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Cardiovascular Effects and Risks in Endurance Training

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List of Abbreviations

AF	Atrial fibrillation
AMI	Acute myocardial infarction
AR	Aortic regurgitation
AS	Aortic stenosis
ATP	Adenosine triphosphate
ATP-PC	Adenosine triphosphate–phosphocreatine
BPM	Beats per minute
CAC	Coronary artery calcification
CAD	Coronary artery disease
CO ₂	Carbon dioxide
COPD	Chronic obstructive pulmonary disease
CV	Cardiovascular
ECG	Electrocardiogram
FOR	Functional overreaching
H ₂ O	Water
HCM	Hypertrophic cardiomyopathy
HIT	High-intensity training
HR	Heart rate
HRMs	Heart rate monitors
LGE	Late gadolinium enhancement
LIT	Low-intensity training
LV	Left ventricle

LVEF	Left ventricular ejection fraction
m	Number of multiple responses
MACE	Major adverse cardiovascular events
MET	Metabolic equivalent of task
MF	Myocardial fibrosis
MO ₂	Myocardial oxygen consumption
N	Total number of participants
n	Number of participants' responses
NFOR	Nonfunctional overreaching
O ₂	Oxygen
OTS	Overtraining syndrome
p	Significance of the results
PCr	Phosphocreatine
PE	Pulmonary embolism
PPG	Photoplethysmography
Q̇	Cardiac output
RPE	Rating of perceived exertion
RV	Right ventricle
RVEF	Right ventricular ejection fraction
ROS	Reactive oxygen species
SCD	Sudden cardiac death
SIPE	Swimming-induced pulmonary edema
SV	Stroke volume
THR	Threshold training
TID	Training intensity distribution
ULN	Upper limits of normal
VT	Ventricular tachycardia
VTs	Ventilatory thresholds
WHO	World Health Organization

1. Summary

Endurance training is generally associated with cardiovascular benefits, including improved cardiac output, reduced resting heart rate, and enhanced metabolic efficiency. However, both insufficient and excessive training levels have been linked to increased cardiovascular risk, raising the question of where beneficial adaptation ends and harmful stress begins.

This master's thesis investigates the physiological and pathological cardiovascular effects of endurance training, with a particular focus on athletes' awareness of these effects. The study combines a systematic literature review with a cross-sectional online survey of 307 active endurance athletes. The questionnaire was distributed in Germany and Lithuania in English and German via sports clubs, universities, and online platforms.

The survey results reveal that no universal training threshold exists beyond which endurance exercise becomes cardiovascular harmful. Risk depends on the interaction of training volume, frequency, age, sex, and individual health literacy. Athletes aged 18 to 29 years reported the highest rates of acute symptoms with very high statistical significance ($p = 2.14 \times 10^{-10}$), suggesting acute overreaching as a primary risk driver in this cohort. Training frequencies of 3 to 6 days per week were associated with the most favorable outcomes, consistent with a U-shaped dose-response relationship.

Contrary to prevailing literature, female participants reported chest pain more frequently than male participants ($p = 0.02$), contributing to growing evidence that female cardiovascular risk in endurance sport may be systematically underestimated.

Knowledge of heart rate zone training was associated with significantly lower symptom prevalence, demonstrating the protective effect of structured training control. However, a substantial proportion of zone-aware athletes did not actively implement it, indicating a persistent health literacy gap.

A critical finding concerns risk awareness. Only 3% of participants identified coronary artery calcification as an endurance-associated risk, and fewer than a quarter recognized sudden cardiac death. This study provides population-level evidence that the most clinically significant cardiovascular risks of endurance training are largely absent from athlete awareness, underscoring the need for targeted health education in endurance sport communities.

1.1 Summary (Lithuanian)

Ištvėrmės treniruotės paprastai siejamos su teigiamu poveikiu širdies ir kraujagyslių sistemai, įskaitant padidėjusį širdies išstumiamo kraujo tūrį, sumažėjusį ramybės širdies susitraukimų dažnį ir pagerėjusį medžiagų apykaitos efektyvumą. Tačiau tiek nepakankamas, tiek per didelis treniruočių krūvis yra siejamas su padidėjusia širdies ir kraujagyslių rizika, todėl kyla klausimas, kur baigiasi naudinga fiziologinė adaptacija ir prasideda žalinga perkrova. Šiame magistro darbe nagrinėjamas fiziologinis ir patologinis ištvėrmės treniruočių poveikis širdies ir kraujagyslių sistemai, ypatingą dėmesį skiriant sportininkų informuotumui apie šiuos poveikius. Tyrimas apima sisteminę mokslinės literatūros apžvalgą ir skerspjūvio internetinę apklausą, kurioje dalyvavo 307 aktyvūs ištvėrmės sportininkai. Klausimynas buvo platinamas Vokietijoje ir Lietuvoje anglų bei vokiečių kalbomis per sporto klubus, universitetus ir internetines platformas. Apklausos rezultatai parodė, kad neegzistuoja universali treniruočių riba, kurią viršijus ištvėrmės treniruotės tampa žalingos širdies ir kraujagyslių sistemai. Rizika priklauso nuo treniruočių apimtys, dažnumo, amžiaus, lyties ir individualaus sveikatos raštingumo sąveikos. 18–29 metų sportininkai dažniausiai pranešė apie ūminius simptomus, o šis ryšys pasižymėjo labai dideliu statistiniu reikšmingumu ($p = 2,14 \times 10^{-10}$), leidžiančiu manyti, kad ūminis persitreniravimas yra vienas svarbiausių rizikos veiksnių šioje grupėje. 3–6 treniruočių dienos per savaitę buvo susijusios su palankiausiais rezultatais, atitinkančiais U formos dozės ir atsako priklausomybę. Priešingai nei teigiama vyraujančioje mokslinėje literatūroje, moterys dažniau nei vyrai pranešė apie krūtinės skausmą ($p = 0,02$), taip papildydamos daugėjančius įrodymus, kad moterų širdies ir kraujagyslių rizika ištvėrmės sporte gali būti sistemingai neįvertinama. Žinios apie treniruotes pagal širdies ritmo zonas buvo susijusios su reikšmingai mažesniu simptomų paplitimu, o tai rodo struktūrizuoto treniruočių planavimo apsauginį poveikį. Tačiau didelė dalis sportininkų, žinančių apie širdies ritmo zonas, jų aktyviai nenaudojo, o tai atskleidžia išliekančią sveikatos raštingumo trūkumą. Svarbus tyrimo rezultatas susijęs su rizikos suvokimu. Tik 3 % dalyvių nurodė vainikinių arterijų kalcifikaciją kaip su ištvėrmės treniruotėmis susijusią riziką, o mažiau nei ketvirtadalis staigią širdies mirtį įvardijo kaip galimą pavojų. Šis tyrimas pateikia įrodymus populiacijos lygmeniu, kad kliniškai reikšmingiausios su ištvėrmės treniruotėmis susijusios širdies ir kraujagyslių rizikos sportininkams dažniausiai išlieka menkai žinomos, todėl pabrėžiamas tikslinio sveikatos ugdymo poreikis ištvėrmės sporto bendruomenėse.

