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Breathing frequency and breathing volume of recreational cyclists and runners

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Breathing frequency and breathing volume in recreational cyclists and runners

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Ágrip

Almenn hreyfing hefur jákvæð áhrif á bæði andlega og líkamlega vellíðan. Markmið þessarar rannsóknar er að skoða öndunartíðni og öndunarmagn sem fall af hámarkssúrefnisupptöku (VO_2max) meðal frístundahjólreiðamanna og hlaupara. Bæði með beinum og óbeinum mælingum, sem og að bera saman þessar mælingar á milli hjólreiða og hlaupa. Stigmagnandi álagspróf voru tekin á 47 þátttakendum á aldrinum 44,46 ± 10,08 (hjólreiðamenn) og 46,45 ± 10,32 (hlauparar), í samtals 76 mælingum. Þátttakendur voru mældir með Cosmed K5 gasgreiningartæki til að mæla andardrátt beint og TymeWear snjallstuttermabol til að mæla andardráttinn óbeint. Stigmagnandi álagsprófin voru framkvæmd á bæði innihjóli og hlaupabretti, á hjóli hófst það við 75W álag, jókst um 25W á 3ja mínútna fresti, og hlauparar byrjuðu á 5 km/klst hraða, jókst hann um 1 km/klst á 3ja mínútna hraða. og var stöðugur 1% halla, Niðurstöður úr endurteknum mælingum af þríhliða ANOVA sýndu marktækan mun á á öndunartíðni á milli íþróttar og ákefðar (F(3,1. 39,4) = 3,7. p = 0,012), Einnig fanst marktækur munur í benum mælingum á milli kyns og ákefðar (F(4,4. 1,0) = 13,1. p < ,001) og íþróttar og ákefðar (F(4,4. 0,5) = 6,9. p < ,001) Í beinum mælingum og í óbeinum mælingum milli kyns og ákefðar (F(2.,7. 10718,8) = 2,8. p = ,048), Niðurstöður á öndunarrúmmáli eru í samfæmi við fyrri rannsóknir bæði fyrir beinar og óbeinar mælingar. hið sama gildir um beina mælingu á öndunarrúmmáli. Frekari rannsóknir eru nauðsynlegar fyrir þessa tilteknu tegund af óbeinum mælingum og skilgreining á einingu þeirra fyrir rúmmál er nauðsynleg.

Leitarorð: Öndunartíðni, öndunarrýmd, öndunarmagn, hámarkssúrefnisupptaka, VO_2max, hjól, hlaup, hreyfing.

Abstract

Recreational activities positively impact well-being both from mental and physical perspectives. The objectives of this study are to study the breathing frequency and volume as a percentage of VO_2max among recreational cyclists and runners, with both direct and indirect measurements and to compare the measurements between cycling and running. Graded exercise tests were taken on 47 participants, at the age 44.46 ± 10.08 (cyclists) and 46.45 ± 10.32 (runners), with a total of number 76 measurements. Participants wore a Cosmed K5 gas analysing device for breath-by-breath for direct measures and a TymeWear Smart T-Shirt for indirect measures. Graded exercise tests to time of exhaustion were done; cyclists started at 75W, increased by 25W every 3 minutes, and runners started at 5km/hr, increased by 1km/hr every 3 minutes at a steady incline of 1%. Results from repeated measures of three-way ANOVA showed there was a significant interaction between intensity and sport ($F(3.1, 39.4) = 3.7$, $p = 0.012$), for breathing frequency. A significant interaction for direct measures between intensity and sex and intensity and sport ($F(4.4, 1.0) = 13.1$, $p < .001$) and ($F(4.4, 0.5) = 6.9$, $p < .001$) respectively and only between intensity and sex for indirect measures ($F(2.7, 10718.8) = 2.8$, $p = .048$). The difference found in breathing volume is in line with previous studies both for direct and indirect measures, the same is for direct measure of breathing volume. However, further studies are needed for indirect measurements, a definition of their unit for volume is needed.

Keywords: Respiratory rate, ventilatory rate, breath rate, lung volume, lung capacity, tidal volume, maximum oxygen uptake, tidal volume, VO_2max, cycling, running, recreational.

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The journey for a young exercise scientist is just starting.

List of abbreviations

CM = Cardiac Muscle
CO = Cardiac Output
CPET = Cardiopulmonary Exercise Testing
EDV = End-Diastolic Volume
ESV = End-Systolic Volume
FEV= = Forced Expiratory Volume
FEV1 = One Second Forced Expiratory Volume
FVC = Forced Vital Capacity
HR = Heart rate
Kg = Kilograms
LT1 = First Lactate Threshold
LT2 = Second Lactate Threshold
Min = Minutes
Ml = Milliliters
Patm = Atmospheric Pressure at sea level
PCO_2 = Partial Pressure of Carbon Dioxide
pH = Potential of Hydrogen
Pip = Intrapleural Pressure
Pmax = Maximal power
PO_2 = Partial Pressure of Oxygen
Ppul = Intrapulmonary Pressure
RER = Respiratory Exchange Ratio
RER = Maximum Power Output
Rf = Respiratory Frequency
RPE = Rate of Perceived Exertion
RQ = Respiratory Quotient
SV = Stroke Volume
VCO_2 = Carbon Dioxide Output
VE = Minute Ventilation
VLamax = Maximal Lactate Production Rate
VO_2 = Oxygen Consumption
VO_2max = Maximal Oxygen Uptake
Vt = Tidal Volume
VT1 = First Ventilatory Threshold
VT2 = Second Ventilatory Threshold

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Introduction

Physical activity, recreation, and sports are popular around the world, and these activities have been shown to increase many different health benefits (Ham et al., 2009; Hulteen et al., 2017), both mental well-being and physical health (Oja et al., 2015) with studies that show evidence of beneficial impact from both a short period of physical activity and a long period of extended activity (Mahindru et al., 2023). Increased physical activity has been shown to increase life satisfaction and happiness in all life phases (An et al., 2020), physical activity can also increase sleep quality (Sejbuk et al., 2022) and help individuals who are suffering from insomnia with increased sleep (Ferreira et al., 2023). Physical activity can help with the fight against lifestyle conditions and diseases like obesity, high blood pressure, and heart-related diseases (Elagizi et al., 2020). The human cardiovascular system plays a crucial role in physical activity as a recreational activity (Hahn et al., 2017). Physical activity and recreational sports interact with physical health and social engagement and can differ in effort and time (Dishman et al., 1985). In the effort to increase physical performance and well-being, individuals often assess various measurable marks of their fitness and overall health, one of which is the use of smart wearable gadgets (Henriksen et al., 2018), maximal oxygen consumption (VO_2max) being a central point for many manufacturers and individuals (Düking et al., 2022).

The popularity of performance smart gadgets and online training platforms dedicated to sports training has been continuously growing over the last decades, in correlation with increased technology and the evolution of the Internet of Things (Wang et al., 2021). GPS technology became available to recreational athletes in the mid-2000s, allowing them to track their routes, keep pace, and measure distance, along with other performance variables (Vera-Rivera et al., 2019).

At the time, as these advancements were taking place, smartphones and mobile applications revolutionized the fitness landscape further (Li et al., 2023). Developers began creating apps specifically designed for runners and cyclists that offered training plans, tracking features, and social connectivity options (De Cock et al., 2023). Users could now engage in competition with friends. Participate in virtual races while sharing their accomplishments in real-time, creating a strong sense of community support and motivation (L. R. West, 2015).

The integration of these devices with platforms marked a significant milestone. Online platforms emerged for training, offering ecosystems where users could connect their devices, monitor their progress, and access tailored training programs. These platforms used algorithms and data analysis to offer insights assisting users in setting goals and optimizing their training routines (McIlroy et al., 2021). They also provided a range of multimedia content like video tutorials, interactive challenges, and expert-led classes to enhance the training experience (McIlroy et al., 2021; Tang et al., n.d.).

The impact of measures on physical activity and active recreation varied across different age groups and sexes. In a systematic review of temporal trends in physical activity by Knuth and Hallal (2009), with an exclusion of papers earlier than 1980, physical activity increased for adults in all countries, even though the total activity was defined as low worldwide. As a part of the marketing and the change of marketing trends (Kotler et al., 2019), Nike moved more to the digital area and founded the Nike Running Club, a digital platform to increase participation in recreational running or activity, where individuals could track their performance, participate in guided runs led by a professional, and interact socially with friends or club members (*Nike Run Club App. Nike.Com*, n.d.). A study by Rodrigues and colleagues (2021) found that social circles can impact physical activity through online platforms or, in other words, gamification. A similar online platform, Strava, is an online platform focusing on all activities both inside and outside, where you can track activity and segments, plan routes, and follow friends, clubs, or companies. This online platform is popular amongst recreational activists and pro athletes, with 95 million registered users (*Strava Revenue and Usage Statistics (2023)*, n.d.).

The COVID-19 pandemic has challenged all countries and their populations, causing a new way of living with lockdowns or other restrictions. This has resulted in decreased participation changes in settings and a greater decline in backcountry recreation compared to those living in regions. In other words, the individuals directly impacted by the pandemic have also faced the greatest difficulties in dealing with it (Arundell et al., 2022; Rice et al., 2020). After the restriction liftoff, athletes are excited to return to their sport, but many are still worried about their health (Martin et al., 2021). One example of companies encouraging physical activity during the pandemic is Peloton, which focuses on indoor running and indoor cycling through an online platform with over $607 million in revenue at its peak (Mayer, 2023). Even though the pandemic led to changes in physical activity (Dahlen et al., 2021), the use of online platforms continues to increase, which can lead to increased physical activity and increased motivation for recreational athletes (Stragier et al., 2018). This is just an example of how physical activity has become more common, as even during the lockdown during the pandemic, people did manage to look for alternative ways to promote health.

As we engage in physical activity or recreational sports events, our bodies try to adapt through a complex process to enhance their performance and promote health. This adaptation process is connected to all human systems (Widmaier et al., 2023). The improvements to the human system or intensity can be measured in many different ways, depending on the total work done over a period of time or the percentage of intensity during the activity, commonly used heart rate, speed, power, RPE, percentage of VO_2max, training thresholds (Carey et al., 2005; Day et al., 2004, 2004). Along with these methods, the breathing rate has been validated as a use of training intensity (Neary et al., 1995) and as a marker for exercise thresholds (Carey et al., 2005; Carrier et al., 2023). Even though the technology and access to smaller wearables have increased, as mentioned above, only a few smart wearables measure breathing frequency and breathing volume simultaneously to monitor physical activity during training. TymeWear is one of those few companies developing technology to monitor activity and measure lower and upper ventilatory thresholds by calculating breathing volume and frequency. In this literature review, we describe two human system processes, the respiratory and cardiovascular systems, as they play a significant role in this adaptation (McArdle et al., 2023).

Objectives

The objectives of this study are twofold:

a) To study the breathing frequency and breathing volume as a function of VO_2max among recreational cyclists- and runners, with direct and indirect measurements.
b) To compare the measurements between running and cycling using both direct and direct measures.

For direct measurements, the Cosmed K5 metabolic measurement system was used, and for indirect measurements, the TymeWear smart t-shirt was used. Cosmed K5 metabolic measurement system measures parameters like oxygen consumption (VO_2), carbon dioxide production (VCO_2), breathing frequency (Rf), tidal volume (Vt), heart rate (HR), and more. While the TymeWear smart t-shirt was used. The Cosmed K5 metabolic measurement system measures parameters like oxygen consumption (VO_2), -shirt measures breathing frequency (Rf), tidal volume (Vt), and heart rate (HR).

Extended literature review

The respiratory system

The respiratory system is a complex design and plays a vital role in the human body. It is the gateway for exchanging gases that sustain life beyond the organs involved. It extends into aspects of anatomy, biochemistry, and genetics (Levitzky, 2022). The primary function of this network is to take in oxygen from the atmosphere and expel carbon dioxide, which is crucial for cellular respiration and energy production. The system's design and adaptability allow it to navigate environmental challenges like surviving in changing environments and participating in different activities or sports (McKenzie, 2012). It acts as an interface where external and internal environments intersect, playing a part in physiological processes. From understanding how breathing works mechanically to exploring the intricacies of airway anatomy and studying molecular mechanisms related to gas transport – all contribute to unraveling the complexity of this multifaceted system (Kenney et al., 2015; McKenzie, 2012; J. B. West & Luks, 2016). In the following subchapters, each part of the respiratory system is described, and the role is explained.

Table 1. The Upper Respiratory System.

Structure	**Distinctive features**	**Function**
Nose	External portion is supported by bone and cartilage. Internal nasal cavity is divided by midline nasal septum and lined with mucosa.	Produces mucus, filters, warms and moistens incoming air, resonance chamber for speech.
Paranasal sinuses	Mucosa lined and air filled cavities in cranial bones surrounding nasal cavity.	Lighten skull. Warms, moisten and filter incoming air in some way.
Pharynx	Passageway connecting nasal cavity to larynx and oral cavity to esophagus. Has three subdivisions: Nasopharynx, oropharynx and layngopharynx	Passageway for both air and food.

