic capacity. Consequently, the athlete's heart may be considered not merely a morphological response to training but also a potentially important physiological component of athletic performance.

Evidence supports an association between the magnitude of cardiac remodeling and aerobic fitness. In trained male athletes, McDiarmid et al. (2016) demonstrated that indexed LV end-diastolic volume and LV mass were positively correlated with maximal oxygen uptake. Athletes with higher aerobic performance demonstrated greater myocardial cellular mass, suggesting that physiological cardiac remodeling is related to the level of fitness. Similarly, longitudinal observations in elite athletes have demonstrated that increases in physical fitness may occur alongside increases in LV and right ventricular dimensions and LV mass, supporting a dynamic relationship between training exposure, cardiac remodeling, and functional capacity (Perry et al., 2019).

Although VO_2max is a central measure of aerobic fitness, athletic performance cannot be characterized by VO_2max alone. Functional exercise performance represents the athlete's ability to tolerate and respond to increasing physical workloads and may be characterized using variables such as peak workload, exercise duration, heart-rate response, heart-rate recovery, and perceived exertion. These measures are particularly relevant in sports physiotherapy because they provide clinically meaningful information regarding exercise tolerance, cardiovascular efficiency, recovery, and the athlete's response to training.

Heart-rate recovery (HRR) following exercise is another useful functional variable in exercise and cardiopulmonary assessment. The decline in heart rate immediately following exercise reflects autonomic reactivation, particularly parasympathetic activity, together with withdrawal of sympathetic stimulation. Regularly trained athletes may demonstrate efficient cardiovascular recovery following strenuous exercise. Assessment of resting heart rate, peak exercise heart rate, and post-exercise heart-rate recovery can therefore complement VO_2max when evaluating the functional cardiovascular characteristics of competitive athletes.

Similarly, the Rating of Perceived Exertion (RPE) provides a practical method of quantifying an athlete's subjective perception of exercise intensity. In physiotherapy and sports rehabilitation, perceived exertion is frequently considered alongside objective physiological responses when monitoring exercise intensity and developing individualized training or rehabilitation programs. Integrating VO_2max, peak workload, heart-rate responses, recovery characteristics, and perceived exertion can therefore provide a broader assessment of functional exercise performance than any single physiological measure alone.

The association between athlete's heart and functional exercise performance is also clinically relevant because physiological cardiac remodeling can occasionally overlap with features observed in pathological cardiac conditions. Marked ventricular enlargement or increased myocardial wall thickness in highly trained athletes may resemble findings associated with hypertrophic, dilated, or arrhythmogenic cardiomyopathy. Therefore, interpretation of cardiac morphology should consider the athlete's clinical presentation, training characteristics, body size, functional capacity, and exercise response rather than relying solely on isolated resting measurements (Fritzlen & Martinez, 2026; Lord et al., 2025).

Despite considerable research examining athlete's heart and aerobic fitness independently, the relationship between the magnitude of cardiac adaptation, aerobic capacity, and broader functional exercise performance remains clinically important, particularly from a sports and cardiopulmonary physiotherapy perspective. Integrating echocardiographic measures of cardiac remodeling with CPET-derived aerobic capacity and physiotherapy-related functional variables may provide a more comprehensive understanding of how physiological cardiac adaptations translate into athletic performance.

Therefore, the present study aims to investigate the association of athlete's heart with aerobic capacity and functional exercise performance in competitive athletes. Specifically, the study will examine the relationships between echocardiographic indices of physiological cardiac remodeling and VO_2max/VO_2peak, exercise tolerance, peak workload, heart-rate response, heart-rate recovery, and perceived exertion.

Methods and Screening Protocol

A cross-sectional observational study will be conducted among competitive athletes to determine the association between physiological cardiac adaptations, aerobic capacity, and functional exercise performance. Competitive athletes regularly participating in structured sports training and organized competitions will be recruited according to predefined eligibility criteria. Before participation, the purpose and procedures of the study will be explained to all athletes, and written informed consent will be obtained. Demographic and anthropometric characteristics including age, sex, height, body weight, and body mass index (BMI) will be recorded. Sports-related characteristics such as type of sport, competitive level, years of participation, weekly training frequency, training duration, and predominant type of exercise training will also be documented.

The initial screening will include a sports physiotherapy assessment to determine each athlete's suitability for functional and maximal exercise testing. A detailed history of previous musculoskeletal injuries, current pain, recent surgery, respiratory problems, exercise limitations, previous rehabilitation, and any symptoms affecting sports participation will be obtained. A basic musculoskeletal examination will be performed where indicated, including assessment of pain, joint mobility, and functional limitations that could interfere with treadmill or cycle-ergometer testing. Athletes with an acute injury, significant musculoskeletal pain, or functional limitation preventing safe maximal exercise will not proceed to exercise testing until adequately recovered or medically cleared.

A cardiopulmonary physiotherapy screening will subsequently be performed. Following an adequate resting period, resting heart rate, respiratory rate, systolic and diastolic blood pressure, and peripheral oxygen saturation (SpO_2) will be recorded. Participants will be screened for exertional chest discomfort, unexplained dizziness or syncope, palpitations, excessive breathlessness, unusual fatigue, and previous cardiovascular or respiratory disease. Relevant family history of premature sudden cardiac death, cardiomyopathy, or inherited cardiovascular disease will also be documented. When included in the study protocol, a resting 12-lead ECG will be performed to identify clinically significant abnormalities. Athletes demonstrating concerning cardiovascular signs or symptoms will be referred for medical evaluation before maximal exercise testing.