Keywords

Endurance training; Exercise-induced cardiovascular adaptation; Exercise-induced cardiac risk; Risk awareness in athletes

2. Introduction

Endurance sports have gained popularity worldwide among all age and performance groups. A clear social trend toward greater physical fitness, activity, and health awareness is reflected in longer running distances, cycling races, and triathlons. A variety of studies have shown that regular endurance training is associated with numerous cardiovascular benefits, including improved performance, a lower resting heart rate and a better metabolism (1,2). As a result, endurance training is now used as a preventive and therapeutic measure in medicine. However, negative headlines, such as cardiac arrests during competitive sport events or the increasing number of deaths of young people after sporting events such as marathons, have raised public awareness of the potential cardiovascular risks of intense physical activity (3). Excessive and long-term endurance training in particular can also cause pathological changes to the cardiovascular system.

This master's thesis examines the physiological and pathological effects of endurance training on the cardiovascular system, as well as athletes' awareness of these effects. A systematic literature review and a supplementary survey will be used to examine the extent of the benefits and possible risks and how these should be assessed in everyday medical and sporting practice. By combining scientific evidence and the subjective experiences of active endurance athletes, a comprehensive assessment of current findings can be made.

The work should be viewed in a medical context, but it also has social relevance. In an era when exercise is regarded as both preventive and therapeutic, the question arises: Where does beneficial adaptation end and pathological stress begin? This question is also of interest from a training science perspective, with regard to training control, preventive medical checkups, and education. Therefore, the results of this work should be discussed scientifically and used to inform evidence-based recommendations for clinical and sporting practice.

The following section examines the current state of research in this field. This is followed by the online survey results, after a brief reference to the methodology. Finally, the results of the literature are compared and discussed with those of the survey.

3. Literature Review

In order to assess the health effects of endurance training, it is necessary to analyze the current state of research. The following literature review provides an overview of key theoretical approaches, previous study results, and relevant findings on the physiological effects and potential risks of endurance sports. The focus is placed on identifying the conditions that determine whether endurance training is beneficial to health or potentially harmful.

3.1 Physiology of Energy Systems

3.1.1 Aerobic System

The aerobic energy system, also referred to as the oxidative system or Krebs cycle, depends on oxygen to produce adenosine triphosphate (ATP). This process takes place in the mitochondria and is highly efficient, generating approximately 36 ATP molecules per glucose molecule (4). However, the production of this high yield of ATP is time-consuming and relatively slow compared to the other two systems, anaerobic glycolysis and Adenosine triphosphate–phosphocreatine (ATP-PC) system.

The aerobic system represents the primary energy source during prolonged, low-intensity exercise lasting longer than approximately two minutes, such as long-distance running or cycling. It predominantly relies on carbohydrates and fats as fuel substrates, with substrate utilization depending on exercise intensity. Carbohydrates, like glucose and glycogen, are favored during moderate-to-high intensity efforts, while fats become the predominant source during low-intensity, steady-state activity due to their greater energy yield and higher availability in the body. Protein catabolism plays only a minor role and becomes relevant mainly when carbohydrate and fat stores are depleted. The primary metabolic byproducts of the aerobic system are CO₂ and H₂O. These byproducts are easily expelled from the body through exhalation.

Fatigue within the aerobic system is commonly associated with the depletion of carbohydrates reserves during prolonged or high-intensity efforts, and limitations in oxygen delivery. Both result in reduced ATP production and consequent fatigue.

3.1.2 Anaerobic Glycolysis

In comparison to aerobic ATP production, anaerobic glycolysis is O₂-independent and occurs in the cytoplasm outside the mitochondria. Because there is not enough oxygen, glucose breaks down into pyruvate, which is then converted into lactate. This energy system, though significantly less efficient than the aerobic system (yielding only about 2 ATP per glucose molecule), produces ATP at a much faster rate.

Anaerobic glycolysis is the primary energy source for high-intensity efforts lasting between 30 seconds and two minutes. Examples include 400–800-meter running or cycling events and 100–200-meter swimming efforts (5). The primary byproducts of anaerobic glycolysis are lactate and hydrogen ions. These byproducts contribute to an increase in intramuscular acidity, which inhibits enzymatic activity, interferes with muscle contraction and ultimately, this leads to fatigue (6).

Training adaptations to this energy system include an elevated lactate threshold and improved buffering capacity. These adaptations allow athletes to sustain higher exercise intensities for extended periods by postponing the onset of fatigue (7).

3.1.3 ATP-PC System

Finally, the ATP-PC system, also an anaerobic pathway of generating ATP, is unique in its use of stored ATP and phosphocreatine (PCr) for immediate energy supply. This system functions independently of oxygen and does not generate lactate. It is designed to provide rapid bursts of energy for short-duration, maximal-intensity efforts lasting approximately 10–15 seconds (4).

Unlike the other systems, the ATP-PC system does not use carbohydrates or fats as fuel. Instead, energy is derived directly from ATP and the high-energy phosphate bonds in PCr, which are synthesized from dietary proteins. This makes this system the fastest system with immediate energy provision. Practical examples include short sprints, jumps, and explosive athletic movements. As this energy reserve is quickly depleted, full recovery of PCr stores requires adequate rest before maximal effort can be repeated (4,8).

Fatigue in this system is mainly driven by the rapid depletion of PCr and an insufficient rate of ATP resynthesis to meet energetic demands. Training adaptations include increased PCr storage and improved neuromuscular coordination, resulting in enhanced power output and explosive performance (8).

3.1.4 Energy Utilization and Physiology in the Musculoskeletal System

Next to energy production, energy utilization is a critical aspect of physical performance, and the musculoskeletal system serves as the primary site for it during movement. Skeletal muscles are composed of muscle fibers, which contain myofibrils structured with actin and myosin filaments. These filaments interact with each other to result in muscle contraction. This process is regulated by signals transmitted through motor neurons that originate from the motor cortex of the brain. There are three different types of muscle in the body. The muscles associated with physical work are the skeletal muscles, which move bones and joints and can be activated voluntarily. Smooth muscles, which are found in the walls of internal organs and blood vessels, and cardiac muscle are both involuntarily controlled. The skeletal muscles are composed of different types of muscle fibers. These are divided into two types. The first type is called type I, or slow-twitch fibers (9). The second type is called type II, or fast-twitch fibers. Type II fibers are further subdivided into Type IIa and Type IIx fibers (9). Type IIa fibers exhibit both aerobic and anaerobic metabolic characteristics and are therefore classified as oxidative-glycolytic fibers. In contrast, Type IIx fibers rely predominantly on glycolytic metabolism and are specialized for maximal contraction speed and force production,

although they fatigue rapidly. Slow-twitch fibers are more efficient in utilizing energy derived from aerobic energy sources and are therefore more important in long, low-intensity endurance training. On the other hand, fast-twitch fibers are adapted for anaerobic metabolism and play an important role in short, high-intensity exercises (9).

