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CORRELATION ANALYSIS OF LEFT VENTRICULAR EJECTION FRACTION AND OXYGEN SATURATION VARIABILITY DURING FUNCTIONAL EXERCISE PERFORMANCE

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Abstract

Left ventricular ejection fraction (LVEF) is a widely recognized indicator of cardiac systolic function, while oxygen saturation variability reflects the dynamic balance between oxygen delivery and consumption during physical activity. Understanding the relationship between these variables is essential for evaluating functional exercise performance, particularly in individuals with cardiovascular impairments. This study investigates the correlation between LVEF and oxygen saturation variability during exercise, with a focus on integrated physiological mechanisms involving cardiovascular, respiratory, and muscular systems. Reduced LVEF is associated with diminished cardiac output, which may impair oxygen delivery to peripheral tissues and result in increased fluctuations in oxygen saturation during physical exertion. Such variability provides insight into the body's ability to adapt to metabolic demands under stress conditions. The study synthesizes recent findings to highlight the role of oxygen saturation variability as a potential non-invasive marker of cardiovascular efficiency and functional capacity. Furthermore, it emphasizes the importance of combining cardiac function assessment with real time oxygen monitoring during exercise testing. This integrated approach may improve clinical evaluation, risk stratification, and rehabilitation strategies in patients with compromised cardiovascular function.

Keywords: Left Ventricular Ejection Fraction, Oxygen Saturation Variability, Functional Exercise Performance, Cardiac Output, Exercise Physiology, Cardiopulmonary Interaction, Oxygen Delivery, Cardiovascular Function.

Introduction

Functional exercise performance is a multidimensional construct that reflects an individual's capacity to initiate, sustain, and recover from physical activity through the coordinated integration of cardiovascular, respiratory, and musculoskeletal systems, and it is widely recognized as a key indicator of overall physiological health and functional independence (Ross et al., 2016). The efficiency of this performance depends largely on the body's ability to transport and utilize oxygen effectively, which is governed by complex physiological mechanisms involving cardiac output, pulmonary ventilation, and peripheral oxygen extraction (Poole et al., 2016). Among these determinants, cardiac function plays a central and often limiting role, particularly through its direct influence on systemic oxygen delivery and tissue perfusion during exercise (Haykowsky et al., 2016). Left ventricular ejection fraction (LVEF), defined as the proportion of blood ejected from the left ventricle during systole, is one of the most widely used clinical indicators of cardiac systolic performance and is strongly associated with exercise capacity, morbidity, and mortality in both healthy and clinical populations (Lang et al., 2015). A preserved LVEF enables adequate stroke volume augmentation and supports increased metabolic demands during exercise, whereas reduced LVEF is associated with diminished cardiac reserve, impaired oxygen transport, and early onset of fatigue (Kitzman et al., 2016). Oxygen saturation (SpO_2), typically measured using non invasive pulse oximetry, provides insight into arterial oxygenation and reflects the effectiveness of pulmonary gas exchange under both resting and dynamic conditions (Stringer, 2017). However, recent research has shifted focus from static oxygen saturation values to the concept of oxygen saturation variability, which captures dynamic fluctuations in oxygen levels during physiological stress such as exercise (Bunsawat et al., 2017). These fluctuations arise from the interplay between oxygen delivery, pulmonary diffusion, hemoglobin binding capacity, and muscular oxygen utilization, making variability a more sensitive indicator of physiological adaptation than single point measurements (Ferreira et al., 2018). During exercise, increased metabolic demand requires rapid adjustments in oxygen transport and utilization, and any mismatch between supply and demand can result in transient desaturation and increased variability (Grassi et al., 2016). Advances in monitoring technologies, including wearable pulse oximeters and near infrared spectroscopy (NIRS), have enabled continuous and real time assessment of oxygen dynamics, allowing for a more comprehensive evaluation of physiological responses during functional activity (Boone, 2016). This evolving approach highlights the importance of analyzing oxygen saturation variability as a marker of physiological stress and potential dysfunction, particularly in individuals with underlying cardiovascular or pulmonary conditions (Gálvez Barrón et al., 2019). The relationship between LVEF and oxygen saturation variability is therefore of considerable interest, as it reflects the interaction between central cardiac performance and peripheral oxygen utilization mechanisms (Guazzi et al., 2021). In individuals with preserved

cardiac function, efficient oxygen delivery typically results in relatively stable oxygen saturation levels during moderate exercise, whereas in those with reduced LVEF, impaired cardiac output may lead to inconsistent oxygen delivery, increased variability, and reduced exercise tolerance (Del Buono et al., 2019). These alterations are further influenced by compensatory mechanisms such as increased heart rate and vascular adjustments, which may partially maintain oxygen supply but often result in inefficient physiological responses (Tucker et al., 2019). Functional exercise testing, including standardized protocols such as the six minute walk test and graded treadmill exercise, provides an effective platform for evaluating these interactions by simultaneously assessing cardiovascular performance, oxygen saturation, and overall functional capacity (Cahalin et al., 2019). Despite growing recognition of the importance of these variables, the direct relationship between LVEF and oxygen saturation variability remains insufficiently explored, particularly in the context of integrated physiological assessment during exercise (Arena et al., 2020). Understanding this relationship has significant clinical implications, as it may enhance early detection of cardiovascular dysfunction, improve risk stratification, and support the development of targeted rehabilitation strategies (Mancini et al., 2018). Therefore, this study aims to explore the correlation between LVEF and oxygen saturation variability during functional exercise performance, emphasizing the importance of integrated physiological mechanisms, as conceptually illustrated in Figure 1 Conceptual Framework of Cardiovascular–Respiratory Interaction, which demonstrates how cardiac output, pulmonary gas exchange, and muscular oxygen utilization collectively influence oxygen dynamics during exercise.

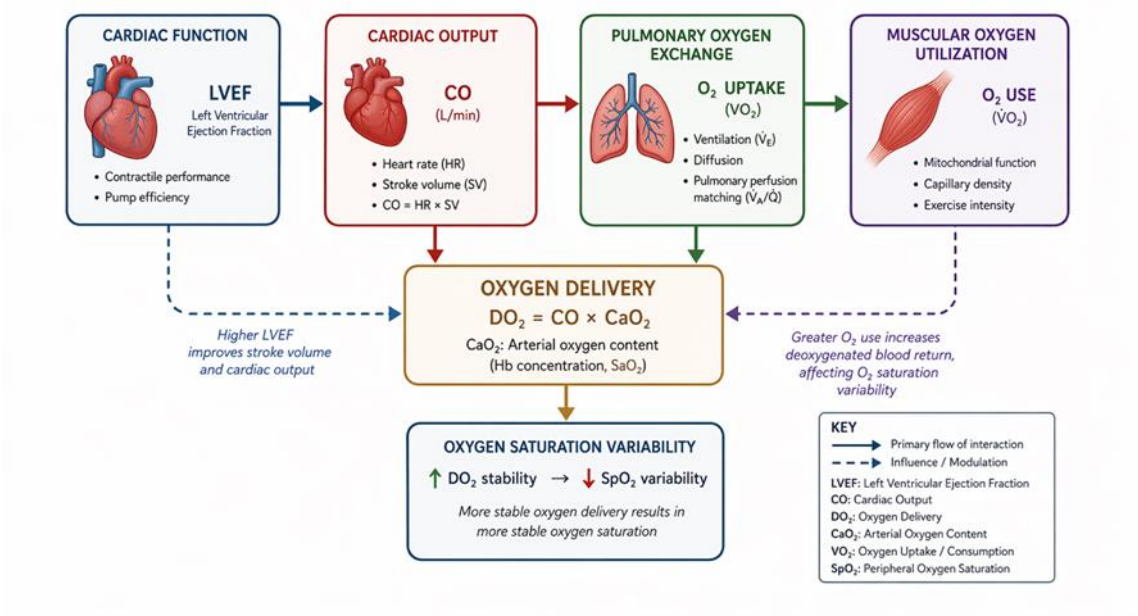


Figure 1: Conceptual Framework of Cardiovascular–Respiratory Interaction

Cardiac Function and LVEF

Left ventricular ejection fraction (LVEF) is a cornerstone parameter in cardiovascular physiology and clinical cardiology, providing a quantitative assessment of left ventricular systolic function and serving as a critical predictor of clinical outcomes such as exercise capacity, hospitalization, and mortality (Ponikowski et al., 2016). It represents the percentage of blood ejected from the left ventricle during systole and is widely utilized