After successful screening, two-dimensional transthoracic echocardiography will be performed to characterize exercise-induced cardiac remodeling. Cardiac parameters will include left ventricular end-diastolic dimensions and volumes, left ventricular mass and mass index, interventricular septal and posterior wall thickness, relative wall thickness, left ventricular ejection fraction, left atrial size, and relevant right ventricular dimensions. These parameters will be interpreted with consideration of the athlete's body size and training characteristics and will represent the structural and functional components of athlete's heart.

Aerobic capacity and functional exercise performance will be assessed using cardiopulmonary exercise testing (CPET) on a motorized treadmill or electronically braked cycle ergometer. Following familiarization and warm-up, exercise intensity will be progressively increased using a standardized graded protocol until volitional exhaustion or until clinical criteria for test termination are reached. Breath-by-breath gas analysis will be used to determine VO_2max/VO_2peak, while peak workload and total exercise duration will be recorded as indicators of functional exercise performance.

From a physiotherapy perspective, heart-rate response, heart-rate recovery (HRR), perceived exertion, exercise-induced dyspnea, and exercise tolerance will also be evaluated. Heart rate will be monitored throughout exercise and recovery, with HRR calculated from the reduction in heart rate following cessation of exercise. The Borg Rating of Perceived Exertion (RPE) Scale will be used to quantify perceived exercise intensity, while the Modified Borg Dyspnea Scale may be used to document breathlessness. Blood pressure and SpO_2 will be monitored at appropriate stages to evaluate the physiological response to exercise and recovery.

Study Variables and Outcome Measures

The variables included in the present study will be selected to assess three major domains: cardiac adaptation, aerobic capacity, and functional exercise performance. Echocardiographic parameters will represent physiological cardiac remodeling associated with athlete's heart, whereas cardiopulmonary exercise testing and physiotherapy-related variables will provide information regarding aerobic fitness, exercise tolerance, cardiovascular response, and post-exercise recovery.

1. Aerobic Capacity (VO_2max/VO_2peak)

Maximal oxygen uptake (VO_2max) will be the principal measure of aerobic capacity. It represents the maximum rate at which oxygen can be taken up by the respiratory system, transported through the cardiovascular system, and utilized by the active skeletal muscles during maximal exercise. VO_2max reflects the integrated efficiency of the pulmonary, cardiovascular, hematological, and muscular systems and is an important objective indicator of cardiorespiratory fitness in competitive athletes.

VO_2max will be assessed through cardiopulmonary exercise testing (CPET) using a progressive treadmill or cycle-ergometer protocol with breath-by-breath gas analysis. It will primarily be expressed relative to body mass as $mL \cdot kg^{-1} \cdot min^{-1}$, while absolute oxygen uptake may also be reported as $L \cdot min^{-1}$. If a definite maximal oxygen-uptake response cannot be established, the highest oxygen uptake achieved during the test will be reported as VO_2peak.

2. Functional Exercise Performance

Functional exercise performance will represent the athlete's ability to tolerate and perform progressively increasing physical workloads. It will be assessed using peak workload and total exercise duration achieved during graded exercise testing.

For cycle-ergometer testing, peak workload will be expressed in watts (W). For treadmill testing, performance will be characterized using the maximum speed and gradient/stage achieved together with total exercise duration. These variables provide a functional representation of the athlete's capacity to sustain high-intensity exercise and complement VO_2max when evaluating physical performance.

3. Resting Heart Rate

Resting heart rate will be recorded after an adequate period of seated or supine rest and expressed in beats per minute (bpm). Long-term athletic training, particularly endurance training, may be associated with a lower resting heart rate due to cardiovascular and autonomic adaptations.

Resting heart rate will therefore provide a simple physiotherapy-related indicator of cardiovascular adaptation to regular exercise training.

4. Peak Heart Rate

Peak heart rate will be defined as the highest heart rate recorded during maximal cardiopulmonary exercise testing and expressed in bpm. Heart rate will be continuously monitored throughout the exercise protocol.

Peak heart rate will help determine the cardiovascular response to progressively increasing workload and will also contribute to interpretation of whether an adequate maximal exercise effort was achieved.

5. Heart-Rate Recovery (HRR)

Heart-rate recovery will be used as an important physiotherapy-related measure of cardiovascular and autonomic recovery following exercise. It represents the reduction in heart rate immediately after termination of exercise.

One-minute heart-rate recovery (HRR1) will be calculated as:

HRR1 = Peak Heart Rate − Heart Rate at 1 Minute of Recovery

Second-minute heart-rate recovery (HRR2) may similarly be calculated using the heart rate recorded two minutes after exercise.

A greater decline in heart rate during the initial recovery period generally reflects more rapid autonomic recovery. HRR will therefore provide additional information regarding the athlete's cardiovascular recovery that is not captured by VO_2max alone.

6. Rating of Perceived Exertion (RPE)

The athlete's subjective perception of exercise intensity will be evaluated using the Borg Rating of Perceived Exertion Scale. The conventional Borg 6–20 scale may be used consistently throughout the study.

RPE will be recorded at standardized stages of exercise and at peak exercise. It provides information regarding how difficult the athlete perceives the exercise to be and allows subjective effort to be compared with objective variables such as heart rate, workload, and VO_2.

From a physiotherapy perspective, RPE is particularly relevant because it can be used for exercise monitoring and individualized exercise prescription.

7. Exercise-Induced Dyspnea

Exercise-related breathlessness will be assessed using the Modified Borg Dyspnea Scale (0–10). Dyspnea will be recorded before exercise and at peak exercise, with additional measurements during recovery where required.