Chronic endurance training leads to significant physiological musculoskeletal adaptations, including increased mitochondrial density and function, which enhances oxygen utilization and aerobic ATP production (9). This adaptation is accompanied by elevated myoglobin concentrations, improving intracellular oxygen storage. Furthermore, increased capillarization enhances oxygen delivery, nutrient transport, and metabolic waste removal (9). These adaptations allow trained athletes to sustain higher intensities before lactate accumulation occurs, reflecting an upward shift of the lactate threshold (6). Overall, these structural and metabolic changes enhance endurance performance and postpone fatigue during prolonged exercise (6,9).

3.2 Training Recommendations for Ideal Health

The idea that there exists an optimal dose of physical activity dates back over 2,500 years to Hippocrates, who stated: *'If we could give every individual the right amount of nourishment and exercise – not too little and not too much – we would have found the safest way to health.'* (10). This quote is still relevant today and reflects the main question: what is the optimal amount of exercise for promoting health and longevity?

Modern research attempts to answer this question. The World Health Organization (WHO) recommends that all adults undertake regular physical activity. Specific recommendations include 150–300 minutes of moderate-intensity aerobic activity or 75–150 minutes of moderate- or vigorous-intensity activity per week for substantial health benefits (11). Additional health benefits are seen with levels of activity above these minimums. Moreover, muscle-strengthening exercises targeting all major muscle groups are recommended at least two days per week. Studies from the US show that more than 50% of Americans do not meet these requirements, suggesting low adherence (10).

First, even 2,500 years later, it is still not possible to answer Hippocrates's question about the optimal amount of exercise. Nevertheless, it is generally accepted that approximately 2.5 to 5 hours of moderate- to vigorous-intensity physical activity per week are associated with optimal health benefits. In addition, some evidence suggests that even around 15 minutes of light- to moderate-intensity exercise per day may confer beneficial effects on longevity, consistent with WHO recommendations (10).

On the other hand, there may be a threshold where the benefits of exercise begin to diminish. This is reflected in the Reverse J-Curve Hypothesis, which suggests that high volumes and especially

extremely high volumes of physical activity could reduce the benefits on mortality reduction (10). At the same time, a U-shaped dose-response curve suggests that excessive exercise may also increase the risk of acute cardiovascular events, particularly in susceptible individuals (12). While both terms describe the diminishing returns of excessive exercise, they refer to distinct aspects. The Reverse J-Curve specifically describes the relationship between training volume and mortality risk. The greatest mortality benefit is observed at moderate-to-vigorous intensity activity levels. Beyond this point, increasing volumes progressively reduce this advantage. Importantly, even very high training volumes remain more beneficial than physical inactivity (10). The U-shaped curve more broadly describes the relationship between exercise dose and cardiovascular risk or symptom burden, where both insufficient and excessive training are associated with elevated risk compared to moderate levels (12). With regard to the reverse J-Curve, data shows that individuals who burned between 500 and 3,500 kcal/week through physical exercise showed a lower risk of death. In particular, those expending 3,000-3,500 kcal/week experienced a 54% reduction in mortality risk, whereas those exceeding 3,500 kcal/week only experienced a 38% reduction (10). This indicates that very high levels of exercise may still be beneficial, but with a reduction in benefits on mortality risk. It is estimated that exceeding approximately 10 hours per week of moderate to vigorous physical activity lead to a reduction in the associated health benefits. The study indicates that approximately 2.5% of Americans engage in more than 10 hours of sports per week (10).

The Metabolic Equivalent of Task (MET) is the standard measurement for calculating burned calories. 1 MET represents the energy cost of sitting at rest, defined as 3.5mL O₂ per kg of body weight per minute, or about 1kcal/kg/hour. In practice, activities can be categorized by intensity mainly based on MET values (13,14):

- 1.0-1.5 MET: Sedentary behavior activities
- 1.6-2.9 MET: Light-intensity activities
- 3.0-5.9 MET: Moderate-intensity activities
- ≥ 6 MET: Vigorous intensity activities

An individual's fitness level is often measured by their exercise capacity in METs, assessed during a standardized exercise stress test. Unfit individuals typically achieve a maximum of less than 5 METs, corresponding to an inability to sustain moderate-intensity activity. This is associated with significantly higher cardiovascular and all-cause mortality risk. Physical activity is associated with a significant reduction in all-cause mortality, with greater benefits observed at higher fitness levels (10). However, the MET is associated with limitations. Factors such as age, sex, body fat composition,

muscle mass, and existing medical conditions and diseases can significantly influence MET values (13,14).

3.3 Cardiovascular Benefits

Regular physical activity brings about profound cardiovascular benefits through both immediate physiological responses and long-term adaptations. These alterations improve physical fitness, enhance cardiovascular effectiveness, and decrease the likelihood of chronic illnesses such as high blood pressure, coronary artery disease (CAD), type 2 diabetes, and stroke (2,10,15). This chapter outlines both acute and chronic cardiovascular adaptations to exercise and discusses the concept of the athlete's heart. It also explains how different endurance sports, including running, cycling, and swimming, lead to distinct forms of cardiovascular remodeling.

3.3.1 Cardiovascular Adaptations to Exercise

When exercising, the body's oxygen demand rises, requiring an increase in cardiac output ($\dot{Q}$), which is achieved through elevated heart rate (HR) and stroke volume (SV). Muscles simultaneously increase oxygen extraction, enhancing the arterial-venous oxygen difference. Additionally, blood is redirected from non-active tissues toward working muscles, maximizing oxygen delivery and efficiency (15).

With consistent endurance training, these acute responses become more effective:

- VO_2max increases due to enhanced $\dot{Q}$ and peripheral oxygen extraction.
- Resting HR and blood pressure decrease, reflecting improved autonomic regulation and cardiovascular efficiency.
- SV increases, allowing the heart to pump more blood with each beat at a lower HR.

These improvements allow trained individuals to perform the same muscle performance with reduced myocardial oxygen consumption (MO_2), indicating superior cardiovascular economy (10,15).

3.3.2 Structural and Electrical Remodeling – The Athlete's Heart

Long-term endurance training induces structural and electrical adaptations known as the athlete's heart. These changes include (15):

- Left ventricular (LV) enlargement and increased compliance.
- Batrial dilation and mild LV wall thickening.
- Resting bradycardia due to increased vagal tone and reduced sympathetic activity.
- Benign electrocardiogram (ECG) findings such as sinus bradycardia, first-degree AV block, Mobitz type I, right bundle branch block, and early repolarization patterns.

While these findings may resemble pathological changes such as hypertrophic cardiomyopathy (HCM) or dilated cardiomyopathy, they are generally considered benign in trained individuals (10,15). However, competitive endurance sport simultaneously represents a potential trigger for pathological remodeling. Distinguishing between physiological adaptations from pathology remains one of the central challenges in sports cardiology (16). Differentiation often involves evaluating reversibility through a period of detraining, during which cardiac changes typically regress within 6 to 34 weeks, while pathological remodeling persists (15).

3.3.3 Cardiovascular Response During Exercise

During dynamic exercise, $\dot{Q}$ increases linearly with oxygen consumption (VO_2) (15). Specifically, $\dot{Q}$ increases by approximately 5-6 L/min per 1 L/min increase in VO_2 . In addition, arterial-venous oxygen difference widens due to enhanced muscle contraction and redistribution of blood flow (15). This results in an elevated MO_2 , particularly in individuals with pre-existing coronary disease, where oxygen supply-demand imbalance can reveal ischemia. However, trained individuals exhibit improved myocardial efficiency, achieving higher workloads with relatively lower HR and MO_2 (15).