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Nasal Cavity

The internal part of the nose and its posterior connect to the Pharynx. During regular breathing, air enters the cavity by passing through the nostrils. The nasal cavity is separated into two parts by a structure called the nasal septum. The front part of the septum is made up of cartilage, while a combination of the bone and the perpendicular plate of the ethmoid bone forms the back part (Marieb & Hoehn, 2023). The back part of the nasal cavity connects seamlessly with the section of the pharynx via openings at the back called posterior nasal apertures. Within the nasal cavity is an area known as the nasal vestibule, which is covered by skin that contains sweat glands as well as numerous hair follicles. These hairs serve as a filter, helping to trap particles from the air we breathe. The rest of the nasal cavity is lined with olfactory mucosa and respiratory mucosa lines containing seromucous glands (Widmaier et al., 2023). The paranasal sinuses are located in the frontal, sphenoid, ethmoid, and maxillary bones, which lighten the skull and are held to warm up and moisten the inhaled air.

The Pharynx

Usually referred to as the throat, it is the second part of the pulmonary system and is divided into three regions: Nasopharynx, oropharynx, and laryngopharynx. (Marieb & Hoehn, 2023) The nasopharynx location is posterior to the nasal cavity, inferior to the sphenoid bone, and superior to the level of the soft palate. Due to its location and lies about the point where nutrition enters the body, the only role of the nasopharynx is an air pathway. It has a soft valve or palate that closes (the uvula moves superiorly) the nasopharynx as a preventional mechanism for food to enter the nasal cavity (Levitzky, 2022). The Oropharynx is located posterior to the oral cavity. It can pass air from nasal and oral cavities to the Laryngopharynx. The Oropharynx is also the pathway for receiving nutrition and passing it along to the esophagus in the digestive system during the initial stages of swallowing. The third part of the Pharynx, the Laryngopharynx, has the same role as the second region of the pharynx, the oropharynx; it helps air move from the nose and mouth to the larynx and into the trachea. This section also plays a role in protecting the respiratory tract from foreign particles and germs (Marieb & Hoehn, 2023). The laryngopharynx acts as a passage for air and food when we ingest or drink. To prevent choking or inhaling food, a flap-like structure called the epiglottis ensures that food goes down the esophagus and enters the trachea. This helps with digestion. The voice of the human body is produced within the vocal folds that are located below the epiglottis within the larynx (Marieb & Hoehn, 2023; J. B. West & Luks, 2016).

Table 2. The Lower Respiratory System.

Structure	Distinctive features	Function
Larynx	Connects pharynx to trachea. Cartilage framework and dense connective tissue. Glottis can be closed by epiglottis or vocal folds.	Air passageway. Prevents food from entering the lower respiratory
Trachea	Flexible tube from the larynx to the two main bronchi. C-shaped cartilages that are incomplete posteriorly where connected by trachealis.	Air passageway. Cleans, warms and moisten incoming air.
Broncial tree	Consists of right and left bronchi, which subdivide within the lungs to from lobar and segmental bronci and bronchioles. Bronciolar walls lack cartilage but contain completa layer of smooth muscle. Constriction of this muscle umpedes exporation.	Air passageways connecting trachea with alveoli. Cleans, warms and moistens incoming air.
Alveoli	Microscopic chambers at termini of bronchial tree. Walls of simple squamous epithelium overlie thin basement membrane. External surfaces are intimately associated with pulmonary capillaries.	Main sites of gas exchange.
	Special alveolar cells produce surfactant.	Surfactant reduces surface tension; helps prevent lung collapse.
Lungs	Paired composite organs that flank mediastinum in thorax. Composed primarily of alveoli and respiratory passageways. Stroma is elastic connective tissue, allowing lungs to recoil passively during expiration.	House respiratory passages smaller than the main bronchi.
Pleurae	Serous membranes. Parietal pleura lines thoracic cavity; visceral pleura covers external lung surfaces	Produce libricating fluid and compartmentalize lungs.

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The Trachea

It connects the larynx to the bronchi. It is a flexible 10 – 12cm long tube with reinforced cartilage rings to provide structural support and keep it from collapsing and closing during inhalation. The inner lining of the trachea is covered with a mucous membrane that contains ciliated pseudostratified columnar epithelial cells (J. B. West & Luks, 2016). The cilia and mucosa are crucial in trapping and moving particles and debris away from the lungs. Within the wall structure of the Trachea is a muscular layer with the ability to contract and adjust the diameter of the Trachea, causing expired air to rush upwards from the lungs with greater force and at a speed of up to 160km/hr (Lumb & Thomas, 2021; Marieb & Hoehn, 2023). As air passes through the trachea, it undergoes warming and humidification, an essential factor for optimising air conditions before it reaches the lung tissue.

The Bronchi and its Subdivisions

From the Trachea, the air passageway is through a pattern that branches up to 23 times (Marieb & Hoehn, 2023) and is called the Bronchial Tree. It´s divided from the trachea to the right and left main bronchi. The right main bronchus is wider, shorter, and more vertical than the left, and due to its structure, this is where inhaled objects usually get. Inside the lungs, the main bronchus is subdivided into the lobar and the secondary bronchi, three on the right and two on the left, each supplying the lung lobe. The lobar bronchi then branch into this order, the segmental (tertiary) bronchi, which repeatedly divide into smaller and smaller bronchi (J. B. West & Luks, 2016). Passages smaller than 1 mm in diameter are called bronchioles, and those less than 0.5mm in diameter are called terminal bronchioles (Marieb & Hoehn, 2023).

The wall structure in the trachea and the main bronchi have similarities. There are changes in the conducting tubes of the bronchi. As we move towards the bronchioles, the cartilage rings are replaced by patches or plates (Broaddus et al., 2022). At this point, there is no supportive cartilage in the tube walls. However, elastic fibers can be found throughout the tree. The mucosal epithelium becomes thinner as it transitions from a pseudostratified shape to a columnar shape and eventually to a simple cuboidal shape in the terminal bronchioles. The number of mucus-producing cells and cilia is limited in the bronchioles. Therefore, most of the debris located at or below the level of bronchioles needs to be cleared by macrophages in the alveoli. As these passageways decrease in size, smooth muscle proportion increases within their walls. The bronchioles have a layer of smooth muscle and no supporting cartilage (which could hinder constriction). This arrangement allows for resistance to air passage under certain circumstances and exercise (Marieb & Hoehn, 2023).

Respiratory Zone Structures

The respiratory zone, characterized by alveoli air sacs, begins when the terminal bronchioles merge into bronchioles within the lungs. From these bronchioles alveoli are scattered. The respiratory bronchioles are then transitioned into ducts with walls of smooth muscle cells, connective tissue fibers, and protruding alveoli arranged diffusely. These alveolar ducts lead to clusters of alveoli called alveolar sacs or saccules (Moini, 2020).

The lungs contain 300 million gas-filled alveoli that comprise a portion of lung volume and provide a large surface area for gas exchange. The walls of the alveoli mainly consist of a layer made up of epithelial cells known as type I alveolar cells. A basement membrane envelops these cells. Despite being very thin, it's difficult to grasp how thin they are; they're 15 times thinner than a sheet of paper (Marieb & Hoehn, 2023). The respiratory membrane, consisting of the alveolar walls and their basement membranes, is crucial in facilitating gas exchange through simple diffusion. A barrier measuring 0.5 micrometers allows oxygen (O_2) to move from the alveolus into the blood while carbon dioxide (CO_2) exits the blood and enters the gas-filled alveolus (Broaddus et al., 2022).

Surrounding the alveoli are fibers similar to those found around bronchial trees. The presence of pores between alveoli helps maintain equal air pressure throughout the lungs and provides alternative pathways for air in case bronchi collapse due to any disease. Despite exposure to microorganisms, these surfaces within the alveoli typically remain sterile due to various defense mechanisms. These "end" structures' unique structure necessitates preventing dead macrophage accumulation. Most of the macrophages are carried away by air currents in regions, ultimately reaching our pharynx. As a result, more than 2 million alveolar macrophages are ingested every hour through this process (Marieb & Hoehn, 2023; Moini, 2020).

Pressure in the Thoracic Cavity

Atmospheric pressure at sea level (Patm) is 760mm of mercury or 1 atmosphere. Negative respiratory pressure values indicate pressures below atmospheric pressure, while positive values indicate above (Lumb & Thomas, 2021). There are two types of pressure within the thoracic cavity: Intrapulmonary Pressure (Ppul) and Intrapleural Pressure (Pip).

Intrapulmonary pressure (Ppul) refers to the pressure inside our alveoli. It fluctuates with our breathing cycle and matches up with the pressure. Intrapleural pressure (Pip), is the pressure found within the cavity, which remains 4 mmHg lower than Ppul throughout breathing phases. It consistently maintains a value. Negative intrapleural pressure occurs due to opposing forces at play within our thorax. Lung elasticity and surface tension caused by fluid tend to collapse our lungs. Are counteracted by the elasticity of our chest wall. This delicate balance is maintained through forces between the parietal and visceral pleurae, with only minimal pleural fluid needed to prevent lung collapse (Levitzky, 2022; Lumb & Thomas, 2021; Marieb & Hoehn, 2023).

Transpulmonary Pressure and Pulmonary Ventilation

To prevent the collapse of the lungs and maintain a lung air space, the lungs rely on the pressure produced with the difference between pulmonary pressure and intrapleural pressure. This pressure, influenced by pressure, highlights the strong connection between the lungs and the thorax wall. Pulmonary ventilation involves inspiration and expiration driven by changes in thoracic cavity volume following Boyle's law (J. B. West, 1999). By altering the volume of the thoracic cavity through actions, pressure changes occur, allowing for equalization of air pressure. During inspiration, the diaphragm and external intercostal muscles are primarily involved, while deep inspirations engage accessory muscles to increase thoracic volume during activities like exercise or specific pulmonary diseases (Levitzky, 2022).

In individuals, expiration is typically a process driven by lung elasticity (Broaddus et al., 2022). As the inspiratory muscles relax, the rib cage. The lungs recoil, resulting in decreased thoracic and intrapulmonary volumes. This compression of alveoli increases pressure, expelling gases from the lungs. Forced expiration is a process that involves the contraction of wall muscles, especially oblique and transverse muscles. This action increases pressure, pushing organs against the diaphragm and depressing the rib cage. Internal intercostal muscles assist in depressing the rib cage and reducing thoracic volume. Precise regulation of airflow during expiration relies on accessory muscles that are essential for activities such as singing, where coordination among muscles is crucial, for forced expiration. Air movements that are not related to respiration, such as coughing, sneezing, crying, laughing, hiccupping, and yawning, can impact the airflow in the lungs. While some of these movements are voluntary, others, like sneezing and hiccups, happen reflexively (Marieb & Hoehn, 2023).

Factors like airway resistance and alveolar surface tension influence pulmonary ventilation. Airway resistance depends on the diameter of the conducting tubes. Diameters. Increased branching reduces resistance. Alveolar surface tension is countered by surfactant produced by type II alveolar cells (Moini, 2020). This surfactant helps minimize the energy required to expand the lungs and prevents collapse. Lung compliance refers to how healthy lungs can stretch. It indicates how much the lung volume changes in response to a given alteration in pressure (the difference between pressure and intrapleural pressure). Higher lung compliance suggests that lungs can be easily inflated at a transpulmonary pressure. Lung compliance is influenced by tissue distensibility and alveolar surface tension. Healthy lungs have compliance due to their tissues and low alveolar surface tension maintained by surfactant production (Ionescu, 2013).

Respiratory Volumes

Four respiratory volumes can relate to regular breathing and exercise: Tidal volume, inspiratory reserve volume, expiratory reserve volume, and residual volume. These volumes and capacities, like inspiratory capacity, functional residual capacity, vital capacity, and total lung capacity, provide information about how our system functions. Any abnormalities in these measurements can indicate disorders (Broaddus et al., 2022; Levitzky, 2022). During normal breathing, about 500ml of air moves through the lungs in each breath. This respiratory volume is called Tidal Volume. By controlled and forced breathing, the human body can inspire beyond the tidal volume of 2100 to 3200ml, called inspiratory reserve volume (IRV), and the expiration part, called expiratory reserve volume (ERV), usually is around 1000 to 1200ml. The lung's remaining air is called residual volume (RV) and is about 1200ml in a healthy individual (Lumb & Thomas, 2021; McArdle et al., 2023).

Pulmonary Function Tests

Pulmonary function tests help to evaluate function by distinguishing between restrictive pulmonary diseases. Obstructive diseases increase airway resistance, leading to lung hyperinflation, while restrictive diseases limit lung expansion (Albouaini et al., 2007; Broaddus et al., 2022). We can gather information by evaluating how the gas enters and leaves the lungs with pulmonary function tests: Forced vital capacity (FVC) measures the volume of gas expelled when an individual takes a breath and then forcefully exhales as much air as possible as quickly as possible (Levitzky, 2022). Forced expiratory volume (FEV) determines the amount of air expelled during time intervals within the FVC test. For instance, FEV1 represents the volume exhaled within the second. Healthy individuals typically exhale around 80% of their FVC within one second (Levitzky, 2022). However, those with the disease tend to exhale significantly less than 80% of their FVC in one second. In contrast, individuals with restrictive disease can still manage to exhale 80% or more of their FVC in one second despite having a reduced overall FVC (Albouaini et al., 2007).