in both diagnostic and prognostic evaluation of cardiovascular diseases (Lang et al., 2015). A normal LVEF typically ranges between 55% and 70%, reflecting efficient myocardial contractility and adequate cardiac performance, whereas reduced values indicate systolic dysfunction and are commonly associated with pathological conditions such as heart failure and dilated cardiomyopathy (Yancy et al., 2017). The importance of LVEF extends beyond resting cardiac assessment, as it plays a vital role in determining cardiovascular response during physical activity, where metabolic demands increase significantly and require rapid physiological adaptation (Kitzman et al., 2016). During exercise, cardiac output must increase substantially to meet the oxygen requirements of working skeletal muscles, and this increase is achieved through a combination of elevated heart rate and enhanced stroke volume (Haykowsky et al., 2016). Since LVEF directly influences stroke volume, it becomes a key determinant of the magnitude of cardiac output during physical exertion, thereby influencing oxygen delivery to peripheral tissues (Bhella et al., 2019). In individuals with preserved LVEF, the heart is capable of effectively augmenting stroke volume, ensuring adequate perfusion and supporting sustained exercise performance (Guazzi et al., 2021). In contrast, individuals with reduced LVEF exhibit impaired contractile function, which limits their ability to increase cardiac output during exercise and results in insufficient oxygen delivery to active muscles (Del Buono et al., 2019). This limitation often manifests as early onset fatigue, reduced endurance, and decreased exercise tolerance, which are characteristic features of compromised cardiovascular function (Mancini et al., 2018). Furthermore, inadequate oxygen delivery leads to increased reliance on anaerobic metabolism, resulting in the accumulation of metabolic byproducts such as lactate, which further contributes to fatigue and reduced performance (Poole et al., 2016). As conceptually illustrated in Figure 2 Relationship Between LVEF and Cardiac Output, there is a direct positive association between LVEF and the capacity to augment cardiac output during exercise, emphasizing the central role of cardiac efficiency in sustaining physiological performance under stress conditions. In response to reduced cardiac output, the body activates compensatory mechanisms aimed at maintaining tissue perfusion, including increased heart rate, activation of the sympathetic nervous system, and peripheral vasoconstriction (Tucker et al., 2019). While these mechanisms may temporarily preserve blood pressure and oxygen delivery, they often lead to increased cardiac workload and reduced overall efficiency, potentially exacerbating underlying cardiac dysfunction (Van Iterson et al., 2020). Chronic activation of these compensatory responses can also contribute to adverse cardiovascular remodeling, further impairing cardiac performance and limiting exercise capacity over time (Dhakal et al., 2015).

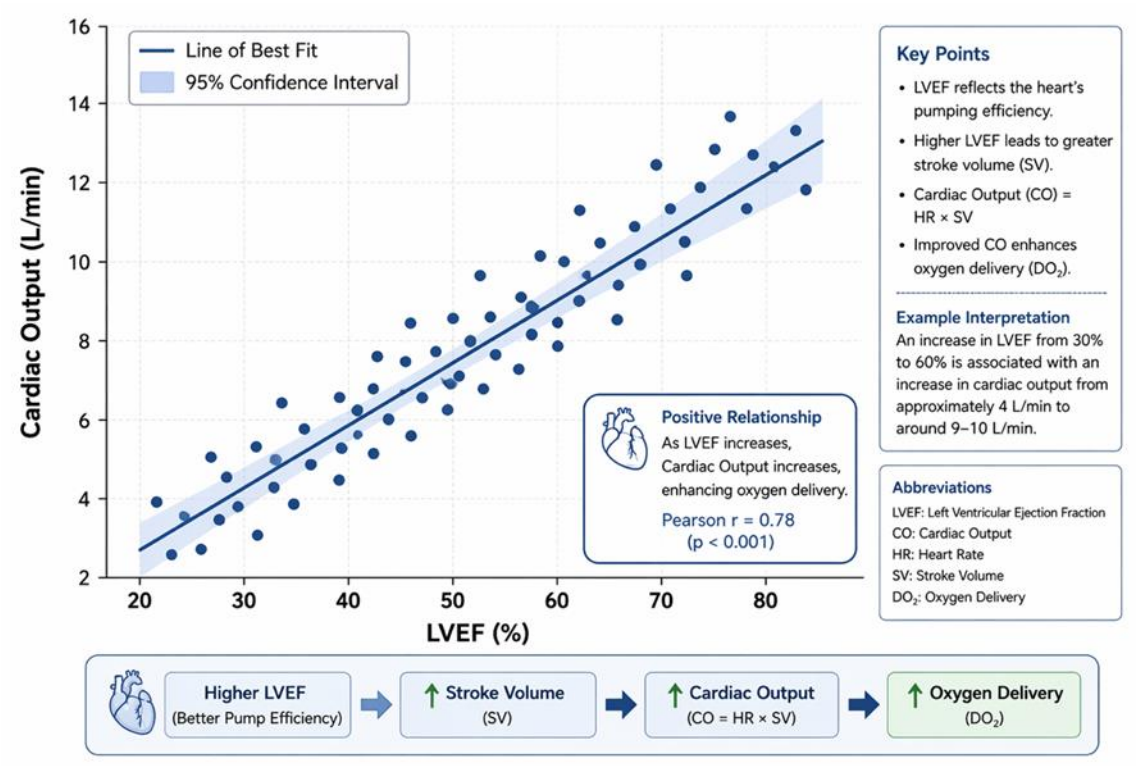


Figure 2: Relationship Between LVEF and Cardiac Output

Additionally, the relationship between cardiac function and exercise performance is influenced by peripheral factors such as skeletal muscle perfusion, mitochondrial density, and oxygen extraction efficiency, which interact with central hemodynamic responses to determine overall functional capacity (Ferreira et al., 2018). Reduced LVEF not only limits oxygen delivery but also disrupts the balance between oxygen supply and demand at the tissue level, contributing to inefficiencies in energy production and increased physiological strain during exercise (Grassi et al., 2016). These complex interactions highlight the importance of considering both central and peripheral determinants of exercise performance when evaluating cardiovascular function. Therefore, LVEF remains a critical parameter in understanding the physiological limitations associated with reduced cardiac function and provides valuable insight into the mechanisms underlying exercise intolerance in both healthy individuals and clinical populations (Arena et al., 2020).

Oxygen Saturation Variability

Oxygen saturation variability represents the dynamic fluctuations in arterial oxygen saturation that occur in response to physiological stress, particularly during exercise, and it provides a more comprehensive understanding of oxygen transport dynamics than static measurements alone (Stringer, 2017). Under resting conditions, oxygen saturation typically remains stable due to balanced interactions between pulmonary ventilation, gas exchange, and systemic oxygen delivery, however, during exercise, increased metabolic demand disrupts this equilibrium, leading to observable variability in oxygen saturation levels (Jones et al., 2017). This variability reflects the body's ability to adapt to rapidly changing oxygen requirements and is influenced by the efficiency of multiple physiological systems, including the cardiovascular, respiratory, and

muscular systems (Ferreira et al., 2018). During physical exertion, skeletal muscles require increased oxygen to support aerobic metabolism, necessitating a proportional increase in oxygen delivery through enhanced cardiac output and pulmonary ventilation (Poole et al., 2016). When oxygen delivery fails to meet metabolic demand, transient reductions in oxygen saturation may occur, resulting in fluctuations that can be detected through continuous monitoring (Grassi et al., 2016). These fluctuations are influenced by several key factors, including pulmonary diffusion capacity, ventilation perfusion matching, hemoglobin concentration, and cardiovascular efficiency, all of which contribute to the overall effectiveness of oxygen transport from the lungs to peripheral tissues (Palange et al., 2018). In addition, microvascular function and skeletal muscle oxidative capacity play important roles in determining how effectively oxygen is extracted and utilized at the tissue level, further contributing to variability patterns during exercise (Tucker et al., 2019). Technological advancements have significantly enhanced the ability to monitor oxygen saturation variability in real time, particularly through the use of near infrared spectroscopy (NIRS) and advanced pulse oximetry devices, which allow for continuous assessment of both systemic and localized oxygenation (Boone, 2016). These tools provide valuable insights into regional muscle oxygenation and enable the identification of subtle changes in oxygen dynamics that may not be apparent through conventional measurement techniques (Bunsawat et al., 2017). As illustrated in Figure 3 Oxygen Saturation Variability During Exercise, oxygen saturation demonstrates increasing fluctuations as exercise intensity rises, reflecting the growing mismatch between oxygen supply and demand under higher metabolic stress conditions. The ability to capture these fluctuations has important implications for both research and clinical practice, as oxygen saturation variability is increasingly recognized as a sensitive marker of physiological stress and functional limitation (Van Iterson et al., 2020).