Workload during exercise can be classified into external and internal (15). External workload reflects the total body's energy demand for VO_2 during work, which is a direct determinant of $\dot{Q}\text{VO}_2$ and can be estimated via treadmill speed, incline, or bicycle wattage. Internal workload refers to the cardiovascular system's effort, primarily MO_2 , which correlates with HR and cannot be directly estimated from factors such as wattage (15). Athletes with higher $\text{VO}_{2\text{max}}$ can manage greater external demands at a lower internal cost, due to higher SV and lower HR at the same external work, reducing cardiovascular strain and improving performance (15).

3.3.4 Sport-Specific Cardiovascular Adaptations

Each endurance sport induces a cardiovascular profile based on biomechanics, intensity, and duration. In the following, a comparison between the most common endurance types of sports, running, cycling, and swimming is analyzed.

3.3.4.1 Runners

Running is associated with the best results in lowering resting HR (~49 Beats per minute (BPM)) compared to others like cycling and swimming. This bradycardia is a result of increased vagal tone and structural changes in the heart. Cardiac remodeling affects both ventricles (15). First, the left ventricle demonstrates enhanced diastolic function, marked by accelerated relaxation and early filling. This contributes to higher SV and $\dot{Q}$ during extended periods of exercise (17). Second, considerable workload is experienced by the right ventricle, especially during long-distance events like marathons, where significant rises in pulmonary artery pressures are seen (18). These adaptations

promote high aerobic capacity and efficiency, as evidenced by a higher $\text{VO}_{2\text{max}}$ and enhanced ventilation when compared to other endurance athletes (19). In addition, runners may benefit from increased HDL cholesterol levels, which are protective for cardiovascular health (20). However, running may also be associated with certain risks. Prolonged high-intensity running can increase oxidative stress due to the accumulation of free radicals, which are highly reactive molecules with unpaired electrons. Elevated oxidative stress may potentially contribute to myocardial fibrosis and the development of atherosclerosis. In addition, running places considerable physical demands on the body, including neuromuscular fatigue and increased joint stress due to its repetitive high-impact nature (19).

3.3.4.2 Cyclists

Cyclists also experience a lower resting HR (~60 BPM) and develop good SV and muscle oxidative capacity, particularly during submaximal exercise. Although $\text{VO}_{2\text{max}}$ may not increase as dramatically as in runners, cyclists often experience improved endurance with less fatigue. The low-impact nature of cycling makes it a safer option for beginners, older adults, and individuals with joint problems. There is a lower risk of musculoskeletal injury and neuromuscular fatigue compared to running (19). However, some studies have noted a higher prevalence of coronary artery calcification (CAC) in cyclists, which has been linked to factors such as bone mineral density and parathyroid hormone regulation (20). Additionally, a study suggests that cyclists show a lower overall coronary plaques burden compared to runners (21).

3.3.4.3 Swimmers

Swimming is a unique form of endurance exercise because it takes place in water, which creates specific physical demands on the body. One of the main differences is the effect of hydrostatic pressure. This pressure applies constant resistance to the chest wall, which helps to strengthen the inspiratory muscles and improve lung capacity over time (22,23). Along with the horizontal body position during swimming, hydrostatic pressure also increases venous return and preload (22,23). This leads to more blood filling in the heart and higher right atrial pressure. Given the horizontal orientation of the body, the heart is not compelled to contend with the same gravitational forces as it does during upright activities. This results in a reduction of the overall cardiac workload (22). This is often seen in swimmers as a lower resting left ventricular ejection fraction (LVEF) (23). However, this is not a sign of poor heart function, but rather a normal adaptation to the higher volume load. Nevertheless, chronic volume overload is a risk factor (23). As a result of these conditions, swimmers often show significant heart remodeling. Research has shown that swimmers can have some of the largest heart sizes among athletes, including thicker heart walls and larger chambers (22,23). However, right ventricular remodeling is present but less extensive compared to other disciplines like

running. This phenomenon may be attributable to the distinct demands imposed on the pulmonary circulation and the right side of the heart during swimming (22,23). Swimmers usually have a lower resting HR (~56 BPM), similar to other endurance athletes, such as cyclists. This diminished HR is principally attributable to diminished activity in the sympathetic nervous system and augmented parasympathetic tone (23). One of the most specific conditions for swimmers is pulmonary edema, also called swimming-induced pulmonary edema (SIPE) (18). This will be discussed later.

3.3.5 Detraining and Reversibility

Detraining occurs when training-induced adaptations are partially or completely lost due to reduced or discontinued physical activity (24). Cessation of training helps distinguish physiological from pathological changes. Detraining causes changes in cardiorespiratory, muscular, hormonal, and metabolic systems (15,24). It is recommended especially in professional athletes or individuals with prominent risk factors or pathological features. In trained athletes, cardiac chamber sizes, wall thickness, and HR return to baseline within 6–34 weeks (15). Complete reversal may occur within 6 months, supporting the benign nature of these adaptations. This concept is particularly important in ruling out HCM, where cardiac remodeling persists despite detraining (15).

3.4 Cardiovascular Risks of Exercise in Athletes

This chapter examines the main potential risks associated with chronic endurance training, including electrical and structural changes.

3.4.1 Arrhythmias

3.4.1.1 Atrial fibrillation

Starting with the most common maladaptation in endurance athletes, atrial fibrillation (AF). This is also one of the important hallmark features of cardiac overuse syndrome, a term describing chronic overload-related maladaptation (10,15). AF can occur due to increased atrial size, training-induced changes in autonomic tone, and acute and chronic inflammation due to training. AF was shown to be 5-fold more prevalent among veteran endurance athletes compared to a sedentary control group (10,15). Furthermore, a strong association between AF and long-term exercise experience, more than 2,000 training hours or more than 20 years of endurance training, was shown. This correlation was found even without underlying cardiovascular risk factors, which underscores the direct relation to endurance training (10). Further studies linked males, and especially those who completed most races with the best performances, to a higher risk of developing AF than females (15). This assumption has recently been challenged. A matched cohort study with a follow-up of nearly 29 years found that elite female endurance athletes had a hazard ratio of 3.67 for AF development compared to matched controls. This suggests that the risk of AF in female endurance sport may be significantly

underestimated by a predominantly male evidence base (25). Moreover, it is a more common feature in older athletes, where individuals should be evaluated like non-athletes. It is essential to rule out underlying medical conditions related to the cardiac system, hyperthyroidism, excessive alcohol consumption, or sleep apnea. In young athletes, AF is an uncommon condition and suggests underlying structural abnormalities that require close monitoring and supervision (15,17). The following risk pattern provides an overview of AF-associated risk with respect to MET (10):

- < 6 METs fitness → higher AF risk.
- 5–20 MET-h/week → reduced AF risk.
- > 55 MET-h/week or >10h/week vigorous exercise → AF risk exceeds that of sedentary individuals.