Alveolar ventilation

Alveolar ventilation (AVR) refers to the amount of gas entering or exiting the tract within one minute (McArdle et al., 2023; J. B. West & Luks, 2016). In breathing, healthy individuals typically have minute ventilation of around 6 liters per minute (calculated by multiplying 500 milliliters per breath by 12 breaths per minute). However, during exercise, this value can increase significantly. Reach up to 200 liters per minute. While minute ventilation serves as a measure for evaluating the efficiency of the minute rate (VE), it provides a better indication of effective ventilation. AVR is the volume of fresh air that reaches the alveoli during a specific time interval and is available for gas exchange in the blood. AVR is calculated with the following equation; AVR = Frequency (breath/min) × (Volume (ml/min - Dead Space (ml/breath))

In individuals, AVR is typically around 12 breaths per minute multiplied by the difference between 500 ml and 150 ml per breath, resulting in an approximate value of 4200 ml/min. It's worth noting that since anatomical dead space remains constant for an individual, increasing the volume of each inhalation (breathing depth) has an impact on enhancing AVR and gas exchange compared to raising the ratio (Marieb & Hoehn, 2023; J. B. West & Luks, 2016).

The air reaching the exchange sites decreases significantly when someone breathes rapidly and shallowly, leading to a drop in AVR. Additionally, the speed at which a person breathes effective ventilation approaches zero as the tidal volume reaches the space value (Marieb & Hoehn, 2023).

External Respiration

External respiration transforms red blood in the pulmonary circuit into scarlet blood for distribution throughout the body. Oxygen (O_2) binds rapidly to hemoglobin during this process, while carbon dioxide (CO_2) is exchanged swiftly. Several factors influence respiration, including pressure gradients, properties of the respiratory membrane, and ventilation-perfusion coupling (Marieb & Hoehn, 2023; Plowman & Smith, 2014).

The exchange of O_2 and CO_2 across the membrane occurs due to their partial pressure gradients. Despite O_2 having a gradient, equal exchange occurs because CO_2 has solubility. The membrane thickness (0.5 to 1 μm) contributes to gas exchange. To ensure gas exchange, ventilation (the movement of air) must be coupled with perfusion (blood flow), which is regulated by mechanisms responding to PO_2 (partial pressure of oxygen) and PCO_2 (partial pressure of carbon dioxide). PO_2 controls arteriolar diameter to regulate perfusion, while PCO_2 influences bronchiolar diameter to control ventilation (Clark, 2022; Levitzky, 2022).

The impact of oxygen and carbon dioxide levels on blood flow

Insufficient air supply leads to decreased oxygen levels (PO_2), narrowing arteries and directing blood flow towards areas with better air supply (Des Jardins, 2020; Marieb & Hoehn, 2023). When the air sacs (alveoli) are well-ventilated, they expand, causing the pulmonary arteries to widen and allowing more blood to flow through them. In areas where carbon dioxide (CO_2) levels are high, the bronchioles expand to eliminate CO_2 from the body, while in areas where CO_2 levels are low, they constrict. The changes in the diameter of both bronchioles and arterioles help maintain a balance between air exchange in the alveoli and blood flow through them (Des Jardins, 2020).

Internal respiration

During respiration, gases are exchanged within capillaries located in body tissues. This process occurs with reversed concentration gradients compared to respiration. Oxygen moves from capillaries into tissues, while carbon dioxide moves from tissues into capillaries. As venous blood returns to the heart after this gas exchange process, it typically has an oxygen level (PO_2) of around 40 mmHg. A carbon dioxide level (PCO_2) is around 45 mmHg. Transportation of oxygen occurs primarily through hemoglobin found within blood cells or by dissolving into plasma (Marieb & Hoehn, 2023).

1.5% of the oxygen dissolves in water due to its solubility. However, hemoglobin overcomes this limitation by carrying 98.5% of the oxygen in a chemical combination (Des Jardins, 2020). This means there is no need for a level of oxygen pressure (PO_2) or an increase in output. Hemoglobin, which consists of four chains connected to iron-containing heme groups, forms an association with oxygen known as oxyhemoglobin. The loading and unloading of oxygen are regulated by factors such as PO_2, temperature, blood pH, PCO_2, and 2,3-bisphosphoglycerate (BPG), as demonstrated by the oxygen hemoglobin dissociation curve (Marieb & Hoehn, 2023).

The influence of carbon dioxide (CO_2) on blood pH

Carbon dioxide is transported in the blood through three mechanisms: dissolved in plasma, chemically bound to hemoglobin as carbaminohemoglobin, and bicarbonate ions in the plasma(Levitzky, 2022; Marieb & Hoehn, 2023). The bicarbonate buffer system present in blood cells and plasma plays a role in maintaining stable blood pH levels. The Haldane effect, influenced by blood oxygenation levels, connects oxygen dissociation from hemoglobin with increased carriage of CO_2. Changes in rate or depth can rapidly impact blood pH by altering acid levels (Moini, 2020). This respiratory adjustment serves as a mechanism for regulating blood pH and contributes to maintaining acid-base balance.

Hypoxia

When body tissues do not deliver oxygen, it is called hypoxia. It can be classified based on its cause (Levitzky, 2022). Insufficient or abnormal hemoglobin levels can lead to hypoxia, while impaired blood circulation causes hypoxia. Histotoxic hypoxia occurs when cells are unable to utilize oxygen despite its delivery. On the other hand, reduced arterial PO_2 indicates hypoxemic hypoxia. One particular and dangerous form of hypoxemia is carbon monoxide poisoning, as it can use oxygen for binding sites on hemoglobin.

Interestingly, this type of poisoning may not exhibit signs of hypoxia (Clark, 2022; Moini, 2020). Treatment often involves hyperbaric therapy, which provides 100% oxygen until carbon monoxide is eliminated from the body. Some factors can affect how we breathe in terms of rate and depth. The centers' stimulation of motor neurons plays a role in determining the depth of our inhalation. When these centers are more stimulated, muscle contractions occur, leading to force in breathing.

On the other hand, the duration of activity in the center influences our respiratory rate. Our body's demands can cause changes in both the depth and rate of our breathing. This is regulated by the medulla and pons, which respond to stimuli (Moini, 2020).

Chemical factors also play a role in controlling our breathing. Changes in CO_2, O_2, and H+ levels in the blood affect our breathing patterns. Chemoreceptors located centrally in the brainstem and peripherally in areas like the arch and carotid arteries respond to these fluctuations (Marieb & Hoehn, 2023). Among these factors, CO_2 influences our breathing. It is carefully regulated to maintain PCO_2 40 mmHg. When CO_2 levels rise, central chemoreceptors are stimulated, increasing both breath- depth and rate.

Moreover, elevated levels of blood CO_2 (known as hypercapnia) trigger chemoreceptors due to an accumulation of CO_2 in the brain. This response increases breath depth and rate to enhance ventilation for expelling CO_2 from our system. Even a slight increase in PCO_2 can impact boosting alveolar ventilation (Des Jardins, 2020; Marieb & Hoehn, 2023).

The impact of oxygen levels (PO_2), on our body

When the oxygen level in our arteries drops below 60 mmHg, the peripheral chemoreceptors in the carotid bodies become highly responsive. This triggers an increase in respiration as a way to address the hypoxia. However, excessive ventilation can lead to hypocapnia, producing high blood pH (Marieb & Hoehn, 2023). Regardless of carbon dioxide (CO_2) and oxygen (O_2) levels, changes in arterial pH can affect both the rate and rhythm of respiration. In response to decreasing pH, peripheral chemoreceptors amp up ventilation to remove CO_2 and restore proper pH levels. This compensatory mechanism plays a role in maintaining acid-base balance (Des Jardins, 2020; Levitzky, 2022).

Influence from brain centers

Emotions, pain, and temperature alterations impact our centers through signals sent by the hypothalamus and limbic system. The hypothalamus helps regulate responses like gasping for breath, breath holding, increased respiratory rate, or even temporary cessation of breathing based on stimuli (Dahlen et al., 2021; Levitzky, 2022). While involuntary regulation of breathing is primarily governed by the brainstem, we also have control over our breathing rate and depth thanks to signals from our cerebral motor cortex. This allows us to adjust our breathing patterns based on decisions. However, it's important to note that when critical levels of CO_2 are reached in our body, involuntary mechanisms take precedence over control (Marieb & Hoehn, 2023).

Exercise

During activity, the respiratory system reacts to changes in the intensity and duration of the exercise. The muscles involved in the activity require an amount of oxygen (O_2). Release a substantial amount of carbon dioxide (CO_2). This results in increased ventilation, which can be 10 to 20 times higher during exercise (Des Jardins, 2020; Levitzky, 2022). This increased ventilation, known as hyperpnea, responds to metabolic demands. In hyperpnea, respiratory changes do not significantly impact the levels of O_2 and CO_2 in the blood, even though the body acts with changes in the respiratory. The increase in ventilation during exercise is unrelated to changes in PCO_2 levels or decreasing levels of oxygen pressure (PO_2) and pH in the blood for two reasons (Marieb & Hoehn, 2023):

1. At the beginning of exercise, ventilation sharply increases and then gradually rises until it reaches a steady state. When exercise stops, ventilation suddenly declines, followed by a return to pre-exercise levels.
2. Despite variations in levels, arterial PCO_2 and PO_2 remain surprisingly stable during exercise. PCO_2 may fall below levels, while PO_2 may increase slightly due to respiratory adjustments.

The sudden increase in breathing when exercise begins is often explained by three factors related to the system (Marieb & Hoehn, 2023):

1. Psychological factors, like being aware that exercise is about to start.
2. The activation of both muscle and respiratory centers in the brain.
3. Proprioceptors stimulate moving muscles, tendons, and joints that reach the centers.

The subsequent gradual increase and leveling off of breathing depends on how quickly carbon dioxide (CO_2) is delivered to the lungs, often referred to as "CO_2 flow" (Levitzky, 2022). The rise in acid levels during exercise happens because of respiration, not breathing problems. Both the amount of air reaching the alveoli (ventilation) and blood flow through the lungs (perfusion) are well-matched during exercise and rest. This difference can be attributed to limitations in output or the inability of muscles to consume more oxygen (Widmaier et al., 2023).

Respiratory adjustments during exercise, referred to as hyperpnea, depend on the intensity and duration of the exercise (Des Jardins, 2020). Ventilation increases significantly but efficiently maintains levels of PCO_2 and PO_2. Factors such as stimuli, simultaneous motor activation, and proprioceptor input contribute to the rise in ventilation at the beginning of exercise. Despite acid levels, this increase in ventilation is not attributed to respiratory limitations but instead reflects constraints related to cardiac output or muscle oxygen consumption limits. Inhaling oxygen does not assist oxygen-starved muscles during exercise because the deficiency lies within the muscles themselves rather than in the lungs (Marieb & Hoehn, 2023; Moini, 2020).

Cardiovascular system

The human cardiovascular system is crucial in sustaining every organ and tissue. It consists of the heart, blood vessels, and blood working together to ensure the circulation of oxygen, nutrients, and hormones while eliminating waste products (Moini, 2020). Beyond its pumping action, this intricate network involves physiological processes such as regulating blood pressure, facilitating immune cell transportation, and maintaining hemodynamic dynamics. The cardiovascular system is an aspect of anatomy and physiology showcasing the body's ability to adapt and maintain balance (Smith & Fernhall, 2023). At the center of it all is the heart - an organ with rhythmicity that propels blood throughout the circulatory system. The extensive network of blood vessels, including arteries, veins, and capillaries, spans the body to transfer and deliver oxygen and nutrients to cells and tissues. In this part of the literature review, the cardiovascular system and its role in exercise and activities like recreational running and cycling are investigated.

Table 3. The components and function of components in the cardiovascular system.

Component	Function
Heart	
Atria	Chambers through which blood flows from veins to ventricles. Atrial contraction adds to ventricular filling but is not essential for it.
Ventricles	Chambers whose contractions produce the pressures that drive blood through the pulmonary and systemic vascular systems and back to the heart.
Vascular system	
Arteries	Low-resistance tubes conduct blood to the various organs with little loss in pressure. They also act as pressure reservoirs for maintaining blood flow during ventricular relaxation.
Arterioles	Major sites of resistance to flow; responsible for regulating the pattern of blood-flow distribution to the various organs; participate in the regulation of arterial blood pressure.
Capillaries	Major sites of nutrient, gas, metabolic end product, and fluid exchange between blood and tissues.
Venules	Capacitance vessels are sites of migration of leukocytes from the blood into tissues during inflammation and infection.
Veins	Low-resistance, high-capacitance vessels carry blood back to the heart. Their blood capacity is adjusted to facilitate this flow.
Blood	
Plasma	Liquid portion of blood that contains dissolved nutrients, ions, wastes, gases, and other substances. Its composition equilibrates with that of the interstitial fluid at the capillaries.
Cells	Includes erythrocytes that function mainly in gas transport, leukocytes that function in immune defenses, and platelets (cell fragments) for blood clotting.