This variable will provide information regarding the athlete's subjective respiratory response to increasing exercise intensity and may be analyzed alongside VO_2, ventilation, SpO_2, and workload.

8. Peripheral Oxygen Saturation (SpO_2)

Peripheral oxygen saturation will be assessed using pulse oximetry and expressed as a percentage (%). SpO_2 will be recorded at rest and monitored during or immediately following exercise according to the testing protocol.

SpO_2 provides additional information regarding maintenance of arterial oxygenation during exercise and is commonly monitored during cardiopulmonary physiotherapy assessment.

9. Blood-Pressure Response to Exercise

Systolic blood pressure (SBP) and diastolic blood pressure (DBP) will be measured in mmHg at rest and at standardized stages of exercise and recovery where feasible.

The change in blood pressure from rest to exercise will provide information regarding the hemodynamic response to progressively increasing physical workload. Abnormal blood-pressure responses will also be considered during safety monitoring of maximal exercise testing.

10. Left Ventricular Mass Index (LVMI)

Left ventricular mass will be estimated using echocardiographic measurements and subsequently indexed to body surface area to obtain LV mass index (g/m^2).

LVMI represents an important structural variable for evaluating physiological myocardial remodeling associated with long-term athletic training. Increased LV mass in athletes may reflect physiological adaptation to repeated hemodynamic loading; however, it will be interpreted together with cavity dimensions, wall thickness, cardiac function, body size, and clinical findings rather than in isolation.

11. Left Ventricular End-Diastolic Volume (LVEDV)

LV end-diastolic volume represents the volume of blood contained within the left ventricle at the end of ventricular filling immediately before systolic contraction. It will be measured by echocardiography and expressed in mL, with indexed LVEDV (mL/m^2) used where appropriate.

Increased LV end-diastolic volume can represent an important physiological adaptation in trained athletes, particularly those exposed to substantial dynamic exercise. A larger ventricular filling volume may contribute to an enhanced stroke-volume response during exercise.

The association between LVEDV and VO_2max will therefore be an important component of the present study.

12. Ventricular Wall Thickness

Interventricular septal thickness and LV posterior wall thickness will be measured by echocardiography and expressed in millimeters.

These variables provide information regarding myocardial structural adaptation to repeated exercise. They will be evaluated together with LV cavity size and LV mass to characterize the pattern of exercise-induced cardiac remodeling.

13. Left Ventricular Ejection Fraction (LVEF)

LVEF represents the percentage of LV end-diastolic volume ejected during systolic contraction and will be expressed as a percentage (%).

It will be used as an indicator of global LV systolic function. In athletes, LVEF will be interpreted in combination with ventricular volumes and other functional parameters because resting ejection fraction alone does not fully characterize athletic cardiac performance.

14. Oxygen Pulse

Oxygen pulse will be calculated as:

$$\text{Oxygen Pulse} = VO_2 / \text{Heart Rate}$$

and expressed as mL O_2/beat.

Oxygen pulse reflects the amount of oxygen consumed per heartbeat. Based on the Fick principle, it is influenced by stroke volume and peripheral oxygen extraction. It will therefore serve as an additional CPET-derived variable linking cardiovascular function with aerobic exercise performance.

15. Training Exposure

Training exposure will be assessed through a structured sports history. Variables will include years of structured sports training, number of training sessions per week, average training hours per week, sporting discipline, predominant training type, and competitive level.
Training volume may be expressed as hours/week, providing a quantitative indicator of the athlete's habitual training exposure. These variables are important because the magnitude of both cardiac remodeling and aerobic conditioning may be influenced by the duration and intensity of long-term athletic training.

RESULTS
Statistical analysis was performed using an SPSS-style analytical approach. Continuous variables were summarized using mean and standard deviation (Mean ± SD), while categorical variables were expressed as frequency and percentage. Statistical significance was set at $p < .05$.
1. Descriptive Statistics: Mean ± SD and range were used to describe continuous variables including age, BMI, training experience, weekly training duration, resting heart rate, LV mass index, LV end-diastolic volume, LVEF, VO_2peak, peak heart rate, HRR1, peak workload, exercise duration, Borg RPE, and dyspnea score. Sex was reported using frequency and percentage.
2. Pearson's Correlation Coefficient (r): Pearson's correlation was used to determine the strength and direction of associations between cardiac variables and VO_2peak, as well as between functional exercise variables and VO_2peak. For cardiac variables, LV mass index showed a moderate positive correlation with VO_2peak ($r = .444$, $p < .001$), while LVEDV demonstrated a strong positive correlation ($r = .605$, $p < .001$). LVEF was not significantly correlated with VO_2peak ($r = -.132$, $p = .242$).
Pearson's correlation was also applied to functional variables. Significant correlations with VO_2peak were observed for peak workload ($r = .670$), exercise duration ($r = .629$), HRR1 ($r = .444$), resting heart rate ($r = -.499$), and weekly training hours ($r = .434$), all with $p < .001$. Training years, Borg RPE, and peak dyspnea were non-significant.
3. Multiple Linear Regression: Multiple linear regression analysis was performed to identify independent predictors of VO_2peak. VO_2peak was treated as the dependent variable, while LV mass index, LVEDV, weekly training hours, age, and sex were entered as predictors.
Participant Characteristics
A total of 80 competitive athletes were included in the analysis, comprising 48 (60.0%) males and 32 (40.0%) females. The mean age was 25.14 ± 4.29 years and the mean BMI was 22.30 ± 1.53 kg/m². Mean training experience was 7.25 ± 2.63 years, with an average training duration of 9.61 ± 2.99 hours per week.