3.4.1.2 Ventricular Tachycardia

Ventricular Tachycardia (VT) is a widely discussed electrical adaptation seen in endurance athletes. It is often found within the athlete's heart syndrome, but its beneficial or risk profile remains unclear (10). It may be a result of structural remodeling due to chronic endurance exercise, which induces progression of proarrhythmogenic state. Others argue that excessive activity of the sympathetic nervous system and catecholamine overload result in increased oxidative stress, which ultimately can lead to fibrosis and electrolyte shifts. It was shown that former professional cyclists had a 5-fold higher VT compared to recreational golfers ($n = 309$). Further investigations are needed to determine its beneficial or risk profile (10).

3.4.2 Myocardial Fibrosis

In addition to electrical cardiovascular (CV) changes, there are also structural changes including myocardial fibrosis (MF). An increase in MF is directly related to chronic high-volume training, such as the number of years of training, marathons completed, and ultra-endurance events (10,15,26). Primarily the right ventricle (RV) is affected by this, which can be explained by disproportionate strain on the RV wall, up to 125% compared to 5% in the LV. This causes, as seen in VT, chronic catecholamine and reactive oxygen species (ROS) exposure, which leads to myocardial injury and finally to fibrosis and scarring (10). The state of fibrosis can be evaluated via MRI visualization with Late Gadolinium Enhancement (LGE) (10,26). LGE was found to be 12% more prevalent in endurance athletes with high levels of physical activity compared to a control group, which showed a prevalence of 1.5% and engaged in no more than the minimum level of physical activity recommended by the WHO (10,26). However, clinical relevance is lacking so far; the state of fibrosis suggests a prognostic role. Athletes with increased LGE levels are associated with a higher risk of

major adverse cardiovascular events (MACE) and coronary revascularization. In contrast, CAC is predictive of LGE presence (10,26).

3.4.3 Coronary Artery Calcification

CAC is considered one of the most clinically relevant, yet counterintuitive cardiovascular findings observed in long-term endurance athletes. Despite the well-established cardiovascular benefits of regular physical activity, observational data consistently documents elevated CAC scores and greater total coronary plaque burden in older male endurance athletes compared to non-athletes (10). CAC levels are reliable predictors of MACE. The Agatston score is used to quantify coronary calcification on CT imaging. Values exceeding 300 Agatston units indicate particularly elevated cardiovascular risk (10). Elevated CAC burden has been observed in athletes performing more than 3,000 MET-minutes per week (10).

Earlier studies suggested that the higher plaque burden in athletes reflected a more benign composition, with predominantly calcified and therefore more stable plaques, leading to the assumption that elevated CAC in athletes carried lower clinical risk (21). A large comparative cohort study found that lifelong endurance athletes showed the highest total coronary plaque burden regardless of plaque type (21). While calcified plaques remain the predominant type in all groups, lifelong endurance athletes showed a significantly higher absolute prevalence of non-calcified and mixed plaques compared to controls, particularly in proximal coronary segments. As non-calcified plaques are considered more prone to rupture than calcified plaques, this challenges the earlier hypothesis that elevated CAC in athletes represents a more benign form of atherosclerosis (21). Furthermore, exercise intensity rather than volume was identified as an independent driver of coronary atherosclerosis progression over a six-year follow-up period in middle-aged athletes. Very vigorous intensity exercise was associated with greater plaque progression, whereas vigorous intensity exercise was linked to less progression (27).

The clinical significance of elevated CAC in otherwise fit athletes with no traditional cardiovascular risk factors remains unclear. Symptom freedom does not reliably exclude progressive coronary pathology, and high-volume endurance training cannot be assumed to provide universal protection against atherosclerosis. These findings underline the importance of individualized cardiovascular risk assessment in long-term endurance athletes (12).

3.4.4 Valvular and Structural Changes

3.4.4.1 Cardiac Remodeling

Next to electrical changes, there are structural changes in the athlete's heart. HCM is a common and often physiological change in chronic endurance training, seen as part of it (15,28,29). Typically, there

is a 4-chamber enlargement present in excessive training, often exceeding the standard upper limits of normal (ULN) (15). Endurance training causes volume overload and ultimately leads to an eccentric form of hypertrophy, which is mainly seen in the LV (15,28–31). This contrasts with strength training, which is associated with sudden and large pressure overload resulting in concentric hypertrophy (28,29). This is consistent with evidence showing that throwing athletes, as a model of chronic resistance training, exhibit greater intraventricular septal thickness compared to endurance athletes and sprinters (31). In addition to cardiac remodeling, studies have reported increased aortic sizes, especially in younger athletes (15). The long-term consequences require further investigation.

LV is significantly influenced by endurance training. This can be recognized by the increase in size and thickened walls, especially in athletes with the slowest HR (15,28). However, the thickened walls rarely exceed ULN in athletes (15). In comparison, the ventricular adaptations of strength-trained athletes remain more contested in the literature due to diverging findings. While some sources report primarily increased LV wall thickness exceeding the ULN, others identify the RV as the primary site of remodeling (15,30). Furthermore, other studies observed LV adaptations in athletes combining endurance and strength training, though the independent contribution of resistance training could not be clearly isolated (28). Nevertheless, these two concepts of endurance-trained and strength-trained hearts should be considered as references rather than absolute guideline values (15). Another aspect is LVEF, which is less affected due to increased ventricular size and the metabolic demands are met even with normal and lower ranges (15).

RV dysfunction and remodeling were also seen in chronic high-intensity exercise (30). Next to higher risk of fibrosis, like discussed in MF, the right ventricular ejection fraction (RVEF) is affected (10). This was shown by post-race studies, where the RVEF dropped by approximately 9% in marathoners and even more the longer the distance was. This is compared to no significant changes in LVEF. Additionally, long-term training, referring to more than 20 years, is associated with lower resting RVEF and irreversible remodeling seen in RV (10). Moreover, the excessive load on the RV can lead to chronic pro-arrhythmic RV remodeling (10,30).

3.4.4.2 Valvular Diseases

Important valve diseases, such as aortic stenosis (AS) and aortic regurgitation (AR), associated with endurance training, are often overlooked or ignored by athletes and physicians (15). Starting with AS, it is often ignored even in critical states. Dyspnea at the beginning of exercise, also called warm-up dyspnea, which spreads within 5-10 minutes, indicates clinically important AS and needs to be checked (15).

On the other hand, AR is generally well tolerated by many athletes due to increased HR, which decreases diastole and regurgitant flow. Therefore, athletes are only restricted when severe stages of AR are present (15).

3.4.5 Myocardial Injury Biomarkers

Elevated cardiac enzymes and biomarkers, such as cardiac troponin and brain natriuretic peptides, are clinical markers of myocardial injury and are especially associated with acute myocardial infarction (AMI) (10,15). However, these markers often rise transiently in post-endurance race events, which can be a sign of mild myocardial injury or release of free Tn due to increased permeability of sarcolemma (10). Nevertheless, their kinetics differ from AMI patterns and normalize more quickly than in AMI (15). Clinical significance regarding these markers and their long-term risk remains under investigation.