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The Heart

The heart is a vital part of the cardiovascular system and controls blood flow through the veins to organs and muscles (Marieb & Hoehn, 2023). The right side of the heart receives oxygen (O_2), which is poor blood from the body tissues, and pumps it to the lungs for gas exchange to pick up more oxygen (O_2) and dispel carbon dioxide (CO_2). Blood is transported through the veins to the lungs and back in a pathway that forms the pulmonary circuit (Aaronson et al., 2020). The left side of the heart receives oxygen (O_2) rich blood from the lungs and transports it to the organs and body tissue through veins in a pathway that forms the systemic circuit. The heart has two receiving chambers: The right atrium receives oxygen (O_2) poor blood from the systemic circuit, and the left atrium receives oxygen (O_2) rich blood from the pulmonary circuit (Aaronson et al., 2020). To deliver the blood, it has two pumping chambers: the right ventricle that pumps oxygen (O_2) poor blood to the pulmonary circuit and the left ventricle that pumps oxygen (O_2) rich blood to the systemic circuit.

Blood flow

The flow of blood within the cardiovascular system is managed by the heart. Cardiac output (CO) is defined as the amount of blood pumped out by each ventricle in one minute measured in liters per minute (L/min) (Harris, 2023). Two factors affect the cardiac output: Heart rate (HR) as the heart beats per minute (bpm) and stroke volume (SV), as the amount of blood pumped out of each ventricle in each beat (L/min). The formula used is as follows: CO (Cardiac output) = HR (Heart Rate) x SV (Stroke Volume).

Cardiac output is highly variable and changes markedly in response to increased and decreased demands, as when we exercise or relax (Aaronson et al., 2020).

Stroke volume (SV)

Stroke volume (SV) refers to the amount of blood pumped out by a ventricle with each heartbeat. It is determined by the difference between end volume (EDV), which represents the amount of blood in the ventricle during relaxation, and end volume (ESV), which is the amount of blood remaining after contraction (Harris, 2023). Normally, EDV can increase due to factors such as prolonged ventricular relaxation or increased venous pressure, and ESV depends on arterial blood pressure and the strength of ventricular contractions. Three factors play a role in SV, ESV, and EDV: preload, contractility, and afterload. Preload refers to stretching heart muscle cells before they contract and directly affects SV. According to the Frank-Starling law of the heart, there is a connection between increased blood filling before each contraction and a higher SV (John Solaro, 2007). Exercise and longer filling time both contribute to an increase in EDV.

During exercise, factors like increased activity in our system and actions performed by skeletal muscles enhance venous return, leading to higher EDV and SV. Still, conditions such as heart rates or severe blood loss result in low venous return, which reduces EDV (Marieb & Hoehn, 2023). Consequently, weaker contractions occur, leading to an SV. In addition to EDV, factors like contractility also influence SV by determining how strong muscle contraction will be. Afterload is the pressure that the ventricles need to overcome to pump blood against resistance from blood vessels. In individuals, afterload remains relatively stable. However, in cases of hypertension, afterload hampers the efficiency of function, resulting in an increase in end volume (ESV) and a decrease in stroke volume (SV).

The autonomic nervous system plays a role in regulating heart rate. When stressors trigger activation, norepinephrine is released, which speeds up heart rate and enhances contractility. Parasympathetic activity counteracts these effects by reducing heart rate after periods of stress. Chemical regulation involves hormones like epinephrine and thyroxine influencing heart rate and contractility (Aaronson et al., 2020; Harris, 2023). Additionally, maintaining a balance of ions and electrolytes is crucial for heart function. Heart rate can also be influenced by factors such as age, sex, exercise level, and body temperature. Exercise increases heart rate through activation; trained athletes may have lower resting heart rates. Heat and cold directly impact heart rate as higher metabolic rates increase heart rate while colder temperatures decrease it.

The Vascular System

The vascular system is the transport link from the heart to human tissue. It consists of arteries, arterioles, capillaries, venules, and veins. Arteries can be divided into three groups by size and function: Elastic arteries, muscular arteries, and arterioles (Smith & Fernhall, 2023).

Elastic arteries, which are located near the heart, like the aorta and its main branches, have walls. These arteries, ranging in diameter from 2.5 cm to 1 cm, are the largest and most flexible among all blood vessels. Often called conducting arteries (Aaronson et al., 2020), they act as pathways with resistance, efficiently transporting blood from the heart to sized arteries. These arteries contain an amount of elastin in their tunica media layer compared to other types of vessels. Forms concentric sheets that resemble structures and are situated between layers of smooth muscle cells (Aaronson et al., 2020). Although elastic arteries also have muscle tissue, they are not very active in narrowing or constricting. Functionally speaking, they can be considered tubes (Smith & Fernhall, 2023). As pressure reservoirs, elastic arteries. Contract with each heartbeat when the heart pumps out blood. This unique property ensures a flow of blood rather than the pulsating rhythm associated with the heartbeat itself. In conditions such as atherosclerosis, where blood vessels become stiff, blood flow becomes more sporadic, similar to water flowing through a rubber hose. The loss of elasticity prevents the recoil of walls, resulting in sudden changes in water flow when pressure is altered (Harris, 2023).

Muscular Arteries

In the muscular arteries, the elastic arteries transition into distributing arteries, which are responsible for carrying blood to specific organs in the body. These distributing arteries are various sizes, ranging from the length of a little finger to the size of a pencil lead. Regarding proportions, muscular arteries have the thickest tunica media among all blood vessels. The tunica media of arteries has smooth muscle and less elastic tissue than elastic arteries (Aaronson et al., 2020; Smith & Fernhall, 2023). This makes them more active in narrowing blood vessels (vasoconstriction) and less likely to stretch. Notably, muscular arteries have a membrane on both sides of their tunica media.

Arterioles

Arterioles, which are the arteries, have a diameter that ranges from 0.3 mm to 10 µm. In arterioles, all three layers of tissue are present. The middle layer (tunica media) is mainly made up of smooth muscle with a few elastic fibers scattered throughout. Smaller arterioles connect to the beds and mainly consist of a layer of smooth muscle cells that wrap around the inner lining (endothelium). Changes influence the regulation of blood flow into beds on a minute-to-minute basis in diameter. This diameter can vary in response to signals, hormonal factors, and local chemical cues (Marieb & Hoehn, 2023). Arterioles, known as resistance vessels, play a role in adjusting blood flow resistance by changing their diameter. When arterioles constrict, they divert blood from the tissues they supply; conversely, dilation significantly increases blood flow into the capillaries (Harris, 2023).

Capillaries

Capillaries, the blood vessels, have thin walls composed of a slim tunica intima surrounded by a basement membrane. In some cases, a single endothelial cell forms the circumference of the wall. Pericytes, which resemble spider-shaped cells, are strategically positioned along capillaries. These contractile stem cells create vessels or scar tissue, stabilizing capillary walls and regulating the capillary permeability (Marieb & Hoehn, 2023). With a length of 1 mm and a lumen diameter of 8–10 μm, capillaries are just wide enough for red blood cells to pass through in the file. While most tissues have a supply of capillaries, there are exceptions, like vascularized tendons and ligaments, that consequently have limited healing capacity. Like back alleys and driveways compared to arteries and arterioles, capillaries act as direct access routes to every cell in the body (Harris, 2023). Their strategic positioning and thin walls make them ideal for exchanging gases, nutrients, and hormones between the bloodstream and interstitial fluid.

Structurally speaking, there are three types of capillaries: ones that have no gaps or openings between cells, fenestrated ones that possess pores or fenestrations, and sinusoidal ones that are wider, with larger gaps allowing for more substantial exchange (Marieb & Hoehn, 2023).

Three types of blood vessels have connections between their cells. These connections, known as junctions, often have gaps called intercellular notches, which allow some fluids and small particles to pass through. Some capillaries have pathways that enhance the movement of fluids. Capillaries form networks called beds, where blood flows from arterioles to venules. These capillary beds are part of the microcirculation system. A terminal arteriole is divided into 10 to 20 capillaries, creating a bed. The capillaries then connect to a postcapillary venule. The flow of blood through the bed is controlled by the diameter of the arteriole and other upstream arterioles. Chemical conditions in the area and nerve fibers that regulate blood vessel size determine how much blood enters a capillary bed (Harris, 2023). This allows for adjustments based on conditions in different parts of the body or organs.

For example, during digestion, blood circulates through the capillaries in organs to receive nutrients from the digestion process (Buss et al., 2012). However, between meals, these pathways are mostly closed off. During exercise, blood is redirected from organs toward the capillary beds in skeletal muscles, where it is immediately needed for energy production. In membranes like mesenteries, some arrangements include a direct connection between a terminal arteriole and a postcapillary venule known as a vascular shunt (Eldridge et al., 2004). This shunt allows blood to bypass capillaries.

Furthermore, each genuine capillary is encircled by a band of muscle known as a sphincter. This muscular cuff acts as a gatekeeper controlling the blood flow into the capillary based on the chemical conditions present locally.

The Human Blood

The human blood serves a number of functions, all as a part of a transport system, regulating blood levels in the body and protecting it. The transport function in the blood includes the delivery of oxygen from the lungs and nutrients from the digestive system to every cell in the body. It transports waste products generated by cells to elimination sites. Carbon dioxide (CO_2) is removed through the lungs, while nitrogenous wastes are excreted through the kidneys in urine. It also carries hormones produced by endocrine organs to their intended target organs (Aaronson et al., 2020; Smith & Fernhall, 2023). Some of the roles of blood during exercise are:

Oxygen Transportation: Blood plays a crucial role during exercise in carrying oxygen (O_2) from the lungs to the muscles. This is done by hemoglobin in blood cells, which binds with oxygen in the lungs and transports it through the bloodstream to cells over the body.

Removal of Carbon Dioxide: Blood also plays a role in eliminating carbon dioxide (CO_2), a byproduct of muscle energy metabolism. It transports CO_2 from the muscles and takes it to the lungs so that it can be exhaled (Aaronson et al., 2020).

Delivery of Nutrients: Blood delivers nutrients like glucose and fatty acids to fuel muscle energy production. These nutrients are crucial for muscle contraction and overall performance during exercise (McArdle et al., 2023)

Body Temperature Regulation: Blood helps regulate body temperature while exercising. It carries heat generated by working muscles towards the skin surface, facilitating heat dissipation through sweating and radiation, which prevents overheating (Campbell, 2008).

Disposal of Metabolic Waste Products: During exercise, waste products like lactic acid accumulate in muscles. Blood plays a role in transporting these waste products from muscles so they can be eliminated from the body. Overall, blood performs functions during exercise, ensuring oxygen delivery, nutrient supply, waste removal, temperature regulation, and optimal muscle performance (Smith & Fernhall, 2023).

Regulation: The body relies on blood to keep its acid-base balance in check, maintaining a pH range for metabolic processes. This becomes especially crucial during exercise when the production of acid escalates (Widmaier et al., 2023).

Heart Rate Regulation: Blood acts as a messenger carrying signals and hormones like epinephrine (adrenaline) to the heart. This ensures that the heart rate adjusts accordingly to meet the heightened demand for oxygen and nutrients during activity (Aaronson et al., 2020).

Other roles during exercise: Volume expansion; our body´s need for oxygen and nutrients increases during exercise, and the blood volume may expand to serve this part more efficiently. Capillary recruitment: Tiny blood vessels, called capillaries, open up during exercise, with more blood flow to working muscle tissues and increased delivery of oxygen and nutrients. Fluid balance; maintaining (Smith & Fernhall, 2023).

Cardiovascular effects on exercise

The cardiovascular system undergoes changes in response to exercise, which are influenced by various factors such as the type of exercise, its intensity and duration, age, and an individual fitness level. When we exercise, our heart rate, output mean arterial pressure and pulse pressure increase significantly to meet the increased metabolic demands of our muscles (Smith & Fernhall, 2023). Notably, sympathetic activity rises due to signals from the cortex, chemoreceptors, and mechanoreceptors. Dynamic exercise primarily leads to decreased resistance because active muscles experience metabolic vasodilation, but static exercise may increase or maintain resistance due to vessel compression. The cardiovascular system adapts by utilizing mechanisms like the skeletal muscle pump and respiratory pump to facilitate return during exercise (Pappano et al., 2013).

Post-exercise recovery varies depending on factors such as the type and duration of the exercise performed and an individual's fitness level. Engaging in exercise or conditioning affects cardiovascular health by improving work capacity, lowering resting heart rate, increasing stroke volume, and enhancing efficiency during physical activity. Trained individuals demonstrate cardiac reserve and a greater demand for oxygen supply. These adaptations involve changes in arteries, arterioles, and capillaries that optimize perfusion and oxygen delivery throughout the body. Dynamic exercise is associated with hypertrophy, while static exercise tends to result in concentric hypertrophy. Exercise training that increases blood volume contrasts with the deconditioning effects caused by bed rest.

Engaging in activity is linked to a lower risk of developing cardiovascular disease and better recuperation after cardiac events, which ultimately promotes overall wellness. Table 4 shows what changes occur during moderate exercise that involves large muscles or muscle groups for an extended time (Widmaier et al., 2023).

Table 4. Cardiovascular changes during moderate exercise.