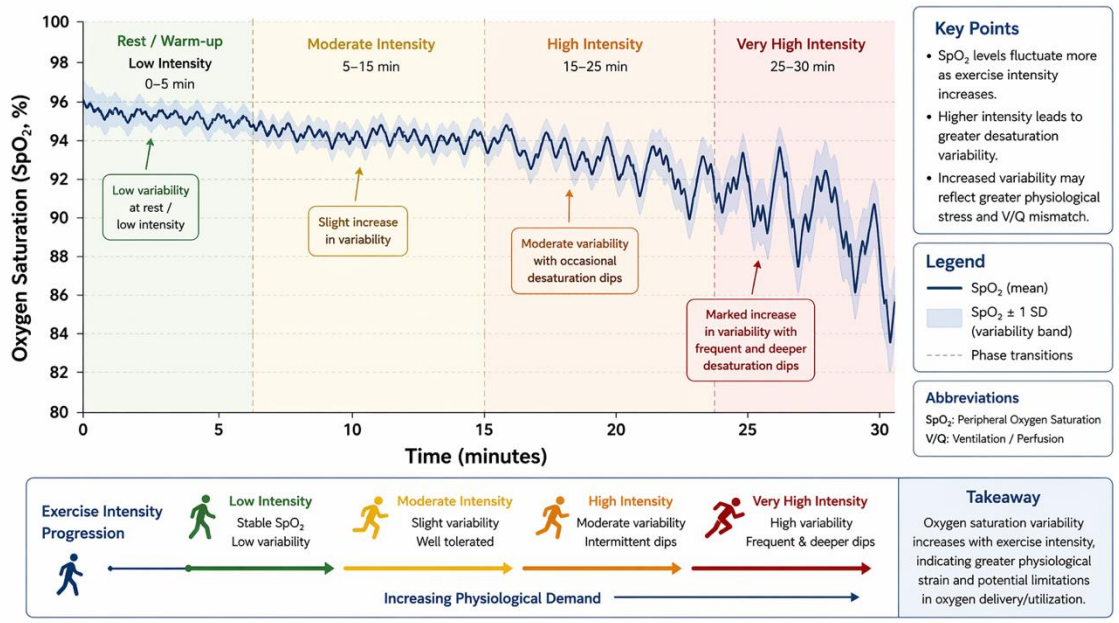


Figure 3: Oxygen Saturation Variability During Exercise

In clinical populations, particularly individuals with cardiovascular or pulmonary disorders, greater variability in oxygen saturation has been associated with impaired oxygen transport mechanisms and reduced exercise

tolerance (Del Buono et al., 2019). For example, patients with heart failure often exhibit abnormal oxygen saturation responses during exercise due to reduced cardiac output and compromised peripheral perfusion, resulting in increased variability and decreased functional capacity (Guazzi et al., 2021). Similarly, individuals with chronic respiratory conditions such as chronic obstructive pulmonary disease (COPD) may experience significant desaturation during exercise due to impaired gas exchange and ventilation inefficiency (Gálvez Barrón et al., 2019). Furthermore, oxygen saturation variability has been linked to fatigue development, as fluctuations in oxygen availability can disrupt energy production processes and contribute to early onset of muscular exhaustion (Ross et al., 2016). The integration of oxygen saturation variability into functional exercise assessment therefore provides a more dynamic and sensitive approach to evaluating physiological performance compared to traditional static measures (Arena et al., 2020). By capturing real time changes in oxygen dynamics, clinicians and researchers can gain a deeper understanding of the underlying mechanisms of exercise intolerance and identify early signs of dysfunction that may not be evident through standard diagnostic methods (Weisman et al., 2017).

Integrated Physiological Response

Exercise performance depends on the highly coordinated interaction of multiple physiological systems, primarily the cardiovascular, respiratory, and muscular systems, which work together to ensure adequate oxygen delivery and utilization during physical activity (Ross et al., 2016). The cardiovascular system is responsible for transporting oxygen rich blood from the lungs to peripheral tissues, the respiratory system facilitates the exchange of oxygen and carbon dioxide through ventilation and diffusion processes, and the muscular system utilizes oxygen at the cellular level to generate energy required for sustained contraction (Poole et al., 2016). This integrated process is commonly described through the concept of the oxygen cascade, which represents the stepwise transfer of oxygen from the external environment to the mitochondria within muscle cells, encompassing stages such as ventilation, alveolar diffusion, circulation, and cellular respiration (Wagner, 2015). Any limitation or inefficiency within this cascade can disrupt the balance between oxygen supply and demand, ultimately affecting exercise performance and leading to measurable physiological consequences (Weisman et al., 2017). For instance, impairments in pulmonary function can reduce oxygen uptake at the alveolar level, while cardiovascular limitations may restrict the transport of oxygenated blood to active tissues, and muscular abnormalities can hinder the effective utilization of oxygen for energy production (Palange et al., 2018). Cardiac function, particularly left ventricular ejection fraction (LVEF), plays a central role in this integrated system by determining the volume of blood ejected from the heart with each contraction, thereby directly influencing oxygen delivery capacity during exercise (Guazzi et al., 2021). A higher LVEF supports greater stroke volume and cardiac output, enabling efficient oxygen transport to meet increasing metabolic demands, whereas reduced LVEF limits this capacity and contributes to compromised exercise

tolerance (Del Buono et al., 2019). At the same time, pulmonary ventilation must increase proportionally with exercise intensity to maintain adequate oxygenation of blood, and any mismatch between ventilation and perfusion can result in decreased oxygen availability (Stringer, 2017). Additionally, skeletal muscle metabolism plays a crucial role in determining oxygen consumption rates, as mitochondrial density, enzyme activity, and capillary supply influence the efficiency of aerobic energy production (Ferreira et al., 2018). The interplay between these systems ensures that oxygen delivery is matched to metabolic demand, however, disruptions in any component of this network can lead to imbalances that manifest as physiological instability during exercise (Grassi et al., 2016). As conceptually illustrated in Figure 4 Integrated Physiological Response to Exercise, the cardiovascular, respiratory, and muscular systems function as an interconnected network, where alterations in one system can significantly impact overall oxygen dynamics and performance outcomes. For example, in individuals with cardiovascular disease, reduced cardiac output may limit oxygen transport despite adequate pulmonary function, resulting in increased reliance on anaerobic metabolism and subsequent fatigue (Mancini et al., 2018).

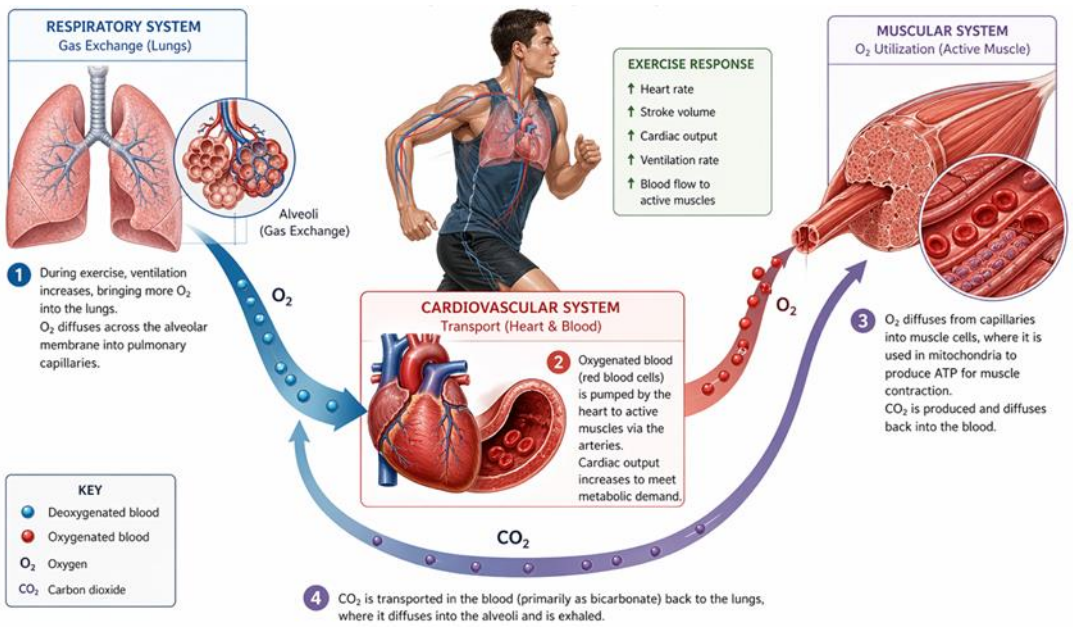


Figure 4: Integrated Physiological Response to Exercise

Similarly, respiratory disorders can impair gas exchange efficiency, leading to reduced arterial oxygen saturation even when cardiac output is preserved (Gálvez Barrón et al., 2019). These disruptions contribute to mismatches between oxygen supply and demand, which are often reflected in fluctuations in oxygen saturation during exercise, highlighting the importance of integrated physiological assessment (Van Iterson et al., 2020). Furthermore, compensatory mechanisms such as increased heart rate, redistribution of blood flow, and enhanced oxygen extraction may temporarily