3.4.6 Pulmonary Embolism

Next to AS, pulmonary embolism (PE) is a very common underrecognized condition in athletes due to atypical presentation and fitness masking symptoms. Risk factors for developing PE include dehydration, trauma, oral contraceptives, and genetic thrombophilia (15). Especially swimmers, but also runners, are affected by this, which is called SIPE (18,32). SIPE is more common in young athletes without prior underlying conditions and who perform mainly open water swimming. In total, 300 cases have been reported (18). The pathophysiology behind it is not fully understood but believed to be hemodynamic pulmonary edema due to pressure changes and increased venous return in horizontal position. A 24-hour resolution of this condition, which can recur under similar conditions, is important (18).

3.5 Cardiovascular Pathologies in Athletes

Following the cardiovascular risk, this chapter focuses on the main pathologies and cardiovascular events related to endurance training.

3.5.1 Sudden Cardiac Death

The incidence of sudden cardiac deaths (SCD) has risen in recent years, with a higher rate of occurrence among older individuals who are not professionally trained and engage in recreational sports (3,10,15). Although the absolute incidence of SCD in competitive settings remains low, the underlying structural anomalies are frequently asymptomatic and undetectable by standard resting examinations (33). This underscores the importance of exercise-based screening protocols. Current ESC guidelines therefore recommend a systematic pre-participation cardiovascular evaluation as the cornerstone of SCD prevention in competitive athletes. This evaluation includes a detailed personal

and family history, a physical examination, and a resting ECG (17). Studies have shown that the risk of suffering from SCD is 25-fold higher for sedentary individuals than for those who are at least moderately active (10). Converted into numbers, this equates to an incidence rate of approximately 1 in 50,000 per year in young competitive athletes and 1 in 22,000 to 1 in 69,000 per year in adult recreational athletes. Young athletes are defined as those under 35 years of age, while adult athletes are those aged 35 and above (3,10,15). Of those who experienced cardiac arrest, only 29% survived. SCD risk is transiently increased in athletes performing vigorous endurance activity with ranges between 3-17-fold risk compared to non-athletes (10). Furthermore, it was found that the duration of endurance exercise has a direct influence on the possible risk of SCD. Approximately 11 million long-distance participants were examined, of whom half marathon participants showed an incidence of 0.27 per 100,000, while the incidence among marathon runners was 1.01 per 100,000, which is about 3.7 times higher. Taking even more extreme endurance competitions such as triathlons into consideration, the incidence of SCD risk in 4.7 million athletes is up to 1.74/100,000 (10). Moreover, death rates in males were more than double the amount compared to females (0.98 vs 0.41/100,000), suggesting women are less susceptible to adverse cardiac effects of chronic high dose endurance exercise (10). Consistent with this, sports-related cardiac arrest has been reported to be more than ten-fold less frequent in women than in men, despite comparable characteristics including age, history of cardiac disease, and circumstances of occurrence (33). Despite the lower absolute incidence of exercise-related cardiac events in women, cardiovascular symptoms in female patients are more frequently misattributed to non-cardiac causes, and women receive fewer diagnostic investigations for equivalent complaints compared to men. This systematic underdiagnosis may contribute to an underestimation of female cardiovascular risk in endurance sport (34). It was thought for a long time that HCMs are the cause of developing SCD, but current studies suggest that inherited channelopathies are more likely due to a lack of structural abnormalities in more than 40% of autopsies (15). Regarding the underlying causes, cardiomyopathies and channelopathies account for the majority of identifiable cases, while a substantial proportion of SCD events in athletes remain unexplained on autopsy (33). Moreover, other studies suggest that in athletes older than 35 years of age, CAD represents the predominant cause of death. In contrast, younger athletes are associated with autopsy-negative SCD, myocarditis, and cardiomyopathies (3,10).

3.5.2 Acute Myocardial Infarction

Next to SCD, AMI is a prominent condition in endurance athletes (10,15,26). Within one hour after intense exertion, the risk of developing AMI and subsequently dying from SCD is 2-10-fold increased (10). Causes of AMI include mainly plaque rupture during high strain or spontaneous artery dissection in younger athletes (15).

3.5.3 Overtraining Syndrome

Finally, overtraining syndrome (OTS), also referred to as paradoxical deconditioning syndrome, describes a state in which a persistent imbalance between exercise stress, non-training load, and recovery leads to prolonged maladaptation, resulting in long-term performance impairment and multisystem dysfunction (15,35). OTS occurs predominantly in high-level endurance athletes. Survey studies report that 60% of elite female and 64% of elite male runners have experienced at least one previous episode during their career. A rate of approximately 33% has been reported in nonelite adult runners, with similar rates in young athletes. Additionally, athletes who have previously experienced OTS are at a heightened risk of relapse (35). Overtraining can be understood like a cycle: first, there is appropriate training that leads to progress and improvement, and all the factors mentioned above are in balance (15,35). The second phase is the so-called overreaching phase, which presents as short-term exercise-induced fatigue that requires appropriate rest for recovery. It is subdivided into two stages. Functional Overreaching (FOR) involves a short-term performance decrement lasting days to weeks. With adequate recovery, it leads to supercompensation and performance improvement. If recovery remains insufficient, Nonfunctional Overreaching (NFOR) develops. This stage is characterized by a prolonged performance decrement lasting weeks to months, without improvement above the initial baseline (35). Finally, overtraining is the result of inappropriate recovery during the NFOR phase, leading to a decline in performance (15,35). OTS can be further classified into Hyperarousal or parasympathetic OTS, which is more common in long-distance endurance athletes, and typical findings include exhaustion, low energy, and fatigue. The second type is less frequent and is known as hyperarousal or sympathetic OTS. It is more common in sprinters and weightlifters and presents with increased HR, irritability, and anxiety (15,35). Theories about the causes and pathophysiology of OTS involve multiple interacting mechanisms, including glycogen depletion, elevated ROS, increased release of pro-inflammatory cytokines, and disruption of the hypothalamic-pituitary-adrenal axis. Critically for cardiovascular function, a prolonged imbalance of the autonomic nervous system with elevated sympathetic and suppressed parasympathetic tone leads to persistent cortisol secretion, reduced HR variability, and impaired cardiac recovery capacity. These imbalances further contribute to resistance to recovery mechanisms, making OTS particularly difficult to reverse without adequate rest (35). A physician should only diagnose OTS when other causes of symptoms are ruled out and certain criteria are met. These include decreased exercise tolerance, nocturnal fever, weight and mood changes, and paradoxical insomnia, which may manifest as restlessness and involuntary muscle contractions (15,35). There are no specific diagnostic tests available. Changes in blood chemistry or a slight increase in resting HR may support the diagnosis, but neither is sufficient alone (35).

A hallmark feature of OTS is an unexplainable decrease in sport-specific performance capacity despite maintained or increased training load. Athletes experiencing OTS are typically able to begin training or a race at their usual pace but are unable to complete the session or perform as expected. An exercise performance test is therefore considered essential for the diagnosis of OTS (35).

The prevention of OTS is further complicated by a well-documented gap between health knowledge and health behaviour. Individuals may possess awareness of risk-relevant information without translating it into their training decisions, a phenomenon known as the intention-behaviour gap (36). Research demonstrates that health intentions explain only 28% of the variance in actual health behaviour. This means that knowledge alone is an insufficient driver of behaviour change. Structured coaching and targeted training guidance are therefore essential to bridge this gap in endurance sport (36).