Variable	Change	Explanation
Cardiac output	Increases	Heart rate and stroke volume both increase, the former to a much greater extent.
Heart rate	Increase	Sympathetic stimulation of the SA node increases, and parasympathetic stimulation decreases.
Stroke volume	Increases	Contractility increases due to increased sympathetic stimulation of the ventricular myocardium; increased ventricular end-diastolic volume also contributes to increased stroke volume by the Frank–Starling mechanism.
Total peripheral resistance	Decreases	Resistance in the heart and skeletal muscles decreases more than resistance in other vascular beds increases.
Mean arterial pressure	Increases	Cardiac output increases more than total peripheral resistance decreases.
Pulse pressure	Increases	Stroke volume and velocity of ejection of the stroke volume increase.
End-diastolic volume	Increases	Filling time is decreased by the high heart rate, but the factors favoring venous return venoconstriction, skeletal muscle pump, and increased inspiratory movements—more than compensate for it.
Blood flow to heart and skeletal muscles	Increases	Active hyperemia occurs in both vascular beds, mediated by local metabolic factors.
Blood flow to skin	Increases	Sympathetic activation of skin blood vessels is inhibited reflexively by the increase in body temperature.
Blood flow to viscera	Decreases	Sympathetic activation of blood vessels in the abdominal organs and kidneys is increased.
Blood flow to brain	Increases slightly	Autoregulation of brain arterioles maintains constant flow despite the increased mean arterial pressure.
Cardiac output	Increases	Heart rate and stroke volume both increase, the former to a much greater extent.

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Oxygen Consumption During Exercise

The amount of increased respiratory response or increased oxygen needed for the muscles depends on the level of intensity of the exercise. Some studies show a close relationship between external power and oxygen consumption during exercise (Beck et al., 2006; Van Ingen Schenau & De Groot, 1983). During the beginning of a workout, there is an increase in oxygen consumption (VO_2) along with an increase in carbon dioxide production (VCO_2) and a slight rise in blood lactate levels. When exercising moderately or engaging in activity, parameters like increased oxygen consumption (VO2) and carbon dioxide production (VCO2) and lactate show a quick escalation before stabilizing within a few minutes (Lumb & Thomas, 2021). The intensity of these changes is influenced by both the power generated during exercise and the person's fitness level.

Defining exercise intensity and thresholds

Maximal Oxygen Consumption – VO_2max

Maximal Oxygen Consumption, commonly known as VO_2max, has been widely recognised and indicates an individual´s aerobic capacity and endurance potential originally described Hill et al. (1923) in 1920 and later developed by Åstrand and Saltin. It represents the limits of an individual's capacity and carries significant importance in understanding human physiology and exercise science (McArdle et al., 2023; Smith & Fernhall, 2023; Widmaier et al., 2023). VO_2max serves as a fundamental metric for evaluating aerobic fitness and endurance by measuring the volume of oxygen consumed during physical activity. Determining VO_2max involves a process through direct or indirect measurement. Direct measurement using a metabolic measurement gas device, and indirect measurements can be done with mathematical formulas on wearable gadgets or software applications (Carrier et al., 2023; Passler et al., 2019). Direct measurement devices measure the amount of O2 in each breath or an average in different timeframes up to 30 seconds (Beijst et al., 2013), and for both methods, breath by breath or mixing chamber, the device measures the amount of oxygen, O_2 (VO_2) and carbon dioxide, CO_2 (VCO_2).

When measuring maximum oxygen consumption, an individual is asked to perform a graded exercise protocol until the time of exhaustion, where speed or resistance is increased in steps. Then, the average maximum oxygen consumption in one minute is calculated using the Fick formula: $VO_2(ml/kg/min) = Q(L/min) \times (a\text{-}vO_{2diff})(mL/L)$, where Q is the cardiac output, and the difference between arterial and venous oxygen volume at the level of the capillary is $a\text{-}vO_{2diff}$ (Fick, 1870). Then, the outcome is divided by body weight in kg, as the VO2max definition is the average minute milliliters per kilogram, which is always described in ml/kg/min (Hill & Lupton, 1923). The significance of VO_2max goes beyond its value. It symbolizes the interplay among physiological systems. Achieving a VO_2max requires coordination among components such as the respiratory system, cardiovascular system, and skeletal muscle function (Bassett & Howley, 2000)

The Role of the Respiratory System when doing VO_2max test:

The respiratory system influences the efficiency of oxygen exchange and determines one's VO2max. The amount of air inhaled and exhaled per minute, known as ventilation, is crucial for ensuring that the working muscles receive oxygen for energy metabolism. When combined with other factors, a high capacity for ventilation contributes to an increased VO_2max (Levitzky, 2022).

Contribution of the Cardiovascular System when doing VO_2max test:

The heart, which plays a role in the cardiovascular system, significantly impacts achieving VO_2max. Cardiac output, which measures the amount of blood pumped by the heart per minute and stroke volume, which represents the volume of blood pumped with each heartbeat, are factors in determining VO_2max. As exercise intensity increases, cardiac output is primarily influenced by heart rate and stroke volume. A trained cardiovascular system can efficiently deliver oxygen blood to working muscles, thereby enhancing VO_2max (Smith & Fernhall, 2023).

Limiting factors for maximum oxygen uptake

Even though the amount of oxygen is measured when doing VO_2max tests, the limiting factor in healthy individuals is usually not the amount of oxygen inhaled from increased ventilation (Hill et al., 1924). Still, the ability to exchange gas in both lungs and muscles can be increased with exercise to a certain level. The physiological limiting factors of maximum oxygen uptake have been addressed as one or more of the four factors: The respiratory system, the maximal cardiac output, and the oxygen-carrying skeletal muscle limitation. At sea level, even during maximal work, the arterial O_2 saturation remains around 95% (Powers et al., 1989), and Hill et al. (1924) predicted that a significant drop in arterial saturation ($S_aO_2 < 75\%$) does not occur, even though some studies have verified that the respiratory system may limit VO_2max under certain circumstances (Bassett & Howley, 2000).

In the early ages of VO_2max and heart rate measurements, cardiac output was recognized as the primary factor explaining the different VO_2max values between subjects (Hill et al., 1924; Hill & Lupton, 1923). Nowadays, beta-blockage use has commonly increased, and an authoritative review of 24 studies found that beta-blockers can decrease the maximum heart rate by 25 – 30% (Tesch & Tesch, 1985). The same study showed the maximal cardiac output decreased by 15 – 20%, while stroke volume increased, with a decrease of VO_2max of 5 – 15% (Tesch & Tesch, 1985). The oxygen-carrying capacity can be changed by changing the hemoglobin content of the human blood (Ekblom et al., 1976). Blood doping practices have been shown in a double-blind study to increase VO_2max by 4 – 9%, which is proof of a link between O2 delivery and VO_2max (Gledhill, 1982, 1985). The difference in skeletal muscle type can limit the value of VO2max. The slow-twitch muscle group tends to have higher

VO_2max while the fast-twitch muscles tends to have lower VO_2max (Bergh et al., 1978; Van Der Zwaard et al., 2016).

Differences in VO_2max during cycling and running

Cycling and running have different biomechanical aspects and different measurements of the physical economy (Caputo et al., 2003; Quigley & Richards, 1996; Swinnen et al., 2018). Studies differ in the results of VO_2max between running and cycling, and there is less difference in untrained individuals. Another difference between the VO_2max of these two sports is the individual's background and/or interest in the preferred sport in favor of a higher VO_2max in the corresponding activity (Caputo et al., 2003; Schneider et al., 1990). Other studies compare the body kinetics difference between running and cycling and the muscle contraction difference between these two activities with results of higher VO_2max in running (Caputo et al., 2003; Carter et al., 2001; Jones & McConnell, 1999). When comparing physiological differences between cycling and running, Millet et al. (2009) compared the variations between cycling and running, revealing that when ru individuals tend to achieve a VO_2max compared to cycling. Cyclists can still reach a similar VO_2max value using cycle ergometry.

Moreover, muscles adapt differently depending on the exercise type, with cycling having an impact than running. Overall, there wasn´t a disparity in VO_2max levels among triathletes who engaged in both activities. However, there was conflicting data regarding the threshold. Other distinctions between these two exercises include heart rate, ventilation rates, and the influence of pedaling cadence.

Heart rate regulation

Maintaining the balance of heart rate during exercise is crucial to ensure that skeletal muscles receive oxygen. The heart rate regulation is controlled by an SA node located in the heart, which controls heart rate and is influenced by two factors: the parasympathetic and sympathetic nervous systems (Harris, 2023). Within the medulla oblongata, a part of the vagus nerve called the cardiovascular control center sends fibers connecting with the heart's SA and AV nodes. When these fibers are stimulated, they release acetylcholine, leading to hyperpolarisation and a decrease in the activity of both SA and AV nodes. This ultimately results in a heart rate change. When you're at rest, vagus nerves maintain a level of parasympathetic tone that affects your heart rate. Changes in activity can cause your heart rate to either increase or decrease. For example, a reduced tone will elevate your heart rate; on the other hand, increased activity will slow it down (Powers & Howley, 2018).

During low-intensity exercise, initially, your heart rate increases due to a reduction in tone. As you engage in physical activity, the sympathetic nervous system comes into play by stimulating both SA and AV nodes. This stimulation leads to an increased heart rate. The sympathetic system is responsible for this and is conveyed through cardiac accelerator nerves. Norepinephrine is released, which acts on receptors and causes an elevation in heart rate and myocardial contraction force (Aaronson et al., 2020). The medulla oblongata, which is the cardiovascular control center, plays a role in maintaining a balance between parasympathetic tone and sympathetic activity during rest. It receives signals from the system. Responds to changes in factors such as blood pressure and oxygen levels (Powers & Howley, 2018). For example, when blood pressure rises, the control center increases activity. This leads to a heart rate. Decreased cardiac output, ultimately helping to normalise blood pressure. Another regulatory reflex involves pressure receptors located in the atrium. These receptors communicate with the control center whenever there is an increase in pressure. In response, the control center activates accelerator nerves, resulting in a heart rate and increased cardiac output. This mechanism helps prevent any backup of blood within the system while simultaneously reducing atrial and venous blood pressure (Harris, 2023; Pappano et al., 2013).

Differences in heart rate during cycling and running

Heart rate, maximum heart rate, and percentage of maximum heart rate are commonly used for guiding and optimizing exercise routines (American College of Sports Medicine et al., 2021). These measurements indicate how your heart works during workouts, allowing you to customize your exercises based on your fitness level and goals. Maximum heart rate is usually estimated using formulas like subtracting your age from 220 (Correa Mesa et al., 2015); it gives you an understanding of your capacity, even though some variations are in use and the number 220 is argued (Robergs & Landwehr, 2002). By using percentages of your heart rate, fitness enthusiasts can determine target heart rate zones corresponding to training intensity levels.

Recreational cycling and running are both cardiovascular activities, but they involve different movements and activate different muscle groups, leading to distinct physiological responses and impacts on the human body as a weight-bearing or weight-supported exercise (Åstrand, 2003). Running engages more muscle groups, as the activity relies on moving the whole body, while in cycling, most muscle activity is for the lower body parts. It´s similar to joint impacts; it´s increased in running as more stress is on the joints while running than cycling, as when cycling, the part of the body weight is supported by the saddle.

Lactate – Lactic acid

Lactate, or lactic acid, is a compound ($C_3H_6O_3$) that has various roles in the metabolic processes in the human body. During normal cellular metabolism, glucose undergoes a process called glycolysis, where it´s converted into pyruvate. Under aerobic conditions, pyruvate enters the mitochondria and undergoes further oxidation within the Krebs cycle to produce energy in the form of ATP (adenosine triphosphate). In the absence of sufficient oxygen in anaerobic conditions (during intense exercises or with limited oxygen delivery), pyruvate is converted to lactate through a lactic acid fermentation process (Hall et al., 2016; Janssen, 2001).

The metabolic process is as follows:

Glycolysis: In the stage of energy production, glucose or glycogen is broken down through a series of chemical reactions called glycolysis. This process takes place in the cytoplasm of cells and doesn't rely on oxygen (McArdle et al., 2023).

Pyruvate Formation: As glycolysis progresses, glucose becomes a pyruvate molecule. Under conditions (with enough oxygen), pyruvate enters the mitochondria of cells and undergoes further breakdown to generate more energy (Widmaier et al., 2023).

Lactate Production: However, when oxygen isn't available, pyruvate converts into lactate and enters the mitochondria. This allows cells to continue producing some energy efficiently without relying on oxygen (Widmaier et al., 2023).

Lactate is eventually carried through the bloodstream to the liver, where it can be transformed back into glucose using a process called gluconeogenesis. This glucose can then be utilized for energy or stored in the liver.

It's important to understand that lactate itself is not a waste product (Hall et al., 2016); it plays a role as an intermediary in energy metabolism. Various tissues, including the heart and brain, can use lactate as an energy source. However, during exercise, lactate buildup in muscles can lead to burning sensations or fatigue. As exercise intensity decreases and oxygen becomes available, lactate gradually converts back into pyruvate, which enters the energy production pathway. Any excess lactic acid is also cleared from the body.

Therefore, lactate is a byproduct of energy production within the body during high-intensity anaerobic activities (Hall et al., 2016). It's important to note that it's not solely responsible for muscle soreness as previously believed but rather a part of the body's energy metabolism process.