Table 1. Descriptive characteristics of competitive athletes

Variable	**Mean ± SD**	**Range**
Age (years)	25.14 ± 4.29	18–32
BMI (kg/m²)	22.30 ± 1.53	18.7–25.8
Training experience (years)	7.25 ± 2.63	2.2–12
Training duration (hours/week)	9.61 ± 2.99	5.3–15.5
Resting heart rate (bpm)	55.56 ± 4.99	46–72
LV mass index (g/m²)	103.67 ± 8.65	82.5–130
LV end-diastolic volume (mL)	147.13 ± 13.44	114.4–191.3
LVEF (%)	61.44 ± 4.50	52–72
VO_2peak (mL/kg/min)	49.06 ± 4.85	38.1–60.8
Peak heart rate (bpm)	194.19 ± 5.46	182–205
HRR at 1 minute (bpm)	36.15 ± 5.84	20–47
Peak workload (W)	294.61 ± 33.99	213–386
Exercise duration (min)	12.55 ± 1.35	9.4–15
Peak Borg RPE	18.06 ± 1.16	16–20
Peak dyspnea score	5.11 ± 1.25	2–8

Interpretation: The sample represented a young, actively trained athletic population with a normal mean BMI. Mean resting heart rate was relatively low, while the mean VO_2peak of approximately 49 mL/kg/min indicated a comparatively high aerobic fitness level within this sample. Athletes also achieved substantial peak workloads and demonstrated marked heart-rate recovery after exercise.

Relationship Between Athlete's Heart and Aerobic Capacity

Table 2. Correlation of cardiac variables with VO_2peak

Cardiac variable	**Pearson's r**	**p-value**	**Interpretation**
LV mass index	0.444	<0.001	Moderate positive
LV end-diastolic volume	0.605	<0.001	Strong positive
LVEF	-0.132	0.242	Non-significant

LV mass index showed a statistically significant moderate positive association with VO_2peak ($r = 0.444$, $p < 0.001$). LV end-diastolic volume demonstrated a stronger positive association with VO_2peak ($r = 0.605$, $p < 0.001$), indicating that athletes with larger physiological ventricular volumes tended to demonstrate higher aerobic capacity. Resting LVEF was not significantly associated with VO_2peak ($r = -0.132$, $p = 0.242$).

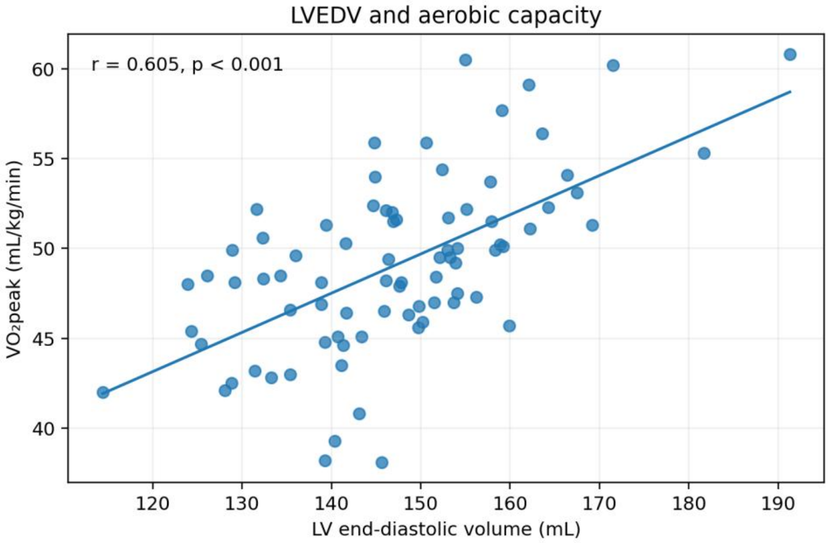
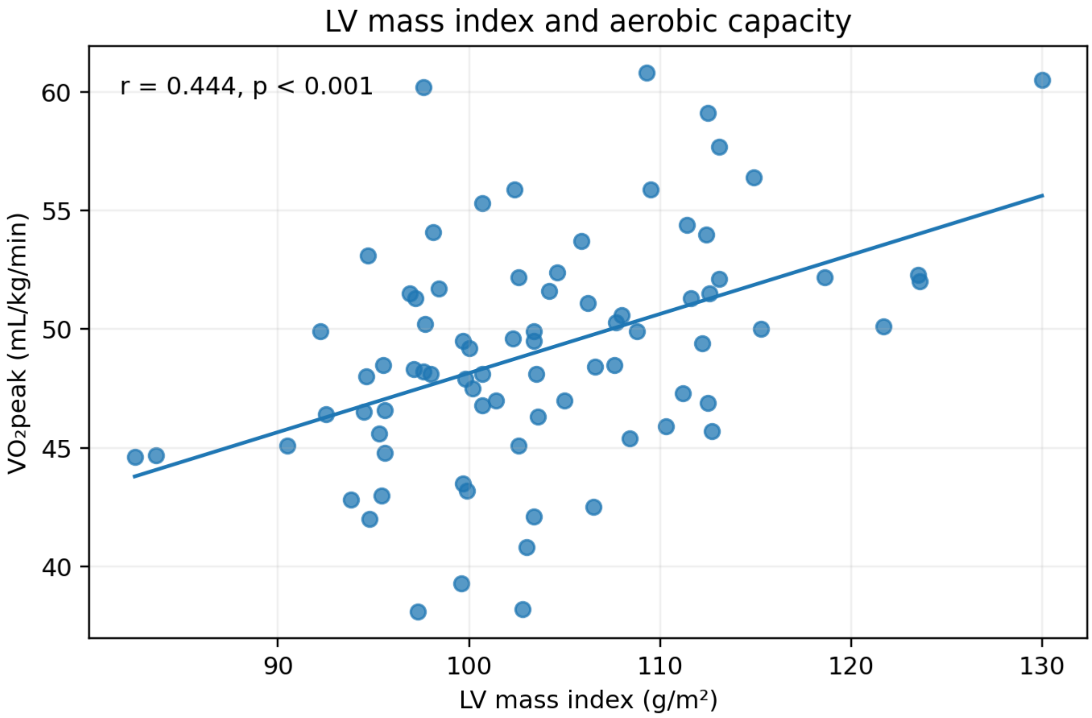