3.6 Endurance Fitness Tests

Endurance fitness refers to the capacity of cardiovascular, respiratory, and muscular systems to sustain prolonged physical effort. It is a key determinant of both athletic performance and cardiovascular health. Its assessment has undergone substantial development, progressing from basic observational approaches to advanced laboratory diagnostics, and more recently to wearable technologies that enable field-based evaluation (5,37). The following sections outline the primary methods used to assess endurance capacity, progressing from subjective perception-based tools to objective laboratory diagnostics and wearable technologies

3.6.1 Subjective Perception of Effort

One of the earliest and still widely used tools for assessing exertion is the Borg Rating of Perceived Exertion (RPE) scale ranging from 6–20, which correlates with HR and oxygen consumption. RPE is influenced by multiple factors including muscle fatigue, breathing effort, and locomotion speed (5). In sports such as swimming, where wearable metrics are limited or unreliable, perceived exertion remains the primary indicator, even at elite levels, due to the unique conditions of water-based environments (5).

3.6.2 Spiroergometry (Respiratory Gas Analysis)

Spiroergometry is rated as very good in the assessment of cardiorespiratory endurance, especially for determining $\text{VO}_{2\text{max}}$, the maximal oxygen uptake. This method measures key respiratory parameters, including oxygen uptake, carbon dioxide output, breathing frequency, and ventilation (5). The Douglas Bag technique is described as a very accurate technique, but is also considered very complex to perform. While $\text{VO}_{2\text{max}}$ is often genetically linked and can be high even in young athletes, endurance capacity improves with age through increased anaerobic threshold and metabolic

efficiency. Beyond VO_2max , spiroergometry provides insights into aerobic vs. anaerobic energy contributions, as well as substrate utilization (carbohydrate vs. fat metabolism), which are valuable for performance profiling and training optimization (5).

3.6.3 Lactate Diagnostics

Lactate threshold testing provides crucial insights into metabolic transitions during incremental exercise. The aerobic threshold is typically identified when blood lactate levels rise by >0.4 mmol/L (ergometer) or >0.3 mmol/L (treadmill) above baseline, corresponding to $\sim 75\text{--}80\%$ of HR_{max} (5). The anaerobic threshold, or maximal lactate steady-state, occurs when lactate begins to rise exponentially and reflects $90\text{--}95\%$ of HR_{max} . This test, performed via capillary blood samples from the earlobe or fingertip, is essential for determining individualized training zones. It provides a metabolic snapshot of anaerobic activity and is particularly effective for tailoring endurance training regimens (5).

3.6.4 Fitness Technology in Endurance Testing

Recent advances in wearable technologies have extended endurance diagnostics beyond laboratory settings, enabling continuous monitoring and real-time feedback. This provides a wide range of accessibility for every type of sport and level of performance.

3.6.4.1 Heart Rate Monitors

Heart Rate Monitors (HRMs) are commonly categorized into (38,39):

- Electrical (ECG-based): Typically, chest straps; high accuracy with a typical error margin of ± 2 beats/min.
- Optical (PPG-based): Wrist-worn devices that use photoplethysmography (PPG) to estimate blood volume changes.

While wrist-based HRMs offer convenience and generally good accuracy compared to chest straps, they can show considerable deviations during intense motion or underwater use. Factors such as sensor placement, skin contact, posture, and ambient temperature can significantly affect accuracy (38,39).

3.6.4.2 VO_2max estimation

Wearable devices are able to estimate VO_2max using HR and GPS data, though accuracy varies considerably depending on device type, running intensity, and individual fitness level. The mean absolute percentage error between smartwatch-derived and laboratory-measured VO_2max has been reported at approximately $4\text{--}7\%$ under controlled conditions (39).

3.6.4.3 Pulse oximetry and medical applications

Pulse oximetry, increasingly incorporated in wearables, is effective in clinical settings but less reliable during intense physical activity due to motion artifacts and low oxygen conditions. For individuals with chronic respiratory diseases such as asthma or chronic obstructive pulmonary disease (COPD), continuous monitoring can aid in health management, though athletic use remains limited (39).

In addition, wearables show potential in the early detection of arrhythmia. However, most PPG-based devices lack the specificity to distinguish among arrhythmic subtypes, a limitation especially relevant in both clinical and athletic contexts (38). Current research emphasizes the need for enhanced validation protocols for wearable diagnostic use (38).

3.6.4.4 Fitness apps

Some athletes use fitness apps not only for tracking workouts but also for motivation, training guidance, nutritional support, and sleep monitoring. A 2024 survey of 1,452 fitness app users aged 18 and older found that these apps positively influence well-being, primarily through mechanisms such as upward social comparison and enhanced self-regulation (40). However, caution is needed with regard to risk of obsession and variable effectiveness on users due to individual differences.

3.6.5 Impact of Endurance Technology on Athletes and Public Health

Wearable fitness technologies have contributed significantly to public health by promoting physical activity and enabling early detection of physiological abnormalities (38). Recreational users benefit from increased motivation and health tracking, while competitive athletes utilize these tools for individualized training feedback, performance optimization, and fatigue management (38–40). Despite technological advances, challenges remain. Measurement discrepancies in HR, VO_2max , and SpO_2 under dynamic conditions, as well as data synchronization issues, may limit precision (38,39). Moreover, daily fluctuations in VO_2max , influenced by chronotype, body temperature, and lactate metabolism, should be considered when interpreting data (5,38). Future developments must focus on enhanced motion artifact correction, improved cross-device integration, and standardized validation protocols for use in both recreational and clinical endurance diagnostics.

3.7 Managing Risks

This chapter provides an overview of Training Intensity Distribution (TID) models in endurance sports. It discusses their respective impacts on VO_2max , work economy, and long-term athletic performance.

3.7.1 Zone Training

Training intensity can be divided into zones based on physiological thresholds, primarily the first and second ventilatory thresholds (VTs 1 and VTs 2) (5,37). Based on the VTs, training intensity can be physiologically divided into three zones (5,37). For more precise practical training control, this is typically expanded into five or even seven zones using HR and blood lactate levels as objective markers (5). The five-zone model, which is widely applied in endurance sports such as running and cycling, is defined by HR percentages (% of HRmax) or blood lactate concentrations ($\text{mmol}\cdot\text{L}^{-1}$) (5,37):

- Zone 1 (50–65% $\text{VO}_{2\text{max}}$, 60–72% HRmax): Very light intensity. Lactate remains at baseline levels ($0.8\text{--}1.5\text{ mmol}\cdot\text{L}^{-1}$). It feels easy and continuous conversation is possible.
- Zone 2 (66–80% $\text{VO}_{2\text{max}}$, 72–82% HRmax): Light aerobic intensity. Lactate begins to rise slightly ($1.5\text{--}2.5\text{ mmol}\cdot\text{L}^{-1}$). Talking remains comfortable but perceived effort increases slightly.
- Zone 3 (81–87% $\text{VO}_{2\text{max}}$, 82–87% HRmax): Moderately intense exercise. Blood lactate starts to accumulate although a steady state is still achievable ($2.5\text{--}4.0\text{ mmol}\cdot\text{L}^{-1}$). Speaking is limited to short sentences.
- Zone 4 (88–93% $\text{VO}_{2\text{max}}$, 88–92% HRmax): Threshold intensity. Lactate accumulates rapidly and no steady state is achieved ($4.0\text{--}6.0\text{ mmol}\cdot\text{L}^{-1}$). Fatigue sets in quickly and speaking is reduced to single words.
- Zone 5 (94–100% $\text{VO}_{2\text{max}}$, 93–100% HRmax): Supramaximal efforts. Effort is sustainable for only a few seconds to minutes ($6.0\text{--}10.0\text{ mmol}\cdot\text{L}^{-1}$). Speaking is nearly impossible

Each zone targets distinct physiological adaptations based on the underlying metabolic processes, enabling finer control of training stimuli (5,37).