Differences in lactate during cycling and running

For lactate production, there can be differences at different stages of intensity. The study made by Quittmann et al. (2021) compared the reliability, differences, and correlation of maximal lactate accumulation rate (VLamax) and power output (Pmax) between cycling and running. This resulted in higher VLamax in running while Pmax was lower, and there was no correlation between VLA max in running and cycling. On the other hand in, a similar study by Withers et al. (1981) comparing the aerobic power and anaerobic thresholds of endurance-trained cyclists and runners resulted in no significant interactions between runners and cyclists when comparing anaerobic threshold as a fraction of maximum oxygen consumption (VO_2max). However, when expressed in absolute values, cyclists had significantly higher anaerobic thresholds on the bicycle ergometer, while runners had higher thresholds on the treadmill.

When looking at time to exhaustion at maximal lactate steady state, it´s similar for cycling and running, despite differences in heart rate, ventilation, blood lactate concentration, and oxygen consumption, suggesting similar cardiorespiratory demand (Fontana et al., 2009). Allowing the same criteria to be used to determine the maximal lactate steady state for cycling and running. Using this criteria, there was no variation in the duration until exhaustion for moderately trained young men when comparing the two types of exercise. Moreover, cycling resulted in lower blood lactate concentration, lower heart rate, less ventilation, and lower oxygen consumption than running. Despite these differences, both exercise modes were perceived as challenging. In conclusion, the study suggests that regardless of these variations, individuals can endure durations at their maximum lactate steady state when engaging in either cycling or running.

Lactate thresholds

The lactate threshold is important in exercise physiology as it provides insights into how our bodies respond to endurance activities (Faude et al., 2009). It represents the point at which lactate production surpasses its removal rate, increasing blood lactate concentration. Understanding both anaerobic thresholds within the concept of lactate threshold is crucial for athletes, coaches, and researchers alike (Hall et al., 2016). It allows them to optimize training methods, enhance performance levels, and gain an understanding of physiology.

The concept of lactate threshold includes two thresholds: the aerobic threshold and the anaerobic threshold (Faude et al., 2009; Janssen, 2001; Wasserman, 1985). The aerobic threshold is often referred to as LT1 (lower lactate threshold). It refers to the intensity of exercise at which our bodies primarily rely on energy production through carbohydrate and fat oxidation. At this point, the transition from low to moderate-intensity exercises is where our bodies can efficiently clear out lactate from our bloodstream (Kenney et al., 2015). However, as we move towards higher-intensity exercises beyond this threshold, lactate production exceeds its clearance rate (Faude et al., 2009; Wasserman, 1985).

A noteworthy characteristic of the threshold is that it coincides with an increase in exchange ratio (RER), indicating a shift towards greater reliance on carbohydrates for energy production (Jeukendrup & Wallis, 2005; Wilber & Moffatt, 1992). This shift occurs due to an increased recruitment of type II muscle fibers that possess capacity.

The point at which lactate production exceeds its clearance is known as the threshold (Faude et al., 2009; Kenney et al., 2015). It is also referred to as the second lactate threshold (LT2) or the lactate turn point (Davis et al., 1983). It indicates an exercise intensity compared to the threshold and represents the limit of sustainable exercise without lactate buildup. Beyond this threshold, the body relies more on metabolism and glycolysis to generate energy. This results in a rise in lactate concentration and a decrease in the blood pH (Ali et al., 2008). Ultimately leads to fatigue. Endurance athletes often strive to delay reaching the threshold to optimize their performance (Wasserman, 1986; Yeh et al., 1983).

Maximum lactate steady state

As mentioned in the previous chapter, lactate production and removal is part of the human process during activity. To measure an individual's endurance capacity, a concept of maximal blood lactate steady state is the point of intensity and the turning point where the body can reach the highest point of removing excess lactic acid and remaining steady. The process of maintaining a balance between production and removal is referred to as turnover (Brooks, 1985). During the lactate state, the amount of lactate that appears is in equilibrium with the amount of lactate that disappears. This means there is a balance in turnover, where lactate's appearance and disappearance are equal (Donovan & Brooks, 1983).

For physiological testing and measurement of individual fitness and endurance, Maximal Lactate steady-state testing is one of the test methods, as it delivers a different approach (Aunola & Rusko, 1992; Beneke & von Duvillard, 1996) than measuring Blood Lactate using a traditional graded exercise protocol (Beneke, 1995; Haverty et al., 1988). The literature presents a paradox regarding the correlation between the anaerobic threshold and the steady state of maximum lactate (Aunola & Rusko, 1992; Dekerle et al., 2003; Urhausen et al., 1993) (Aunola & Rusko, 1992; Urhausen et al., 1993). A study by Haverty et al. (1988) found a significant correlation between Maximal Lactate Steady State MLSS) and Maximal Oxygen Consumption Steady State (MSSVO$_2$). Due to the human possibility to maintain activity for an extended time, studies have found that MLSS and MSSVO$_2$ are great predictors of 5km performance (Haverty et al., 1988).

Ventilatory patterns

The constant interaction between ventilatory patterns and physical activity demonstrates how adaptable the human body is. When we engage in exercise or recreational activity, our breathing patterns change to meet the increased need for oxygen and efficient carbon dioxide removal. As a part of the objective of this study to measure breathing frequency and breathing volume, their role in activity along with minute ventilation is described below.

Breathing Frequency: As already mentioned, oxygen plays a crucial role in physical activity; increased breathing frequency in involuntary breathing is the body´s response to more demand for oxygen (Smith & Fernhall, 2023). Increased breathing frequency is relatively increased with a raised body temperature (Hey et al., 1966).

Although we have extensively discussed the nature of respiratory reflexes, the significance of voluntary control over respiratory movements is worth noting. This control is achieved through pathways descending from the cortex to the motor neurons for respiratory muscles. Voluntary control allows us to regulate our breathing in response to stimuli, such as increased PCO_2 (partial pressure of carbon dioxide) or H+ concentration, which can become quite intense. An example of this is when humans can not hold their breath for periods. On the contrary, deliberate hyperventilation serves as the action resulting in alveolar and arterial PCO_2 levels and increased PO_2 (partial pressure of oxygen) (Widmaier et al., 2023). Hyperventilation is known amongst swimmers as both voluntary and involuntarily and results in better swimming times (Jacob et al., 2015). Controlled breathing pattern during activity. In a study by Brisswalter and Legros of well-trained middle-distance runners showed that respiratory frequency is among VE, HR, and stride rate a stable variable to measure efficiency in running (1994). During High-Intensity Interval Training (HIIT), the rate at which we breathe adjusts quickly and proportionally in response to changes in workload.

Interestingly, this adjustment seems to be influenced by inputs rather than metabolic signals. These findings highlight the importance of understanding the differences between breathing frequency and breathing volume, as they can provide insights into how exercise affects our breathing patterns (Nicolò et al., 2017). Furthermore, studies have shown a close correlation between breathing frequency and how we rate perceived effort in physical activities. Based on these results, it seems that our breathing rhythm can impact how difficult or strenuous we think a workout is. This understanding emphasizes the connection between our patterns and our mental evaluation of exertion during exercise, providing insights into the complex relationship between physiological responses and our subjective assessment of effort during physical activity (Nicolò & Sacchetti, 2019). The measurement of different indirect devices for breathing patterns has been validated for accuracy (Massaroni et al., 2019)

As the breathing patterns differ from person to person, the different body parts are used at different intensities and sports. As in previos chapters, the respiratory system is a complex system created with several body parts. During activity, work is done by the rib cage, chest walls, and abdominal contribution by contraction of the abdominal muscles. A study partitioning the work done by breathing found there was a difference in work done between running and cycling and at different intensities (35% - 100% of VO_2max), they found the increase of volume from rest to VO_2max increased by 223.22% ± 0.26% (Kipp et al., 2021)

Tidal volume

The amount of oxygen in a relaxed and involuntary single breath is described as tidal volume, typically measured in milliliters (ml). The amount of air during the inhalation process is nearly equal to that of exhalation, and the human body uses only part of the lung volume in normal daily breathing. The inspiratory reserve volume (IRV) is around six times greater than the resting breathing volume (RTV) (Widmaier et al., 2023). A study by Nicolò and colleagues (2017) resulted in respiratory frequency being the primary factor linked to increased workload and not deeper breaths (increased tidal volume). Currently, there is a lack of studies measuring tidal volume with activity.

Minute ventilation

Breathing volume is the second important component and can be defined in two ways: per breath and total volume in one minute. Minute ventilation, commonly referred to as VE (Shephard, 2017), is the total volume of air moved in and out of the lungs in one minute. VE is typically expressed in liters per minute (L/min) and is calculated using the following formula: VE = f x Vt. Where f is the frequency of breaths per minute and Vt is the tidal volume.

Differences in breathing patterns during cycling and running

As there is a lack of literature on each part of the breathing pattern previously described above, the differences in breathing patterns as a whole are discussed. Tanner et al. (2014) studied the difference in breathing patterns between maximal effort in cycling and running, showing that ventilatory patterns vary depending on exercise mode, where running resulted in higher oxygen consumption and cycling led to larger ventilatory equivalents for oxygen (O_2) and carbon dioxide (CO_2). Even due to these changes in exercise mode, minute ventilation did not differ. A study by Lucía et al. (1999) comparing the breathing patterns between amateur and professional cyclists found that professional cyclists had both higher oxygen consumption and breathing frequency as they also gradually increased the VE with increased breathing frequency and breathing volume at all intensity levels while the amateur did increase at high exercise intensity.

When comparing the breathing pattern on progressive incremental cycle and treadmill exercise, Kalsås and Thorseon (2009) found similar results as previous studies: perceived breathlessness was higher during cycling than running, and the relationship between tidal volume and minute ventilation differs between cycling and running exercises. Breathing strategies also vary between the two exercises in well-trained individuals. These findings correlate with all biometric and physiological differences between running and cycling described earlier. The individual's interest and history of practicing favored sport also differ in results (Widmaier et al., 2023). Physical training can cause slower and deeper breathing patterns (Åstrand, 2003) that could be seen in different breathing patterns between individuals, but in a study by Martinez and colleagues (2016), they studied ventilatory efficiency and breathing patterns in world-class cyclists over three years. The study resulted in no significant change in ventilatory patterns over the three years.

Ventilation thresholds

The ventilation threshold (VT), also referred to as the ventilatory threshold, plays a role in exercise physiology. It is similar to the lactate threshold but is measured through exercise testing (CPET) instead of blood lactate (Albouaini et al., 2007). During exercise, the Ventilatory Threshold (VT) is reached when breathing increases more than oxygen intake because of increased carbon dioxide production and lactate buildup in the blood. This indicates a shift towards metabolism. Athletes, coaches, and researchers find it essential to understand VT as it provides insights into exercise planning, performance enhancement, and physiological responses to training (Loat & Rhodes, 1993).

Cardiopulmonary Exercise Testing (CPET) is an advanced method for assessing an individual's anaerobic capacities during exercise (Mezzani, 2017). At its core, CPET determines ventilatory thresholds (VT1 and VT2), which serve as markers for understanding an individual's responses as exercise intensity increases (Plato et al., 2008). VT1, or the first ventilatory threshold, highlights the moment in progressive physical activity when breathing escalates more rapidly compared to oxygen intake (VO_2). This transition happens because of the emergence of metabolic acidosis when lactate begins to build up in the bloodstream before it can be eliminated (Binder et al., 2008; Gaskill et al., 2001; Wyatt, 1999). The VT2, or the second ventilatory threshold, is the higher intensity point where the significant increase of ventilation is relative to oxygen consumption; at this point, a buildup of lactate and hydrogen ions (H+) causes metabolic acidosis and an increased urge to breathe out carbon dioxide (Binder et al., 2008; Gaskill et al., 2001; Plato et al., 2008). There are different methods to estimate these two ventilatory thresholds, and they are a popular topic in the literature. The most common methods are to compare the ratio between VE/VO_2, VE/VCO_2, RER, changes in $PETCO_2$, and changes in breathing frequency and breathing volume (Amann et al., 2004; M. Jones & Doust, 1998; Wyatt, 1999).

The effect of ramp duration on ventilatory thresholds and VO_2max

The study of ventilatory thresholds, differences in the measurement method, reliability, and protocols has long been discussed among exercise physiologists and fitness enthusiasts over the years (Amann et al., 2004; Elmer & Toney, 2018; Hill & Lupton, 1923; Nicolò & Sacchetti, 2019; Wyatt, 1999). These thresholds, which indicate the shift from aerobic to metabolism during activity, provide valuable insights into how our bodies respond to exercise stress. These responses can vary between individuals and activity-type Fields (Swinnen et al., 2018). To date, there is no general standard for the number of ramps, increase in intensity, speed or volume, controlled or self-paced, or the length of the metabolic protocol for ventilatory thresholds or VO_2max (Beltz et al., 2016).