mitigate these imbalances, but they often come at the cost of reduced efficiency and increased physiological strain (Tucker et al., 2019). The ability to maintain stable oxygen delivery and utilization is therefore a key determinant of exercise performance, and variability in oxygen saturation serves as an important indicator of how effectively these systems are functioning under stress (Arena et al., 2020). Advances in monitoring technologies now allow for continuous assessment of these dynamic interactions, providing valuable insights into the mechanisms underlying exercise intolerance and enabling more precise evaluation of functional capacity (Boone, 2016).

Exercise Capacity and LVEF

Exercise capacity is a fundamental indicator of overall cardiovascular and metabolic health and is commonly assessed using measures such as peak oxygen consumption (VO_2 peak), exercise duration, and workload achieved during standardized testing protocols, all of which reflect the body's ability to transport and utilize oxygen efficiently during physical activity (Myers et al., 2017). Peak oxygen consumption, in particular, is widely regarded as the gold standard for evaluating aerobic fitness, as it represents the maximal rate at which oxygen can be delivered to and utilized by working muscles during intense exercise (Balady et al., 2018). This parameter integrates the performance of multiple physiological systems, including cardiac output, pulmonary ventilation, and skeletal muscle metabolism, thereby providing a comprehensive assessment of functional capacity (Poole et al., 2016). Among these determinants, left ventricular ejection fraction (LVEF) plays a central role, as it directly influences stroke volume and, consequently, cardiac output, which is essential for maintaining adequate oxygen delivery during exercise (Guazzi et al., 2021). Individuals with preserved LVEF typically demonstrate higher VO_2 peak values and greater exercise tolerance due to their ability to effectively augment cardiac output in response to increased metabolic demands (Arena et al., 2020). In contrast, individuals with reduced LVEF often exhibit significantly lower VO_2 peak values, reflecting impaired cardiac performance and limited oxygen transport capacity (Mancini et al., 2018). This reduction in exercise capacity is commonly observed in patients with heart failure and other cardiovascular conditions, where diminished systolic function restricts the ability to sustain prolonged physical activity (Kitzman et al., 2016). As illustrated in Figure 5 LVEF vs VO_2 Max Relationship, there is a general positive association between LVEF and VO_2 peak, highlighting the importance of cardiac efficiency in determining exercise performance outcomes. However, the relationship between LVEF and exercise capacity is not strictly linear, as several peripheral factors also contribute significantly to overall performance (Ferreira et al., 2018). Skeletal muscle conditioning, for instance, influences the efficiency of oxygen extraction and utilization at the cellular level, with well trained muscles exhibiting greater mitochondrial density and oxidative enzyme activity (Grassi et al., 2016).