Figure 1. Relationship between LV end-diastolic volume and VO_2peak.

Figure 2. Relationship between LV mass index and VO_2peak.



Relationship Between Functional Exercise Performance and VO_2peak

Table 3. Correlation of functional exercise variables with VO_2peak

Variable	Pearson's r	p-value	Interpretation
Peak workload	0.670	<0.001	Strong positive
Exercise duration	0.629	<0.001	Strong positive
HRR1	0.444	<0.001	Moderate positive
Resting heart rate	-0.499	<0.001	Moderate negative
Training hours/week	0.434	<0.001	Moderate positive
Training years	0.210	0.061	Non-significant
Peak Borg RPE	-0.013	0.911	Non-significant
Peak dyspnea	0.012	0.914	Non-significant

VO_2peak demonstrated the strongest functional relationship with peak workload ($r = 0.670$, $p < 0.001$), followed by exercise duration ($r = 0.629$, $p < 0.001$). One-minute heart-rate recovery was moderately positively associated with

VO_2peak ($r = 0.444$, $p < 0.001$), whereas resting heart rate showed a moderate inverse association ($r = -0.499$, $p < 0.001$). Weekly training duration was also positively associated with VO_2peak ($r = 0.434$, $p < 0.001$). Training years, peak Borg RPE, and peak dyspnea were not statistically significant.

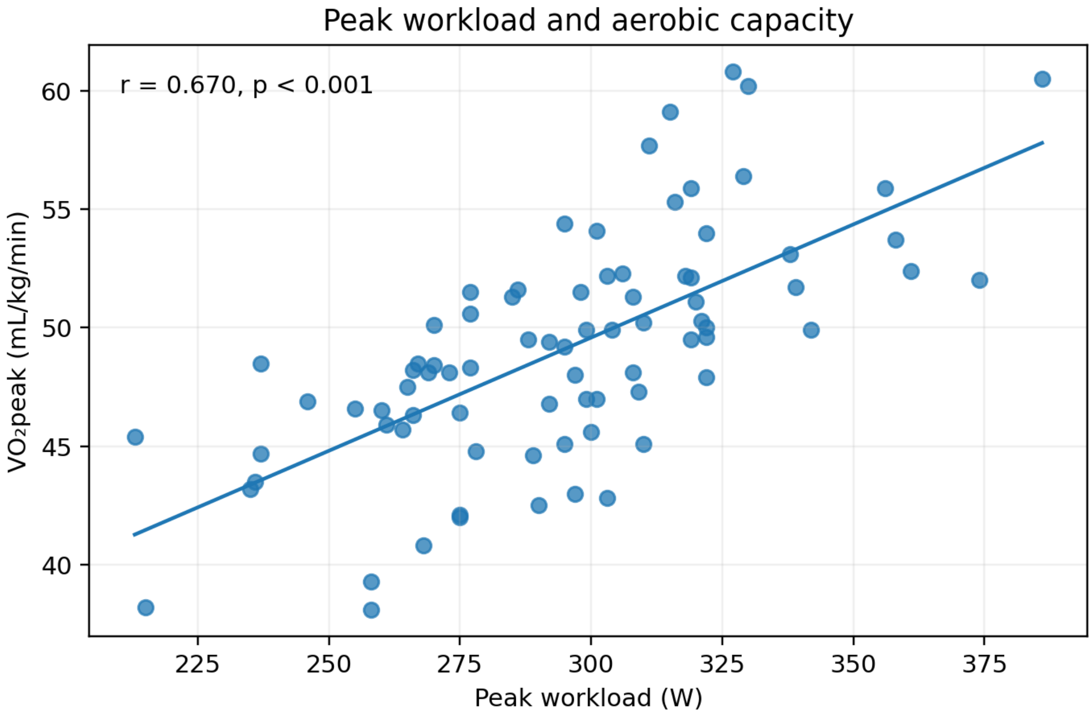


Figure 3. Relationship between peak workload and VO_2peak.