Studies comparing the differences in ramp duration and intensity increase of a graded exercise protocol for ventilatory thresholds and VO_2max have different results. A study by McNaughton and McNaughton ￼examined the findings of two different cycle exercise tests conducted on nine highly trained triathletes. One test involved starting at 150 W and increasing by 30 W every 60 seconds until exhaustion, while the other test started at 50% of the peak power output achieved in the test short test and increased power output by 5% at 3-minute intervals. The results revealed that the peak power output, maximal RER, and breathing frequency were significantly greater in the shorter test than the one with the longer However, the two tests did not differ in oxygen consumption rates. The performance during a cycling time trial correlated with peak power output and ventilation threshold from the test and peak oxygen consumption rate from the shorter test. Notably, varying stage lengths during cycle exercises could impact peak power output and its relationship to oxygen consumption rates. Based on these findings, obtaining peak power output measurements using 3-minute stage increments for trained triathletes appears to predict their performance in a 90-minute cycling session (Bentley & McNaughton, 2003). Comparing different protocols between running and cycling, Buchfuhrer et al. (1983) found differences when doing three different versions of the protocol for running and cycling metabolic tests, where VO_2max and VT2 were measured in a higher value on a treadmill, and the VO_2max was significantly higher on protocols with larger increments. Their study also showed that the total time of a VO_2max test should be around 10 minutes.

When comparing VT1 and VT2 on different protocols, Weston et al. (2002) conducted a study to explore how different exercise approaches impact ventilation thresholds and peak oxygen uptake in trained male cyclists. The findings revealed no variations among the measurement protocols except for VO_2peak, which was observed to be lower during the 10 Watts with 60-second ramp protocol. Additionally, the study highlighted that the work rate recorded at the ventilation thresholds and VO_2peak varied depending on the ramp's incline. These findings suggest that caution should be exercised when prescribing training or assessing performance solely based on these measurements.

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Abstract

Recreational activities positively impact well-being both from mental and physical perspectives. The objectives of this study are to study the breathing frequency and volume as a percentage of VO_2max among recreational cyclists and runners, with both direct and indirect measurements, and to compare the measurements between cycling and running. Graded exercise tests were taken on 47 participants, at the age 44.46 ± 10.08 (cyclists) and 46.45 ± 10.32 (runners), with a total of number 76 measurements. Participants wore a Cosmed K5 gas analyzing device for breath-by-breath for direct measures and a TymeWear Smart T-Shirt for indirect measures. Graded exercise tests to time of exhaustion were done; cyclists started at 75W, increased by 25W every 3 minutes, and runners started at 5km/hr, increased by 1km/hr every 3 minutes at a steady incline of 1%. Results from repeated measures of three-way ANOVA showed there was a significant interaction between intensity and sport (F(3.1, 39.4) = 3.7, p = 0.012) for breathing frequency. A significant interaction for direct measures between intensity and sex and intensity and sport (F(4.4, 1.0) = 13.1, p < .001) and (F(4.4, 0.5) = 6.9, p < .001) respectively and only between intensity and sex for indirect measures (F(2.7, 10718.8) = 2.8, p = .048). The difference found in breathing volume is in line with previous studies both for direct and indirect measures. The same is true for direct measures of breathing volume. However, further studies are needed for indirect measurements, and a definition of their unit for volume is needed.

Introduction

Participating in activities, hobbies, and sports has been shown to increase a wide range of health benefits (Ham et al., 2009; Hulteen et al., 2017), both mental well-being and physical health (Oja et al., 2015), with studies indicating positive effects from both short-term activity and prolonged engagement (Mahindru et al., 2023). Regular and increased physical activity has been linked to increased life satisfaction and happiness across all stages of life (An et al., 2020)and increased sleep quality or insomnia (Ferreira et al., 2023; Sejbuk et al., 2022). Physical activity can also help with the fight against lifestyle conditions and diseases like obesity, high blood pressure, and heart-related diseases (Elagizi et al., 2020). Physical activity and recreational sports interact with physical health and social engagement and can differ in effort and time (Dishman et al., 1985). In the effort to increase physical performance and well-being, individuals often assess various measurable marks of their fitness and overall health. One of these is the use of smart wearable gadgets to measure variables like heart rate, sleep, heart rate variable, steps, cadence, distance, speed, altitude, and track routes (Henriksen et al., 2018). The estimation of maximal oxygen consumption (VO_2max) from those variables is a central point for many manufacturers and individuals using these devices to measure fitness levels and establish correct training load (Düking et al., 2022).

The availability of wearable technology linked with online platforms or apps has had continuous growth over the last decades, in correlation with increased technology and the evolution of the Internet of Things (Vera-Rivera et al., 2019; Wang et al., 2021). The impact of measures on physical recreational activity varies across different age groups and sexes. In an updated guideline from the World Health Organization from 2020, they recommend all adults to do 150-300 minutes of moderate-intensity activity or 75 – 150 minutes of vigorous-intensity activity as a minimum and prefer some combination of those intensities on a weekly basis (Bull et al., 2020). With the use of wearable technology, it´s a great way to measure and track the time spent in various intensities, using variables previously mentioned to estimate and track activity and intensity.

When individuals engage in physical activity or recreational sports events, their bodies try to adapt through a complex process to enhance their performance and promote health. This adaptation process is connected to all human systems (Widmaier et al., 2023). The improvements to the human system or intensity of exercise can be measured in many different ways. By the total work done over some time, the percentage of intensity during the activity, commonly used heart rate, speed, power, RPE, percentage of VO_2max, and training thresholds (Carey et al., 2005; Day et al., 2004, 2004). Along with these aforementioned methods, the breathing rate has been validated as a use of training intensity (Neary et al., 1995) and as a marker for exercise thresholds (Carey et al., 2005; Carrier et al., 2023). Even though the technology and access to smaller wearables have increased, only a few smart wearables measure breathing frequency and breathing volume simultaneously to monitor physical activity during training. TymeWear is one of those few companies that is developing technology to monitor activity and measure lower and upper ventilatory thresholds by calculating breathing volume and breathing frequency.

Recent studies are available on indirect measurements of breathing frequency, breathing volume, and breathing patterns in humans, but few use chest-based wearables (Massaroni et al., 2019), as the technology of the TymeWear smart t-shirt is based on. Therefore, there is a gap in the literature comparing this technology with direct measurements.

The objective of this study is twofold:

a) To study the breathing frequency and breathing volume as a function of VO_2max among recreational cyclists and runners with direct and indirect measurements.

b) To compare measurements between cycling and running from both direct and indirect measures.

Methods

Research design

This study is in a cross-over experimental setup, using repeated measures, between sex (females and males), sports (cycling and running), and direct and indirect measurements.

Participants

Participants were Icelandic recreational cyclists and runners, who all signed an informed consent agreement before participating in the study. All participants were registered in a running or cycling club and participated in competitions over the last 12 months but were not strong enough not to compete for overall medals. The total number of participants was 47 (Female=20, Male=27), and a total number of 76 measurements were taken (Cycling=34 and Running=42); 68 of the measurements (Cycling=28 and Running=40) did measure all values from both direct and indirect measurements and were used in this study. In Table 5, participants‘ age, height, weight, and BMI are listed for both cycling and running for both sexes.

Table 5. Physical characteristics of participants.

	Age	**N**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
Cycling					
Male	45.17 ± 10.42	18	179.1 ± 5.56	77.98 ± 10.24	24.22 ± 2.59
Female	43.20 ± 9.84	10	170.0 ± 3.89	72.70 ± 9.40	25.11 ± 2.79
Running					
Male	45.43 ± 10.37	21	180.4 ± 5.97	81.16 ± 12.81	24.92 ± 3.71
Female	46.47 ± 10.55	19	168.1 ± 4.71	68.37 ± 9.86	24.16 ± 2.97

Instruments

The following instruments were used: Height measuring tape (Seca), and Tanita MC-780U body composition scale. A Cybex 50L R-series treadmill was used for the graded running exercises, and a Wattbike Atom X for the graded cycling exercises. Cosmed K5 breath-by-breath CPET, Scosche Rythm24 heart rate monitor. Indirect measure equipment: TymeWear smart t-shirt, Polar OH1+ heart rate monitor.

Procedure

Participants visited Reykjavik University Sportlab twice, once for cycling and once for running, with approximately 7 days between visits. During each visit, the participants underwent body composition measurements, including height, weight, and fat percentage. They were also requested to specify their t-shirt size and wear a TymeWear t-shirt based on sex and regular t-shirt size. The sized t-shirt was utilized for both the cycling and running assessments. A breathing pressure test was conducted to ensure the face mask's fit for direct measurements.

The process for conducting both running and cycling tests remained identical in all the visits for each participant. Participants were outfitted in sized smart t-shirts and face masks along with various heart rate monitors for direct and indirect measurement tools. Once both devices provided measurement signals, the graded exercise protocol commenced. Before each test, participants engaged in a warm-up routine of their choice. In the cycling test, each participant was initiated at 75W with intensity increments of 25W every 3 minutes until the point of exhaustion was reached. Participants could select their cadence but were encouraged to maintain it above 80rpm. The running test began at 5km/hr with a 1% incline. The velocity was raised by 1 km/hr every 3 minutes, with no change in the incline, and they ran until reaching the point of exhaustion. Data from direct measurements was collected using Omnia 2.3 software and the TymeWear online platform from indirect measurements.

Data analysis

Data from both direct and indirect measurements were pre-analyzed, and the percentage of VO_2max (50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, 100%) from direct measurements was calculated, all data was then sorted and edited in Microsoft Excel (Microsoft, 2024), to fit the requirements for statistical analysis in IBM SPSS 27 (SPSS INC., Chicago, IL, USA) statistical analyzing software. Repeated measures of three-way ANOVA were used to investigate the effects of measurement type, sex, and sport. Given the assumption of sphericity was violated based on Mauchly's test results ($p < .05$), Greenhouse Geisser correction was applied to adjust the degrees of freedom for the F-test.

As the measuring units in breathing volume differed, a different method was used for that part of the data analysis. Repeated measure three-way ANOVA for each type of measurement, and Pearson´s R correlation was used to explore the relationship between the direct and indirect measures. Before conducting the correlation analysis, the data were assessed for normality, linearity, and homoscedasticity to validate Pearson's correlation assumptions. The correlation was calculated at both .05 levels.

Results

Oxygen uptake – VO_2

The results of oxygen uptake show that the male running group had the highest VO_2 in this study. In Table 6 the mean and standard deviation for oxygen uptake (VO_2) at each percentage of VO_2max are presented. The results show there was a significant interaction in the intensity (percentage of VO_2max) ($F(5.6,6.3) = 634.1$, $p < 0.0001$). Additionally, when looking at the interaction between intensity, sex, and sport type, there is a significant interaction between measures ($F(5.6, 6.3) = 2.4$, $p = 0.27$). Results of interactions between sex and intensity and between sport and intensity did not show significant interactions ($F (5.6,18.0) = 1.8$, $p = 0.102$) and ($F (5.6,21.4) = 2.1$, $p = 0.52$), respectively. There was no significant interaction in any % of VO_2max between cycling and running.

Table 6. VO_2max of participants for both females and males, in cycling and running.

	Female		**Male**	
% of VO_2max	**Cycling ml/kg/min**	**Running ml/kg/min**	**Cycling ml/kg/min**	**Running ml/kg/min**
50%	17.0± 4.0	18.4 ± 3.4	20.0 ± 4.5	21.7 ± 4.8
55%	17.7 ± 4.7	20.8 ± 4.2	22.5 ± 4.3	23.6 ± 5.8
60%	22.1 ± 3.4	22.1 ± 4.9	24.9 ± 4.2	27.3 ± 4.8
65%	24.6 ± 3.9	23.8 ± 5.2	27.0 ± 5.0	28.8 ± 4.2
70%	26.4 ± 3.4	26.4 ± 5.5	28.6 ± 5.3	31.8 ± 4.0
75%	28.1 ± 3.8	28.0 ± 4.9*	31.1 ± 5.3	35.7 ± 5.3*
80%	30.2 ± 3.7	30.8 ± 5.6	33.3 ± 5.8	36.7 ± 5.4
85%	31.8 ± 3.6	33.1 ± 5.9	35.2 ± 6.3	38.6 ± 6.3
90%	33.8 ± 4.4	33.6 ± 5.7	37.8 ± 6.5	40.2 ± 6.0
95%	36.8 ± 5.0	37.1 ± 6.4	40.0 ± 6.9	42.6 ± 7.1
100%	39.7 ± 5.5	41.1 ± 7.4	43.0 ± 7.4	49.3 ± 7.7

* Significant interaction between sexes, $p< 0.05$
ml/kg/min = milliliters per kilogram per minute.

Breathing frequency

The results of breathing frequency show a noticeable difference at sub-maximal intensity between sexes, both at direct and indirect measurements. The results of repeated measures three-way ANOVA comparing measures (breathing frequency as a percentage of VO_2max for both direct and indirect measurements), between intensity, sex (male vs. female), and sport type (running vs. cycling). The results show there was a significant interaction in the intensity (percentage of VO_2max), ($F(3.2, 16116.5) = 208.9$, $p < 0.0001$). On the other hand, the interaction between sport type and intensity showed a significant interaction ($F(3.2, 233.1) = 3.0$, $p = 0.028$). When looking at measure type, a significant interaction was found between sport type, intensity and measure ($F(3.1, 39.4) = 3.7$, $p = 0.012$), while no other two-way or three-way interactions yielded significant results.

Table 7. The breathing frequency of female participants was measured using both direct and indirect measurements in cycling and running.