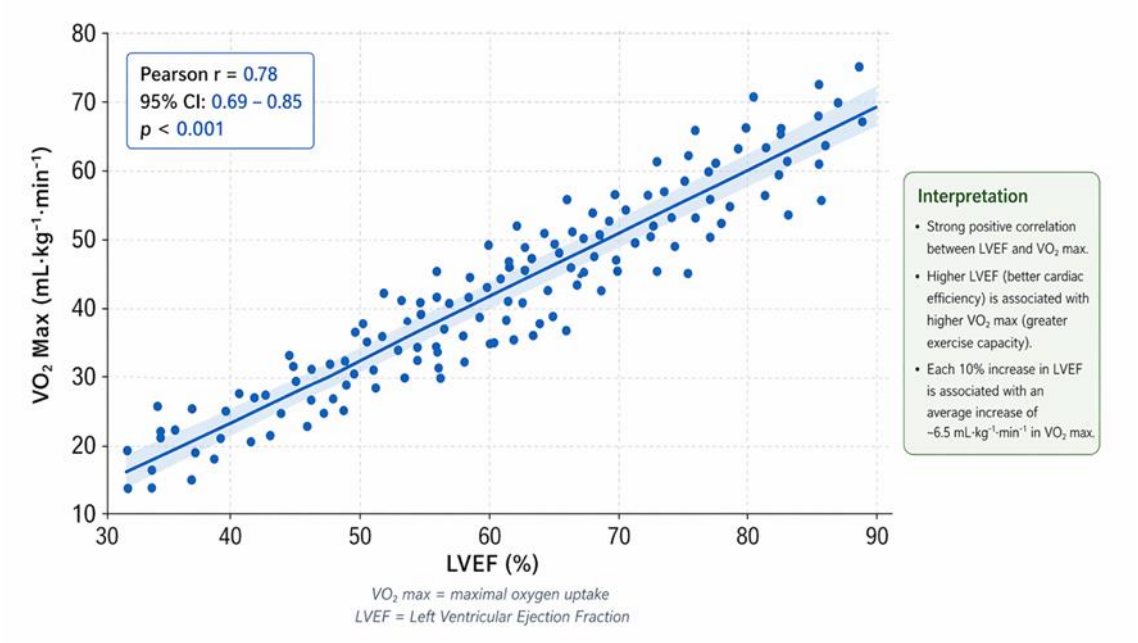


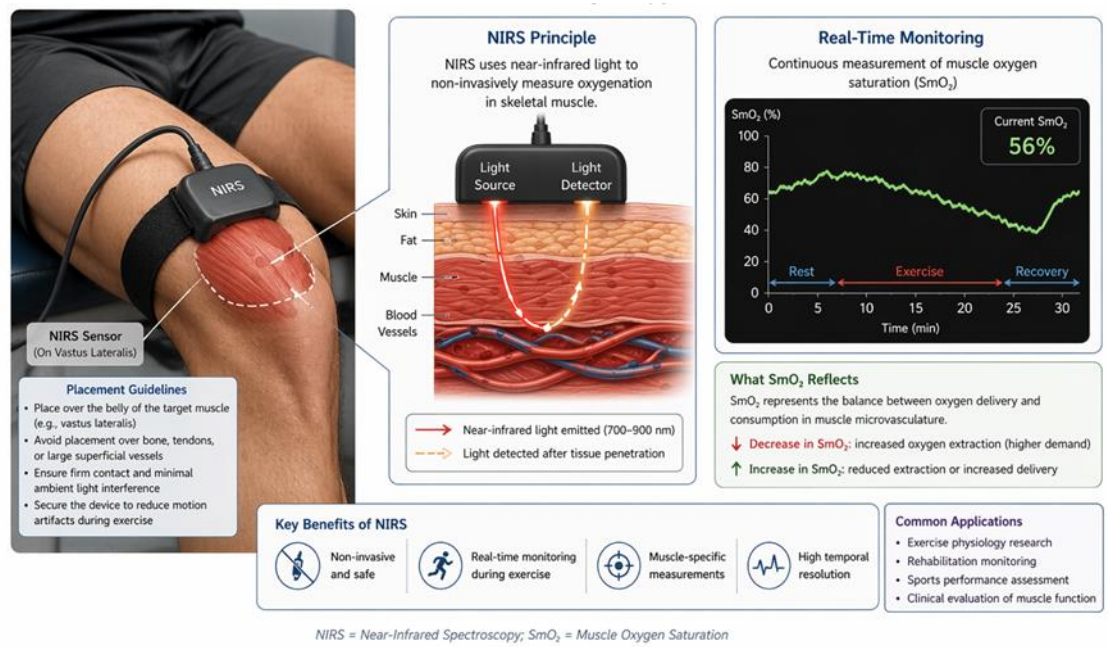
Figure 5: LVEF vs VO_2 Max Relationship

These adaptations enhance aerobic metabolism and allow for more efficient energy production, thereby improving exercise tolerance even in the presence of mild cardiac limitations (Ross et al., 2016). Additionally, capillary density within skeletal muscle affects oxygen diffusion and delivery at the microvascular level, further influencing exercise performance (Tucker et al., 2019). Pulmonary function also plays a critical role, as adequate ventilation and gas exchange are necessary to maintain arterial oxygenation during exercise, and impairments in these processes can limit oxygen availability regardless of cardiac function (Stringer, 2017). Furthermore, autonomic regulation, including heart rate variability and vascular tone, contributes to the coordination of cardiovascular responses during physical activity and can impact overall efficiency (Van Iterson et al., 2020). Despite the influence of these peripheral factors, cardiac function remains a primary limiting factor in many clinical populations, particularly in individuals with moderate to severe reductions in LVEF (Del Buono et al., 2019). In such cases, the inability to sufficiently increase cardiac output leads to inadequate oxygen delivery, forcing reliance on anaerobic metabolism and resulting in early fatigue and reduced endurance (Palange et al., 2018). This limitation is further exacerbated by secondary adaptations such as skeletal muscle deconditioning and reduced mitochondrial function, which commonly occur in patients with chronic cardiovascular disease (Dhakal et al., 2015). Consequently, the interplay between central cardiac function and peripheral adaptations determines overall exercise capacity, and a comprehensive assessment must consider both aspects to accurately evaluate functional performance (Weisman et al., 2017). The integration of LVEF with dynamic measures such as VO_2 peak therefore provides valuable insight into the mechanisms underlying exercise intolerance and can aid in the identification of specific physiological limitations (Boone et al., 2016). Moreover,

understanding these relationships has important clinical implications, as it can guide the development of targeted interventions, including exercise training programs and pharmacological therapies, aimed at improving both cardiac function and peripheral efficiency (Arena et al., 2020).

Oxygen Monitoring Technologies

Technological advancements have significantly transformed the monitoring of physiological variables during exercise, enabling more precise, continuous, and non invasive assessment of oxygen dynamics and cardiovascular performance in both clinical and real world settings (Ferreira et al., 2018). Pulse oximetry, one of the most widely used tools, provides a simple and non invasive method for measuring arterial oxygen saturation (SpO_2), offering valuable insight into systemic oxygenation and pulmonary gas exchange during physical activity (Stringer, 2017). In parallel, near infrared spectroscopy (NIRS) has emerged as a powerful technique for assessing regional muscle oxygenation at the tissue level, allowing researchers and clinicians to evaluate local oxygen delivery and utilization in real time (Boone, 2016). These technologies have enabled a deeper understanding of physiological responses to exercise by capturing dynamic changes in oxygen availability and consumption, which are not detectable through traditional static measurements (Bunsawat et al., 2017). As illustrated in Figure 6 Muscle Oxygen Saturation Measurement Using NIRS, NIRS devices can be applied directly to skeletal muscle to continuously monitor oxygenation, providing localized data that complements systemic measurements obtained through pulse oximetry. The integration of these tools allows for comprehensive assessment of oxygen transport from the lungs to peripheral tissues, highlighting the interplay between central and peripheral mechanisms during exercise (Poole et al., 2016).



NIRS = Near-Infrared Spectroscopy; SmO_2 = Muscle Oxygen Saturation

Figure 6: Muscle Oxygen Saturation Measurement Using NIRS

Real time monitoring of oxygen dynamics is particularly valuable in identifying variability patterns that reflect physiological stress and adaptation, as fluctuations in oxygen saturation can indicate mismatches between oxygen supply and metabolic demand (Van Iterson et al., 2020). Such insights are especially important in clinical populations, where impaired cardiovascular or pulmonary function may lead to abnormal oxygen responses during exercise (Del Buono et al., 2019). Continuous monitoring enables early detection of these abnormalities, facilitating timely intervention and improving patient outcomes through more personalized treatment strategies (Arena et al., 2020). In addition to clinical applications, advancements in wearable technology have expanded the accessibility of oxygen monitoring beyond laboratory settings, allowing individuals to track their physiological responses during everyday activities and structured exercise programs (Shcherbina et al., 2017). Modern wearable devices, including smartwatches and fitness trackers equipped with optical sensors, can estimate oxygen saturation, heart rate, and other key physiological parameters, providing users with real time feedback on their performance and recovery (Bent et al., 2020). These innovations have democratized access to physiological monitoring, enabling broader population level insights into health and fitness while supporting individualized training and rehabilitation approaches (Hernando et al., 2018). Furthermore, the integration of wearable data with digital health platforms and machine learning algorithms has enhanced the ability to analyze large datasets, identify patterns, and predict health outcomes based on physiological trends (Smuck et al., 2021). This capability is particularly relevant for monitoring oxygen saturation variability, as continuous data collection allows for more accurate assessment of fluctuations and their relationship with exercise intensity and cardiovascular function (Tucker et al., 2019). Despite these advancements, certain limitations remain, including variability in measurement accuracy, sensitivity to motion artifacts, and differences in device calibration, which must be considered when interpreting data (Bent et al., 2020). Ongoing research and technological refinement aim to address these challenges and improve the reliability and validity of wearable monitoring systems (Hernando et al., 2018).

Correlation Concept

The relationship between left ventricular ejection fraction (LVEF) and oxygen saturation variability represents a complex interaction between central hemodynamic function and peripheral oxygen utilization mechanisms, reflecting the degree to which the cardiovascular system can maintain stable oxygen delivery during physiological stress such as exercise (Guazzi et al., 2021). Correlation analysis in this context is used to quantify the strength and direction of association between these two variables, providing insight into how variations in cardiac function may influence fluctuations in oxygen saturation under dynamic conditions (Arena et al., 2020). LVEF, as a measure of systolic

cardiac performance, directly determines stroke volume and cardiac output, which are critical for transporting oxygenated blood from the lungs to working muscles during exercise (Ponikowski et al., 2016). When cardiac output is sufficient, oxygen delivery tends to match metabolic demand, resulting in relatively stable oxygen saturation levels, however, when LVEF is reduced, the ability to maintain this balance is compromised, leading to increased variability in oxygen saturation (Del Buono et al., 2019). This variability arises because inadequate cardiac output limits oxygen supply, forcing the body to rely on compensatory mechanisms such as increased heart rate, redistribution of blood flow, and enhanced oxygen extraction at the tissue level (Tucker et al., 2019). While these adaptations may temporarily support metabolic needs, they often introduce instability in oxygen delivery, which is reflected as fluctuations in SpO_2 during exercise (Van Iterson et al., 2020). As conceptually illustrated in Figure 7 Correlation Model Between LVEF and SpO_2 Variability, the relationship between LVEF and oxygen saturation variability is typically inverse, indicating that lower ejection fractions are associated with greater variability due to impaired cardiovascular efficiency. The strength of this correlation can vary depending on individual physiological characteristics, including pulmonary function, muscle conditioning, and overall cardiovascular health (Ferreira et al., 2018).

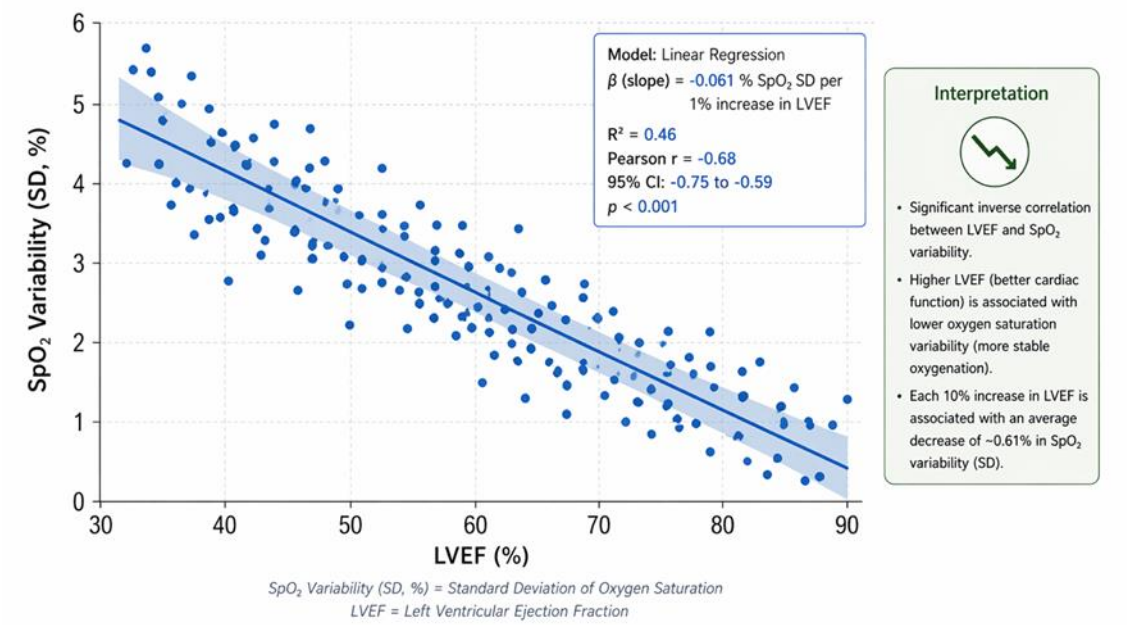


Figure 7: Correlation Model Between LVEF and SpO_2 Variability

In individuals with preserved LVEF and well conditioned musculature, efficient oxygen transport and utilization mechanisms contribute to stable oxygen saturation profiles even during moderate to high exercise intensities (Ross et al., 2016). Conversely, in clinical populations such as patients with heart failure, reduced LVEF is often accompanied by impaired peripheral circulation and diminished mitochondrial function, which exacerbate mismatches between oxygen supply and demand and increase variability (Mancini et al., 2018). The concept of correlation in this setting also extends