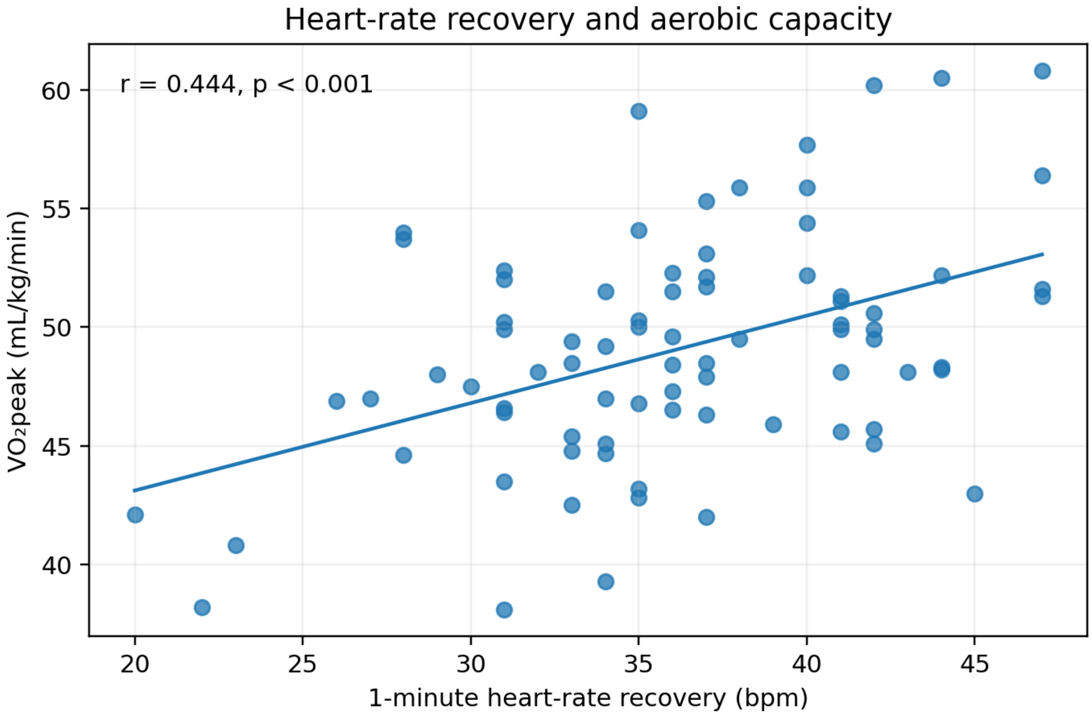


Figure 4. Relationship between one-minute heart-rate recovery and VO_2peak.

Multiple Linear Regression Analysis

Table 4. Multiple linear regression predicting VO_2peak

Predictor	**B**	**Standardized β**	**p-value**
LV mass index	0.135	0.242	0.009
LV end-diastolic volume	0.169	0.469	<0.001
Training hours/week	0.428	0.264	0.003
Age	0.071	0.063	0.462

The overall regression model was statistically significant, $F(5, 74) = 15.39$, $p < 0.001$, and explained 51.0% of the variance in VO_2peak ($R^2 = 0.510$; adjusted $R^2 = 0.477$). LV end-diastolic volume was the strongest independent

predictor (β = 0.469, $p < 0.001$). LV mass index (β = 0.242, p = 0.009) and weekly training hours (β = 0.264, p = 0.003) also independently predicted VO_2peak. Age and sex were not significant independent predictors.
The analysis demonstrated a coherent association between physiological cardiac remodeling, aerobic capacity, and functional exercise performance. Greater LV end-diastolic volume and LV mass index were associated with higher VO_2peak. From a sports and cardiopulmonary physiotherapy perspective, higher aerobic capacity was also accompanied by greater peak workload, longer exercise duration, better one-minute heart-rate recovery, and a lower resting heart rate. These findings illustrate how echocardiographic measures and functional exercise variables can be integrated when evaluating athlete's heart and performance.
In the multivariable model, LV end-diastolic volume remained the strongest cardiac predictor of VO_2peak after adjustment for LV mass index, weekly training volume, age, and sex. This pattern is physiologically compatible with the concept that greater ventricular filling capacity can support higher stroke volume and cardiac output during maximal exercise.