	Running		Cycling	
% of VO_2max	Direct measure bf/min	Indirect measure bf/min	Direct measure bf/min	Indirect measure bf/min
50%	25.1 ± 4.5	25.1 ± 5.6	24.4 ± 6.8	22.1 ± 7.4
55%	25.8 ± 5.4	25.8 ± 5.6	24.6 ± 6.9	23.2 ± 7.6
60%	27.7 ± 5.5	27.7 ± 5.8	24.8 ± 6.8	24.7 ± 6.5
65%	30.0 ± 6.8	29.6 ± 6.7	26.0 ± 8.0	26.3 ± 8.1
70%	31.1 ± 6.5	31.0 ± 6.8	27.5 ± 7.8	27.5 ± 8.0
75%	32.9 ± 6.1	33.0 ± 6.6	28.7 ± 6.9	29.2 ± 7.0
80%	35.1 ± 6.3	34.8 ± 7.7	31.2 ± 7.4	31.2 ± 7.0
85%	37.0 ± 6.5	36.1 ± 7.7	32.1 ± 6.5	32.4 ± 6.4
90%	38.2 ± 5.4	37.6 ± 6.8	33.9 ± 6.7	34.3 ± 6.9
95%	43.8 ± 7.9	42.7 ± 9.3	36.7 ± 8.9	37.0 ± 8.6
100%	46.6 ± 7.5	44.7 ± 9.3	45.0 ± 7.8	45.6 ± 8.1

bf/min = breathing frequency per minute.

Table 8. The breathing frequency of male participants was measured for both direct and indirect measurements in cycling and running.

	Running		Cycling	
% of VO_2max	Direct measure bf/min	Indirect measure bf/min	Direct measure bf/min	Indirect measure bf/min
50%	25.5 ± 4.5	27.7 ± 6.1	23.4 ± 6.0	23.4 ± 6.3
55%	25.9 ± 5.2	28.5 ± 7.5	22.9 ± 5.3	23.1 ± 5.2
60%	28.6 ± 6.3	30.6 ± 7.8	25.1 ± 5.1	24.1 ± 4.5
65%	30.2 ± 6.2	32.4 ± 8.1	25.3 ± 4.7	24.8 ± 4.7
70%	31.6 ± 4.6	32.1 ± 4.9	25.7 ± 5.1	25.4 ± 4.7
75%	31.7 ± 5.6	32.1 ± 5.2	26.4 ± 5.4	26.3 ± 5.1
80%	34.1 ± 5.8	34.2 ± 5.1	27.7 ± 5.7	27.2 ± 5.3
85%	37.1 ± 6.6*	36.9 ± 6.3	28.6 ± 6.1*	28.7 ± 6.3
90%	38.9 ± 6.0	38.4 ± 5.9	30.7 ± 6.5	30.8 ± 6.5
95%	41.6 ± 5.3	41.5 ± 5.1	34.8 ± 7.1	35.0 ± 7.2
100%	47.7 ± 5.7	47.4 ± 5.7	44.2 ± 9.6	44.4 ± 9.5

* Significant interaction between sports, $p < 0.05$
bf/min = breathing frequency per minute

Breathing volume

Since the indirect measuring device uses their unit for volume, which is not defined, a separate three-way ANOVA was done for direct and indirect measures. The results of repeated measures three-way ANOVA compare direct measures (breathing volume as a percentage of VO2max), between sex (male vs. female), sport type (running vs. cycling) and intensity. The results show there was a significant interaction in the intensity (percentage of VO_2max), ($F = 235.716$, $p < 0.0001$). The results of the interaction between Sex and Intensity and Sport Type and Intensity showed significant interactions ($F(4.4, 1.0) = 13.1$, $p < .001$) and ($F(4.4, 0.5) = 6.9$, $p < .001$), respectively. The interaction between sex, sport type, and intensity did not show significant results ($F(4.4, 0.1) = 1.5$, $p = .208$). No significant interaction was found at each percentage of VO_2max between groups.

The results of repeated measures three-way ANOVA comparing indirect measures (breathing volume as a percentage of VO2max), between intensity, sex (male vs. female), and sport type (running vs. cycling). The results show there was a significant interaction in the intensity (percentage of VO$_2$max), (F(2.7, 416772.0) = 107.8, p < 0.0001) and between sex and intensity (F(2.7, 10718.8) = 2.8, p = .048). The results of interaction between sport type and intensity and sex, sport type, sex, and intensity did not show a significant difference, (F(2.7, 6320.7) = 1.6, p = .187) and (F(2.7, 9757.1) = 2.5, p = .065) respectively. No significant interaction was found at each percentage of VO$_2$max between groups.

In Figures 1a and b, and 2a and b, the mean and standard deviation for breathing volume for both direct and indirect measures are depicted; on the left y-axis are direct measures, and on the right y-axis are the indirect measures, as previously noted, the difference between measuring units causes complexity in the statistical calculation. However, a visible trend is shown, even though different values of units are used.

Figure 1a and b. Breathing volume for female participants for both direct and indirect measures.

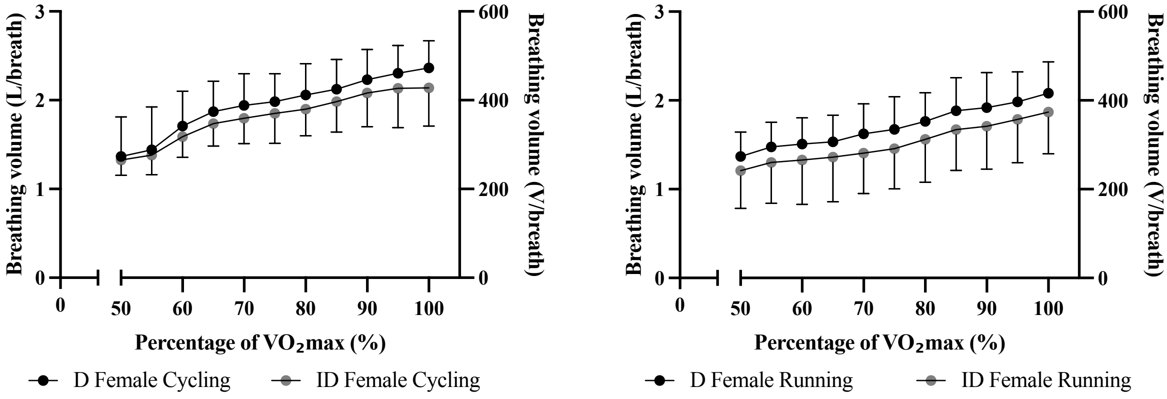
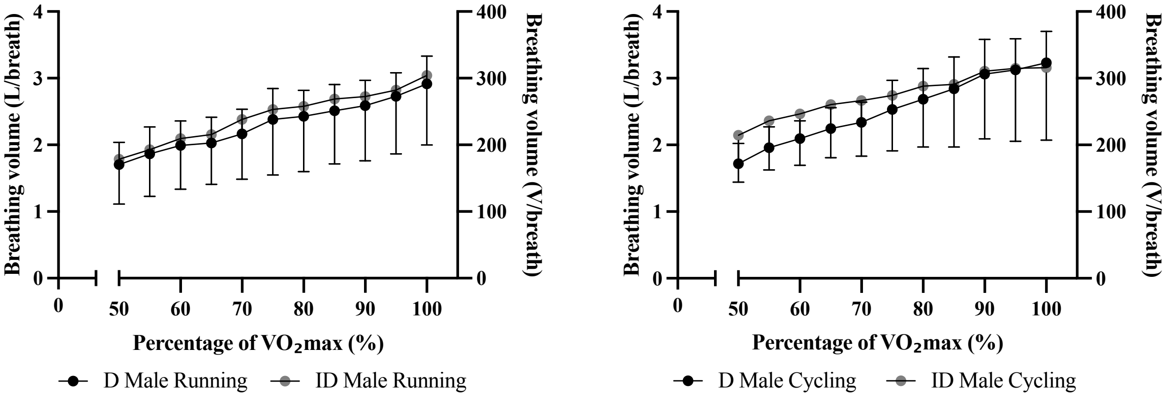


Figure 2a and b. Breathing volume for male participants is measured both directly and indirectly.



Discussion

The study had two objectives: a) to explore the connection between breathing rate and breathing volume in recreational cyclists and runners based on a percentage of their VO_2max using both direct and indirect measuring techniques; b) to compare these measurements between cyclists and runners across both direct and indirect measures.

Breathing frequency increased with increased physical intensity, and the study revealed significant interactions between cycling and running with a lower breathing frequency during cycling for both sexes, as seen in Tables 6 and 7. In a study by Forster et al. (2012), changes in breathing frequency occur with changes in the intensity of the human movement to exchange gases in the lungs to maintain a level of carbon dioxide and oxygen in the blood. The human physiological responses between cycling and running are different, and there are several reasons, like Less weight to carry during cycling, causing less breathing frequency, less muscle activation in cycling, and therefore less oxygen transport to muscles (Coast et al., 1990). Smith & Fernhall (2023) pointed out that involuntary breathing increases with the body´s oxygen demand at increased intensities. These findings of different patterns in breathing frequency are also consistent with studies by Lucia et al. (1999) and Kalsås and Thorseon (2009), who also highlight a similar regression in breathing frequency both between recreational and elite cyclists and between cycling and running.

This study revealed increased breathing volume with increased physical intensity, as previous studies have shown. A significant interaction was found between sex and intensity and sport type and intensity. As for sex difference, the females had lower volume than the males, with clear physical sex differences as total body volume and less lung capacity. There was also a significant interaction in breathing volume between sport type and intensity, resulting in a lower breathing volume in cycling than in running. These results align with previous studies, which found a difference in breathing volume between cycling and running (Hue et al., 2000; Tanner et al., 2014).

There are differences in results between direct and indirect measurements both for breathing frequency and breathing volume, as is shown in Tables 6 and 7. With a mean difference of 2.9 ± 7.8 (cycling) and 1.9 ± 7.5 (running) for females and − 0.2 ± 9.6 (cycling) and 2.5 ± 5.7 (running) for males. In figures 1a and b, and 2a and b. In a study by Kipp et al. (2021), they found a difference in work done by the abdominal area or the rib cage at different intensity levels and a difference in expansion of the rib cage at different intensity levels. They resulted in 40.5% changes in the ribcage volume, while there was only a 33.7% difference in abdominal volume between 45% and 100% of VO_2max. They also resulted in a 75.0% difference in breathing frequency and a 32.0% change in breathing volume. The TymeWear smart t-shirt sensor is located at the upper part of the back side of the t-shirt as a part of their technology; their difference could be caused by the placement of the sensor and the area he can measure. This could cause issues between internal (direct) and external (indirect) measurements. Other discrepancies observed between direct and indirect measurements likely stem from using volume units (volume/breath) in the latter method. The visual expression of figures 1a and b and 2a and b shows a similarity that could be tweaked even further by changing the ratio on the scale on both y-axes. As displayed in the figures, the unit scale for females is higher than for males for the indirect measurements but lower for the direct. The indirect measure indicates that the female’s breathing volume is larger than that of the males. This could be the result of the difference in shape between sexes. Based on the study by Kipp et al. (2021), using indirect Optoelectronic Plethysmography (OEP) measurement, runners generally use less lung volume compared to cyclists at both 35% and 65% of VE_{max} (maximal minute ventilation) while maintaining similar maximal minute ventilation percentages. This finding is consistent with the measurements conducted in this study for both sexes, although indirect measures indicated that female runners exhibited breathing volumes than female cyclists. Based on this, further development of the breathing volume in the TymeWear smart t-shirt is needed.

Strengths and limitations

The main strength of this study is measuring the respiratory effects on recreational cyclists and runners for breathing frequency, breathing volume, and minute ventilation with gold standard measurements and comparing them with indirect measurements with breath-by-breath analysis. The study's limitations are at least two; firstly, the sample is not equal in sex and sport type, and some participants did only running and others only cycling. There might be bias as the participants were more running enthusiastic than cycling. Secondly, when comparing direct and indirect measurements, the measuring units were not the same for breathing volume (direct = L/breath, indirect = volume/breath) and minute ventilation (direct = L/minute, indirect = volume/minute), and as the unit „volume“ is not defined and therefor not equally comparable between measurement types.

Conclusion

In conclusion, we found that cyclists tend to breathe more frequently but take in more air compared to runners at moderate exertion levels, resulting in similar overall ventilation during cycling and running. This discovery is significant as it implies that despite the activities involved, the overall breathing requirements remain consistent across these sports. Indirect measurements of breathing volume showed a trend in the measurements. However, this study emphasizes the need to define the Volume/breath unit used in measurement tools. Such clarity is essential for ensuring accuracy and reliability in research, especially when studying sex differences in breathing patterns. Sex variations can affect how individuals breathe, and having a unit would facilitate synchronization and data comparison across different studies.

Practical application

The main practical application of this study is it confirms that the TymeWear smart t-shirt is a valuable device for measuring breathing frequency for recreational athletes and is an added metric to establish training load and intensity for athletes. As this study compares breathing frequency and breathing volume as a percentage of VO_2max, a similar study could add a comparison with heart rate and fluctuation of both heart rate, breathing frequency, and volume in different environments and nutritional or supplemental changes. Could breathing frequency be a valuable measurement of intensity in activity? From a coaching perspective, the use of these added variables (breathing frequency and breathing volume) to the coach‘s cookbook could give promising information about the athlete's intensity during training, while an aggregation of information over a time period or specially formatted threshold test would be needed to establish thresholds.

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