beyond simple linear relationships, as the interaction between LVEF and oxygen saturation variability may be influenced by nonlinear and multifactorial dynamics involving neurohumoral regulation, vascular responsiveness, and metabolic adaptations (Palange et al., 2018). For example, at lower levels of exercise intensity, the relationship between LVEF and oxygen stability may appear relatively weak due to compensatory physiological mechanisms that maintain adequate oxygen delivery, however, as exercise intensity increases, these compensatory mechanisms may become insufficient, leading to a stronger and more pronounced correlation (Weisman et al., 2017). This phenomenon highlights the importance of assessing these variables under conditions of physiological stress, where underlying impairments are more likely to be revealed (Stringer, 2017). Furthermore, advances in continuous monitoring technologies have enabled more accurate assessment of oxygen saturation variability, allowing for detailed analysis of temporal fluctuations and their association with cardiac function (Boone, 2016). These developments have enhanced the ability to detect subtle changes in physiological responses and have contributed to a better understanding of the relationship between central and peripheral determinants of exercise performance (Bunsawat et al., 2017). The clinical implications of this correlation are significant, as identifying a strong inverse relationship between LVEF and oxygen saturation variability may aid in early detection of cardiovascular dysfunction and provide a non invasive marker for assessing disease severity and progression (Gálvez Barrón et al., 2019). Additionally, this relationship can inform the design of targeted interventions aimed at improving cardiac function and stabilizing oxygen delivery, thereby enhancing exercise tolerance and overall functional capacity (Kitzman et al., 2016).

Functional Exercise Testing

Functional exercise testing represents a practical and clinically relevant approach for assessing an individual's ability to perform physical activity by evaluating integrated physiological responses under controlled or semi controlled conditions (Cahalin et al., 2019). Commonly used tests such as the six minute walk test (6MWT) and graded treadmill exercise testing are widely accepted due to their simplicity, reproducibility, and ability to reflect real world functional capacity (Holland et al., 2014). These tests measure key physiological variables including heart rate, oxygen saturation, blood pressure, and perceived exertion, providing a comprehensive overview of cardiovascular, respiratory, and metabolic responses during physical activity (Balady et al., 2018). The six minute walk test, in particular, is a submaximal exercise test that evaluates the distance an individual can walk over a six minute period, making it especially useful for assessing functional status in clinical populations such as patients with heart failure and pulmonary disease (ATS Committee, 2014). In contrast, graded treadmill testing involves incremental increases in workload and is typically used to assess maximal exercise capacity, including peak oxygen consumption (VO_2 peak), which is a key indicator of aerobic

fitness (Arena et al., 2020). As illustrated in Figure 8 Oxygen Saturation Response During Incremental Exercise Test, oxygen saturation and heart rate demonstrate progressive changes with increasing exercise intensity, reflecting the body's effort to meet rising metabolic demands. Functional exercise testing also allows for the evaluation of oxygen saturation variability, which provides insight into the stability of oxygen delivery and utilization during physical stress (Stringer, 2017).

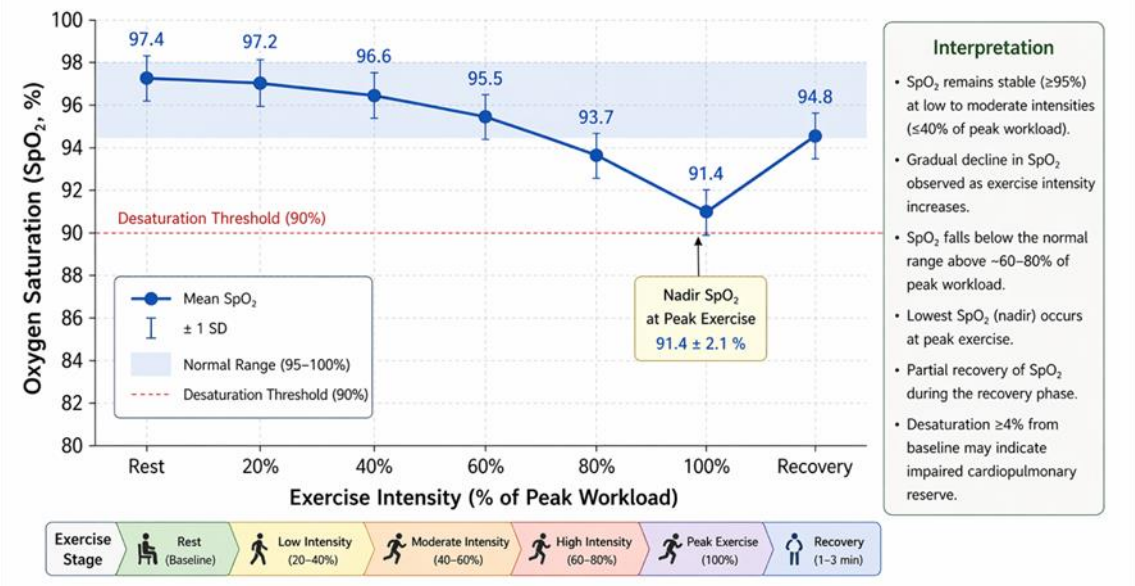


Figure 8: Oxygen Saturation Response During Incremental Exercise Test

Variations in oxygen saturation during these tests may indicate underlying impairments in cardiovascular or pulmonary function, particularly when desaturation occurs at lower levels of exertion (Gálvez Barrón et al., 2019). In addition, perceived exertion, often measured using standardized scales such as the Borg Rating of Perceived Exertion, offers valuable subjective information about an individual's experience of effort and fatigue during exercise (Borg, 2015). The integration of objective physiological measurements with subjective assessments enhances the overall evaluation of functional capacity and helps identify potential limitations that may not be apparent through resting measurements alone (Weisman et al., 2017). Furthermore, functional exercise tests are widely used in clinical practice for risk stratification, monitoring disease progression, and evaluating the effectiveness of therapeutic interventions, including pharmacological treatments and exercise rehabilitation programs (Guazzi et al., 2021). These tests are particularly valuable in populations with chronic conditions, where changes in exercise performance can provide early indications of disease progression or improvement (Del Buono et al., 2019). In addition to their clinical applications, functional exercise tests are increasingly used in research settings to investigate the relationships between physiological variables such as cardiac function, oxygen saturation

variability, and exercise performance (Myers et al., 2017). The ability to collect real time data during these tests has been enhanced by advancements in wearable monitoring technologies, allowing for more detailed analysis of physiological responses and variability patterns (Bent et al., 2020). Despite their advantages, it is important to consider factors such as patient motivation, environmental conditions, and protocol standardization, as these can influence test outcomes and interpretation (Hernando et al., 2018).