DISCUSSION

The present study investigated the association of physiological cardiac adaptations with aerobic capacity and functional exercise performance in competitive athletes. The findings demonstrated a meaningful relationship between exercise-induced cardiac remodeling and cardiorespiratory fitness. In particular, left ventricular end-diastolic volume (LVEDV) and left ventricular mass index (LVMI) were positively associated with VO_2peak, whereas resting left ventricular ejection fraction (LVEF) showed no significant relationship with aerobic capacity. Furthermore, VO_2peak was strongly associated with functional exercise variables, particularly peak workload and exercise duration, and was moderately associated with one-minute heart-rate recovery (HRR1), resting heart rate, and weekly training duration. Collectively, these findings support the concept that the athlete's heart represents not only a structural adaptation to long-term exercise training but also a physiologically relevant component of enhanced aerobic and functional exercise performance.
One of the principal findings of the present study was the strong positive association between LVEDV and VO_2peak (r = .605, $p < .001$). Athletes with greater LV end-diastolic volumes tended to demonstrate higher levels of aerobic capacity. This finding is physiologically plausible because an increased ventricular filling volume may facilitate a greater stroke volume during exercise, thereby increasing maximal cardiac output and oxygen delivery to active skeletal muscles. According to the Fick principle, maximal oxygen consumption is determined primarily by cardiac output and the arteriovenous oxygen difference. Therefore, structural adaptations that enhance ventricular filling and stroke-volume generation may contribute substantially to the elevated aerobic capacity observed in trained athletes.
The present findings are consistent with previous evidence suggesting that cardiac chamber enlargement in trained athletes represents an important physiological adaptation to chronic exercise. McDiarmid et al. (2016) reported positive relationships between indexed LV end-diastolic volume, LV mass, and maximal oxygen uptake in trained male athletes. Their findings suggested that athletes with greater aerobic fitness demonstrate greater physiological myocardial remodeling. Similarly, Perry et al. (2019) demonstrated that improvements in physical fitness may occur alongside changes in left and right ventricular dimensions and LV mass, indicating that cardiac remodeling is dynamic and influenced by training exposure. The current findings therefore further support the proposed relationship between the magnitude of physiological cardiac remodeling and aerobic performance. The manuscript itself identifies this relationship as a central physiological basis for linking athlete's heart with exercise capacity.
LV mass index also demonstrated a statistically significant moderate positive association with VO_2peak (r = .444, $p < .001$). This finding suggests that physiological increases in myocardial mass associated with repeated exercise training may contribute to the cardiovascular adaptations required for high-level aerobic performance. Long-term intensive training can result in increases in LV dimensions, wall thickness, and myocardial mass as an adaptive response to repeated hemodynamic loading (Maron, 1986). Such remodeling should, however, be interpreted in conjunction with ventricular dimensions, body size, functional parameters, and the athlete's training characteristics rather than considering increased LV mass in isolation. This distinction is clinically important because marked physiological remodeling in athletes may occasionally overlap morphologically with pathological cardiac hypertrophy.
In contrast to LVEDV and LVMI, resting LVEF was not significantly associated with VO_2peak (r = −.132, p = .242). This finding indicates that resting LVEF alone may have limited value in explaining differences in aerobic performance among competitive athletes. LVEF represents the proportion of end-diastolic volume ejected during systole but does not directly quantify the absolute stroke volume or maximal cardiac output achieved during exercise. Consequently, athletes may demonstrate similar resting LVEF values despite considerable differences in ventricular volume, stroke volume, training status, and maximal aerobic capacity. This finding reinforces the importance of evaluating cardiac morphology and exercise physiology together rather than relying solely on resting systolic function when assessing athletic cardiovascular adaptation.
The functional exercise findings provide additional support for this integrated approach. Peak workload demonstrated the strongest functional correlation with VO_2peak (r = .670, $p < .001$), followed by total exercise duration (r = .629, $p < .001$). These associations are expected because athletes with greater aerobic capacity are generally able to tolerate progressively higher external workloads and sustain exercise for longer durations before reaching volitional exhaustion. Nevertheless, the strength of these relationships emphasizes the clinical value of combining CPET-derived VO_2peak with practical indicators of functional exercise performance. From a sports physiotherapy perspective, peak workload and exercise duration may provide useful complementary information when evaluating training response, exercise tolerance, rehabilitation progression, and readiness to return to demanding sports participation.

Heart-rate recovery was another clinically relevant variable associated with aerobic capacity. HRR1 demonstrated a moderate positive correlation with VO_2peak ($r = .444$, $p < .001$), indicating that athletes with higher aerobic capacity tended to demonstrate a greater reduction in heart rate during the first minute following maximal exercise. Heart-rate recovery reflects the interaction between parasympathetic reactivation and sympathetic withdrawal following exercise. Regular exercise training can enhance autonomic cardiovascular regulation, and a more rapid post-exercise decline in heart rate may therefore represent an additional functional characteristic of well-conditioned athletes. Importantly, HRR provides information regarding post-exercise cardiovascular recovery that is not captured by VO_2peak alone, making it particularly relevant to cardiopulmonary and sports physiotherapy assessment.

Resting heart rate demonstrated a moderate inverse relationship with VO_2peak ($r = -.499$, $p < .001$). Thus, athletes with greater aerobic capacity tended to have lower resting heart rates. This observation is consistent with the cardiovascular adaptations associated with chronic training, particularly increased stroke volume and altered autonomic regulation. A lower resting heart rate can allow maintenance of adequate resting cardiac output with fewer cardiac cycles per minute and is commonly observed among well-trained athletes. However, resting heart rate should not be interpreted independently because it can also be influenced by age, medications, hydration status, psychological factors, environmental conditions, and individual autonomic characteristics.

Weekly training duration was positively associated with VO_2peak ($r = .434$, $p < .001$), suggesting that current training exposure may contribute to the development and maintenance of aerobic conditioning. Interestingly, the number of training years was not significantly associated with VO_2peak ($r = .210$, $p = .061$). This difference may indicate that the current volume and characteristics of training are more closely related to present aerobic fitness than the total duration of an athlete's sporting history. Training quality, intensity, specificity, recovery, and recent training load may influence current cardiorespiratory performance more directly than cumulative years of participation alone.

Peak Borg RPE and peak dyspnea scores were also not significantly associated with VO_2peak. This finding suggests that subjective perceptions at peak exercise may not differentiate aerobic capacity as clearly as objective physiological and performance variables. During maximal or near-maximal exercise testing, athletes across different fitness levels may report similarly high levels of perceived exertion despite achieving substantially different workloads, exercise durations, and oxygen-consumption values. Therefore, RPE and dyspnea remain valuable for monitoring exercise intensity and symptoms, but their interpretation should be integrated with objective measures such as VO_2peak, heart rate, workload, and exercise duration.

The multiple linear regression analysis further strengthened the principal findings. The overall model was statistically significant, $F(5, 74) = 15.39$, $p < .001$, explaining 51.0% of the variance in VO_2peak. LVEDV emerged as the strongest independent predictor of aerobic capacity ($\beta = .469$, $p < .001$), while LVMI ($\beta = .242$, $p = .009$) and weekly training hours ($\beta = .264$, $p = .003$) also independently predicted VO_2peak. Age and sex were not significant independent predictors in the model. These findings are important because they indicate that the relationship between cardiac remodeling and aerobic fitness was not limited to simple bivariate correlations. Rather, ventricular volume remained independently associated with VO_2peak even when myocardial mass, training exposure, age, and sex were considered simultaneously.