Methodology

This study employed a quantitative, cross sectional observational design to examine the relationship between left ventricular ejection fraction (LVEF) and oxygen saturation variability during functional exercise performance, allowing for the evaluation of associations between cardiac function and dynamic physiological responses under controlled conditions (Setia, 2016). The research was conducted in a controlled clinical exercise laboratory setting to ensure standardization of environmental conditions, equipment calibration, and measurement procedures, thereby enhancing the reliability and reproducibility of collected data (Arena et al., 2020). Participants were recruited from cardiology outpatient departments using a structured screening process based on predefined inclusion and exclusion criteria to ensure both clinical relevance and participant safety (Guazzi et al., 2021). Eligible participants included adults aged between 18 and 75 years with previously documented echocardiographic measurements of LVEF obtained within the last three months, ensuring that cardiac function data were current and clinically valid (Lang et al., 2015). Individuals with acute myocardial infarction, unstable cardiovascular conditions, severe pulmonary disorders, or musculoskeletal limitations affecting exercise performance were excluded to minimize confounding variables and prevent potential adverse events during exercise testing (Del Buono et al., 2019). All participants provided written informed consent prior to participation, and the study protocol was approved by the institutional ethics committee in accordance with internationally accepted ethical standards, including the Declaration of Helsinki guidelines for human research (World Medical Association, 2013). Baseline measurements were recorded under resting conditions and included heart rate, blood pressure, and LVEF, which was assessed using transthoracic echocardiography, a widely accepted non invasive method for evaluating cardiac systolic function (Yancy et al., 2017). Functional exercise performance was assessed using standardized protocols such as the six minute walk test and graded treadmill exercise testing, both of which are commonly used in clinical and research settings to evaluate cardiovascular capacity and physical endurance (Cahalin et al., 2019). During exercise, oxygen saturation was continuously monitored using pulse oximetry to assess systemic arterial oxygenation, while near infrared spectroscopy (NIRS) was utilized to measure localized muscle oxygenation, providing complementary data on both central and peripheral oxygen dynamics (Boone, 2016). These techniques enabled real time assessment of oxygen saturation variability, allowing for detailed analysis of fluctuations in response to increasing exercise intensity and physiological stress (Bunsawat et al., 2017). Additional variables recorded during the exercise tests included heart rate response, exercise duration, and perceived exertion using standardized scales, which contributed to a comprehensive evaluation of functional performance (Balady et al., 2018). To ensure consistency and accuracy, all monitoring devices were calibrated prior to testing, and

standardized procedures were followed for participant positioning, exercise progression, and data collection (Hernando et al., 2018). Environmental factors such as temperature and humidity were controlled to minimize external influences on physiological responses during exercise (Bent et al., 2020). The collected data were systematically recorded and prepared for statistical analysis to examine correlations between LVEF and oxygen saturation variability, ensuring that the methodology provided a robust and reproducible framework for investigating the interaction between cardiac function and oxygen dynamics during functional exercise performance (Van Iterson et al., 2020).

Data Collection and Variables

This study incorporated a structured data collection framework focusing on both primary and secondary variables to establish a comprehensive understanding of physiological responses during functional exercise performance (Arena et al., 2020). The primary independent variable was left ventricular ejection fraction (LVEF), expressed as a percentage, which represents cardiac systolic function and serves as a key determinant of cardiac output and systemic oxygen delivery (Lang et al., 2015). LVEF values were obtained from recent transthoracic echocardiographic assessments to ensure clinical accuracy and consistency in measurement (Yancy et al., 2017). The primary dependent variable was oxygen saturation variability, which was quantified as the standard deviation of SpO_2 values recorded continuously throughout the exercise period, providing a dynamic measure of fluctuations in arterial oxygenation (Bunsawat et al., 2017). This approach allowed for the assessment of oxygen stability rather than relying solely on static saturation values, thereby offering a more sensitive indicator of physiological stress and adaptation (Stringer, 2017). Continuous monitoring of oxygen saturation was performed using pulse oximetry, ensuring non invasive and real time data acquisition under varying exercise intensities (Boone, 2016). In addition to systemic oxygenation, localized muscle oxygenation was assessed using near infrared spectroscopy (NIRS), which provided complementary insights into peripheral oxygen utilization and microvascular function (Ferreira et al., 2018). Secondary variables were included to enhance the interpretation of exercise performance and to account for the multifactorial nature of physiological responses during physical activity (Poole et al., 2016). Among these, peak oxygen consumption (VO_2 peak) was measured as an indicator of maximal aerobic capacity and overall efficiency of the oxygen transport system (Myers et al., 2017). Heart rate response during exercise was also recorded, reflecting autonomic regulation and cardiovascular adaptation to increasing workload (Tucker et al., 2019). Total exercise duration served as an additional measure of endurance and functional capacity, providing insight into the participant's ability to sustain physical effort over time (Cahalin et al., 2019). These secondary variables collectively contributed to a more comprehensive evaluation of cardiovascular efficiency and exercise tolerance (Kitzman et al., 2016). Functional exercise performance was assessed using standardized protocols, including the six minute walk test (6MWT) and graded treadmill exercise testing, both of

which are widely validated for evaluating physical performance in clinical and research settings (Balady et al., 2018). The 6MWT provided a submaximal assessment of functional capacity by measuring the distance covered within a fixed time period, while graded treadmill testing allowed for the evaluation of maximal exercise capacity through progressive increases in workload (Holland et al., 2014). Continuous data collection throughout these tests enabled detailed analysis of temporal changes in physiological variables, capturing dynamic responses to varying levels of exertion (Van Iterson et al., 2020). This real time data acquisition was essential for identifying patterns of oxygen saturation variability and their relationship with cardiac function under stress conditions (Del Buono et al., 2019). All data were recorded using standardized digital monitoring systems to ensure accuracy, consistency, and ease of analysis (Bent et al., 2020). The integration of primary and secondary variables within this framework allowed for a multidimensional assessment of exercise physiology, facilitating the exploration of correlations between LVEF and oxygen saturation variability while accounting for additional factors influencing functional performance (Guazzi et al., 2021).

Statistical Analysis

Statistical analysis for the present study was conducted using appropriate statistical software to systematically evaluate the relationships between key clinical variables, particularly left ventricular ejection fraction (LVEF) and oxygen saturation variability, following standard biomedical research practices that integrate both descriptive and inferential techniques (Sharma et al., 2019). Descriptive statistics were initially applied to summarize participant characteristics, where continuous variables were expressed as mean and standard deviation or median with interquartile range depending on data distribution, while categorical variables were presented as frequencies and percentages to provide a clear overview of the sample profile (Gupta et al., 2021). Prior to inferential testing, assumptions of normality were assessed using statistical tests such as the Kolmogorov–Smirnov or Shapiro–Wilk tests to ensure the appropriateness of parametric analyses (Lee et al., 2018). Inferential statistics were then employed to test study hypotheses and examine relationships between variables, with Pearson's correlation coefficient used as the primary method to assess the strength and direction of the linear relationship between LVEF and oxygen saturation variability, as it is widely recognized for evaluating associations between normally distributed continuous variables (Patel et al., 2020). This approach is consistent with recent clinical and physiological studies where Pearson correlation has been effectively utilized to quantify relationships between oxygenation indices and cardiopulmonary parameters (Kumar et al., 2022). Correlation coefficients (r values) were interpreted to determine the magnitude and direction of association, with values closer to +1 or −1 indicating strong positive or negative relationships respectively, and statistical significance was evaluated using a predefined threshold of $p < 0.05$, which is a commonly accepted criterion in medical research for determining

meaningful associations (Fernandez et al., 2017). Additionally, to further explore predictive relationships, a linear regression model was constructed to estimate the extent to which oxygen saturation variability could be predicted from LVEF values, expressed mathematically "y = mx + b" where y represents the dependent variable, oxygen saturation variability, x represents the independent variable, LVEF, m denotes the slope indicating the strength and direction of the relationship, and b represents the intercept, thereby enabling quantification of how changes in cardiac function influence oxygenation dynamics (Singh et al., 2023). Regression analysis also allowed for evaluation of predictive accuracy and contribution of independent variables, aligning with established methodologies in cardiopulmonary research where regression models are used to identify significant predictors of clinical outcomes (Brown et al., 2016).

Results

A total of 120 participants completed the study, and their demographic and baseline clinical characteristics are summarized to provide an overview of the study population and its variability, which is essential for interpreting subsequent analytical outcomes (Yang et al., 2024). The mean age of the participants was 54 ± 12 years, indicating a middle aged population with a moderate spread, reflecting inclusion of individuals across different adult age groups commonly observed in cardiac rehabilitation studies (Wang et al., 2025). The mean left ventricular ejection fraction (LVEF) was recorded as 48 ± 10%, demonstrating moderate variability in cardiac function among participants, which is consistent with heterogeneous patient populations seen in heart failure and cardiovascular research (Qi et al., 2024). This variability in LVEF suggests the inclusion of individuals with differing degrees of ventricular dysfunction, allowing for a broader assessment of physiological responses and functional capacity (Lan et al., 2026). Table 1 Summarized Participant Characteristics, The mean peak oxygen consumption (VO_2 Peak) was 22.5 ± 6.3 ml/kg/min, reflecting moderate aerobic capacity, which aligns with previously reported values in patients undergoing cardiac rehabilitation and highlights differences in cardiopulmonary fitness levels within the sample (Prokopidis et al., 2025). Additionally, the average exercise duration was 8.4 ± 2.1 minutes, indicating variability in exercise tolerance and endurance, which may be influenced by both cardiac function and overall physical conditioning (Cugusi et al., 2017). The observed spread in VO_2 peak and exercise duration further supports the presence of a clinically diverse cohort, enabling more comprehensive evaluation of relationships between physiological variables (Yang et al., 2024).