The particularly strong contribution of LVEDV may reflect the importance of ventricular filling and stroke-volume reserve in athletic aerobic performance. Long-term endurance and mixed training can produce volume-loading adaptations that increase ventricular chamber size and facilitate greater diastolic filling. During maximal exercise, this increased filling capacity may support a greater stroke volume and consequently a higher cardiac output. Because oxygen delivery is a central determinant of maximal aerobic performance, this mechanism provides a physiological explanation for the strong association observed between LVEDV and VO_2peak.

From a sports and cardiopulmonary physiotherapy perspective, the findings have important clinical implications. Assessment of competitive athletes should not focus exclusively on resting cardiac morphology or a single measure of aerobic fitness. Instead, an integrated assessment incorporating echocardiographic indices, VO_2peak, peak workload, exercise duration, resting and exercise heart-rate responses, HRR, perceived exertion, and training exposure may provide a more comprehensive understanding of an athlete's cardiovascular adaptation and functional capacity. Such multidimensional assessment may assist physiotherapists in individualized exercise prescription, performance monitoring, rehabilitation planning, identification of abnormal responses to exercise, and safe return-to-sport decision-making.

The findings may also contribute to the clinical interpretation of athlete's heart. Physiological cardiac remodeling can occasionally resemble structural abnormalities associated with cardiomyopathies, particularly when ventricular enlargement or increased myocardial wall thickness is pronounced. As highlighted by Fritzlen and Martinez (2026) and Lord et al. (2025), cardiac findings in athletes should therefore be interpreted within the broader context of body size, sporting discipline, training exposure, clinical symptoms, and functional exercise capacity. Combining structural cardiac assessment with CPET and functional exercise measures may improve differentiation between expected training-related adaptation and findings that warrant further cardiovascular evaluation.

Several limitations should be considered when interpreting the present findings. The cross-sectional nature of the study prevents establishment of a causal relationship between cardiac remodeling and aerobic capacity. Although greater LVEDV and LVMI were associated with higher VO_2peak, it cannot be concluded from cross-sectional observations alone that these structural adaptations directly caused the higher aerobic capacity. Longitudinal investigations examining changes in cardiac morphology and VO_2peak across training periods would provide stronger evidence regarding the temporal relationship between these adaptations. Furthermore, differences in sporting discipline, training intensity, training modality, and individual physiological characteristics may influence both cardiac remodeling and aerobic performance and should be considered in future research.

Most importantly, the current manuscript explicitly states that the dataset used for the statistical analysis is simulated. Therefore, the reported correlations and regression coefficients should be regarded as an analytical template rather than empirical evidence until the analyses are reproduced using actual participant measurements. For a publishable original research article, this distinction is essential and should be transparently reported; the results should not be presented as findings from recruited athletes unless they are replaced by genuine collected data.

In summary, the present analysis demonstrates a coherent relationship between physiological cardiac remodeling, aerobic capacity, and functional exercise performance in competitive athletes. Greater LV end-diastolic volume and LV mass index were associated with higher VO_2peak, while peak workload, exercise duration, HRR1, resting heart rate, and weekly training duration further characterized functional aerobic performance. LVEDV emerged as the strongest independent cardiac predictor of VO_2peak, emphasizing the potential importance of ventricular filling capacity in supporting superior aerobic performance. These findings support an integrated sports and cardiopulmonary physiotherapy approach in which cardiac structure, cardiorespiratory fitness, exercise performance, and recovery are evaluated together to provide a comprehensive assessment of the competitive athlete.

CONCLUSION

The present study demonstrates a meaningful association between physiological cardiac remodeling, aerobic capacity, and functional exercise performance in competitive athletes. Greater left ventricular end-diastolic volume (LVEDV) and left ventricular mass index (LVMI) were significantly associated with higher VO_2peak, whereas resting left ventricular ejection fraction (LVEF) showed no significant relationship with aerobic capacity. Among the cardiac variables, LVEDV demonstrated the strongest relationship with VO_2peak and remained the strongest independent predictor after adjustment for LVMI, weekly training duration, age, and sex.

Higher aerobic capacity was also associated with better functional exercise performance, reflected by greater peak workload, longer exercise duration, improved one-minute heart-rate recovery, and lower resting heart rate. Weekly training duration was positively related to VO_2peak, whereas training years, peak perceived exertion, and peak dyspnea did not demonstrate significant associations. These findings highlight the value of integrating echocardiographic assessment with cardiopulmonary exercise testing and physiotherapy-related functional measures when evaluating competitive athletes.

Future Implications

The findings of the present study provide several directions for future research and clinical application in sports and cardiopulmonary physiotherapy. The observed associations between left ventricular remodeling, particularly LV end-diastolic volume and LV mass index, and VO_2peak suggest that future studies should investigate how cardiac structural adaptations change over time in response to different training programs. Since LVEDV emerged as the strongest independent predictor of VO_2peak in the present analysis, longitudinal studies may help determine whether changes in ventricular volume parallel improvements or reductions in aerobic capacity across different phases of athletic training.

Future research should also include larger and more diverse samples involving athletes from endurance, strength, mixed, and skill-based sports. Comparisons according to sex, age, competitive level, training intensity, and sporting discipline may provide a clearer understanding of variations in physiological cardiac remodeling. The present study recorded training exposure and recognized that the magnitude of cardiac remodeling and aerobic conditioning may be influenced by long-term training characteristics.

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