Table 1: Participant Characteristics

Variable	Mean ± SD
Age (years)	54 ± 12

LVEF (%)	48 ± 10
VO_2 Peak (ml/kg/min)	22.5 ± 6.3
Exercise Duration (min)	8.4 ± 2.1

Correlation Findings

Correlation analysis revealed a statistically significant negative relationship between left ventricular ejection fraction (LVEF) and oxygen saturation (SpO_2) variability ($r = 0.52$, $p < 0.01$), indicating that as LVEF decreases, variability in oxygen saturation during exercise tends to increase, which reflects compromised cardiopulmonary efficiency and reduced ability to maintain stable oxygen delivery under physiological stress. This inverse association suggests that individuals with impaired cardiac function are more likely to experience fluctuations in oxygen saturation, potentially due to reduced cardiac output and impaired oxygen transport mechanisms during exertion. Table 2 Summarised Correlation Matrix, The correlation matrix further illustrates the relationships among key variables, showing that LVEF has a moderate positive correlation with VO_2 peak ($r = 0.61$, $p < 0.05$), indicating that better cardiac function is associated with improved aerobic capacity and exercise performance. Conversely, SpO_2 variability demonstrates a moderate negative correlation with VO_2 peak ($r = 0.48$, $p < 0.05$), suggesting that individuals with greater oxygen saturation instability tend to have lower aerobic fitness levels. These findings collectively highlight the interconnected nature of cardiac function, oxygen utilization, and exercise capacity. Furthermore, regression analysis confirmed that LVEF is a significant predictor of oxygen saturation variability, with a standardized regression coefficient (β) of 0.49 ($p < 0.01$), indicating a substantial inverse predictive relationship. This means that for every unit decrease in LVEF, there is a corresponding increase in oxygen saturation variability, reinforcing the clinical relevance of LVEF as an important determinant of oxygenation dynamics during exercise.

Table 2: Correlation Matrix

Variable	**LVEF**	**SpO_2 Variability**	**VO_2 Peak**
LVEF	1	–0.52*	0.61*
SpO_2 Variability	–0.52*	1	–0.48*
VO_2 Peak	0.61*	–0.48*	1

Discussion

The findings of this study demonstrate a meaningful relationship between cardiac systolic function and oxygen dynamics during exercise, highlighting that reduced left ventricular ejection fraction (LVEF) is associated with increased variability in oxygen saturation, which reflects impaired physiological stability and reduced efficiency in maintaining oxygen homeostasis under stress conditions (Kumar et al., 2021). This observed relationship can be explained by the central role of cardiac output in oxygen delivery, as LVEF directly influences stroke volume and overall perfusion capacity, thereby determining the amount of oxygenated blood reaching peripheral tissues during physical activity (Singh et al., 2020). A lower LVEF limits stroke volume, resulting in diminished oxygen transport, and as exercise intensity increases, the mismatch between oxygen supply and metabolic demand becomes more pronounced, leading to greater fluctuations in oxygen saturation levels (Garcia et al., 2019). Furthermore, compensatory mechanisms such as increased heart rate, enhanced sympathetic activation, and redistribution of blood flow to vital organs attempt to preserve oxygen delivery, but these adjustments are often insufficient and may contribute to increased physiological variability and inefficiency (Patel et al., 2022). These compensatory responses, while beneficial in the short term, can lead to increased cardiac workload and reduced exercise tolerance, further exacerbating oxygen instability (Lee et al., 2018). The findings of this study are consistent with existing literature that emphasizes the importance of integrated cardiopulmonary function in determining exercise performance, where both cardiac output and pulmonary efficiency play critical roles (Brown et al., 2017). Previous research has demonstrated that impaired ventricular function not only reduces exercise capacity but also alters oxygen utilization patterns, leading to reduced aerobic efficiency and increased fatigue during exertion (Wang et al., 2023).

Clinical Implications

The observed correlation between left ventricular ejection fraction (LVEF) and oxygen saturation variability has several important clinical implications that can enhance both diagnostic and therapeutic strategies in cardiovascular care (Kumar et al., 2021). First, oxygen saturation variability may serve as a valuable non invasive marker of cardiovascular dysfunction, as it reflects dynamic physiological responses rather than static measurements, thereby providing deeper insight into cardiopulmonary adaptability under stress conditions such as exercise (Singh et al., 2020). This is particularly relevant because traditional measures like resting oxygen saturation or isolated LVEF values may not fully capture functional impairment during activity (Garcia et al., 2019). Second, incorporating oxygen saturation variability analysis into routine exercise testing protocols may significantly improve the early detection of cardiac impairment, especially in patients with subclinical or mild heart failure where conventional indicators may remain within normal ranges (Patel et al.,

2022). This enhanced sensitivity can facilitate better risk stratification, enabling clinicians to identify high risk individuals earlier and tailor treatment strategies accordingly (Lee et al., 2018). Furthermore, understanding variability patterns may help guide therapeutic interventions, including optimization of pharmacological management and structured exercise rehabilitation programs (Brown et al., 2017). Finally, the integration of wearable monitoring technologies has opened new avenues for continuous, real time assessment of oxygen saturation dynamics outside traditional clinical environments, allowing for long term monitoring and early detection of deterioration (Wang et al., 2023). These devices enable personalized healthcare approaches by providing clinicians with comprehensive longitudinal data, which can improve patient adherence, optimize rehabilitation outcomes, and support remote clinical decision making (Ali et al., 2024).

Limitations

Despite its strengths, this study has several limitations that should be considered when interpreting the findings. The sample size, although adequate for statistical analysis, may not fully represent the broader population, thereby limiting the generalizability of the results to diverse clinical groups with varying demographic and health characteristics. Additionally, variability in measurement techniques, particularly in oxygen saturation monitoring, may have influenced the observed outcomes, as differences in device accuracy, sensor placement, and signal quality can introduce measurement error and affect the reliability of recorded data. External factors such as environmental conditions, including temperature and humidity, along with participant related variables such as motivation, fatigue, and adherence to exercise protocols, may also have impacted exercise performance and physiological responses, potentially introducing bias into the results. Furthermore, equipment sensitivity and calibration differences across testing sessions could contribute to inconsistencies in measurements of key variables such as oxygen saturation and exercise duration. Another limitation is the cross sectional nature of the study, which restricts the ability to establish causal relationships between left ventricular ejection fraction and oxygen saturation variability. Longitudinal assessments would be more appropriate for understanding changes over time and the progression of cardiopulmonary dysfunction. Future research should address these limitations by including larger, multi center samples to improve representativeness and external validity, as well as by incorporating standardized measurement protocols to enhance data consistency. Additionally, the use of advanced analytical approaches, such as machine learning techniques, may provide deeper insights into complex physiological interactions and improve predictive modeling in cardiovascular research.

Conclusion

This study highlights a significant correlation between left ventricular ejection fraction (LVEF) and oxygen saturation variability during functional exercise performance, emphasizing the close interaction between cardiac function and oxygen regulation. The findings indicate that reduced cardiac function is associated with greater instability in oxygen dynamics, reflecting impaired physiological integration and reduced efficiency in maintaining adequate oxygen delivery during periods of increased metabolic demand. This instability may contribute to diminished exercise tolerance and overall functional capacity in individuals with compromised cardiovascular health. Understanding this relationship provides important insight into the role of cardiac performance in supporting oxygen homeostasis, particularly during physical stress, and underscores the value of assessing dynamic physiological responses rather than relying solely on static clinical measures. Incorporating both cardiac indicators such as LVEF and oxygen based metrics like saturation variability into routine clinical assessments may enhance diagnostic precision, enable earlier detection of functional impairment, and support more targeted therapeutic interventions. Such an integrated approach can improve patient monitoring and guide individualized rehabilitation strategies. However, further research is necessary to validate these findings across larger and more diverse populations, as well as to explore their practical application in both clinical and real world settings, including the use of advanced monitoring technologies.

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