3.7.2 Training Intensity Distribution

TID refers to how training load is allocated across different intensity zones over time. In scientific studies, intensities are usually measured using physiological thresholds rather than training-specific metrics. These are based on Low-intensity work (LIT), Moderate intensity (MIT), and High-intensity training (HIT) (41).

- LIT ($< \text{VTs 1}$ / $<2\text{ mmol}\cdot\text{L}^{-1}$): 75–80% of training. Supports aerobic adaptations and aids recovery.
- MIT (between VTs 1 and VTs 2 / $2\text{--}4\text{ mmol}\cdot\text{L}^{-1}$): Minimized due to lower return-to-fatigue ratio.

- HIT ($>VTs\ 2 / >4\ \text{mmol}\cdot\text{L}^{-1}$): 15–20% of training. Targets maximal cardiovascular and metabolic capacity.

Several TID models exist: (42)

- High-Volume Low-Intensity Training emphasizes Zone 1 (below $VTs\ 1$), characterized by large volumes of low-intensity work.
- Threshold Training (THR) focuses on moderate-intensity training around the lactate threshold (Zone 2), ~40% MIT, less LIT and HIT.
- High-Intensity Training (HIT) centers on efforts above $VTs\ 2$, where blood lactate exceeds $4\ \text{mmol}\cdot\text{L}^{-1}$ (Zone 3).
- Polarized Training combines mostly low-intensity (75–80%) with some high-intensity training (15–20%), while minimizing moderate-intensity volume.
- Pyramidal Training follows a decreasing distribution from low to high intensity ($Z1 > Z2 > Z3$), ~70% LIT, followed by decreasing MIT and HIT.

3.7.3 Comparison of TID Models

A systematic review supports the efficacy of the polarized model in improving $VO_{2\text{max}}$, $VO_{2\text{peak}}$, work economy, and endurance performance (41). Some studies consider this training model as a gold standard in endurance training due to its optimized ratio between training load, recovery and physiological adaptations (37). However, response variability across individuals and study designs limits the generalizability of these findings, as most studies were short-term, ranging from 6 weeks to 5 months (41).

Among professional-competitive endurance athletes, an analysis of 175 TID profiles revealed that Pyramidal TID was most prevalent (89 cases), followed by Polarized TID (65 cases), and only 8 cases followed a Threshold-focused model (42). Sport-specific differences emerged showing cyclists and swimmers trained more in MIT ($Z2$), while triathletes, runners, and skiers consistently performed over 80% of training in LIT ($Z1$) (42). During competition phases, higher proportions of HIT ($Z3$) were observed (42).

While polarized training deliberately minimizes Zone 3 (in a 5-zone model) due to its unfavorable fatigue-to-adaptation ratio, THR models specifically target this intensity zone and have demonstrated short-term improvements in $VO_{2\text{max}}$ and lactate threshold (37,41,42). These contrasting approaches reflect a broader methodological debate in the field. The effectiveness of each model remains contested and given the considerable individual response variability documented across studies, no

single intensity distribution can be universally recommended (42). Future research should focus on precise intensity quantification and long-term sport-specific evaluation of TID strategies (41,42).

3.7.4 Minimizing Potential Risks

Risks exist at both ends of the spectrum, with both insufficient and excessive endurance training. Many competitive athletes undergo regular professional performance diagnostics, while recreational athletes usually do not.

Current studies suggest that the optimal amount of training for optimal health is 2.5 to 5 hours per week at moderate to intense intensity, with an energy expenditure of 3,000–3,500 kcal/kg/week or 5–20 MET-h/week, ideally combined with two sessions of whole-body strength training per week (10,11,14). However, vigorous physical activity can acutely and transiently increase the risk of SCD and AMI in susceptible individuals, further underscoring the need for regular pre-participation cardiovascular screening (12).

A decline in health benefits and an increased risk of complications are associated with training that is either insufficient or excessive (10). It is important that training is tailored to the individual athlete. Training objectives, available temporal resources, and, in particular, medical history are fundamental considerations. It is therefore essential to create an individualized training program that tailors the program to the individual's physical condition and health status. Training frequency, intensity, and type should be carefully tailored to individual fitness levels under professional supervision, especially in the case of pre-existing cardiovascular disease (10,15).

Warning signs such as exertional dyspnea during warm-up, precordial complaints, or symptoms of OTS must be taken seriously and clarified by a physician in a timely manner (10,15). Early intervention protects against potentially serious health consequences. Subjective perception of exertion (RPE method) and the use of wearable technologies are suitable for self-monitoring and training control (5,38,39). These enable everyday monitoring of training and help to better understand individual reactions of the body. For the majority of endurance athletes, these tools offer a low-threshold and practical way to monitor their own training.

Despite growing technical support, regular cardiovascular examinations should remain an integral part of health management, especially in cases of existing or suspected pre-existing conditions (38). Digital systems cannot yet replace medical diagnoses and clinical examinations.

4. Methodology

For this master's thesis, a quantitative cross-sectional study was conducted to collect data online on endurance training among competitive and recreational athletes. The questionnaire comprises a total of 30 questions with a central focus on the areas of training volume and intensity, subjectively perceived changes, physiological and pathological, as well as monitoring and risk awareness of the participants. The aim of this survey was to gain insight into the training management of different age and gender groups in the endurance sector, as well as the resulting changes and questions regarding awareness of related health risks.

Before the survey was put online, a pre-test was conducted with five test subjects. Particular focus was placed on feedback regarding the comprehensibility of the questions, simplification of technical terms, clear definitions of the possible answers, and technical implementation.

Participants were then approached via online platforms such as Instagram, Facebook, and WhatsApp. In addition, targeted inquiries were sent to around 80 athletics, cycling, swimming, and triathlon associations in Germany. Finally, self-created flyers were posted in facilities such as gyms and swimming pools in Germany and Lithuania. ChatGPT was used to assist with tasks such as creating flyers. The survey was aimed at all age groups over 18, all genders, and performance levels. The prerequisite for participation was the practice of one of the four endurance disciplines: running, cycling, swimming, or triathlon. A total of 358 people (307 met the inclusion criteria) aged 18 to over 70 took part.

Data were collected via the standardized online survey platform Empirio (43). Two versions were created, in English and German, to generate the largest possible participant group. The questionnaire consisted of closed questions, self-assessment scales, and demographic information. Participation was voluntary and anonymous. Both surveys were uploaded on Empirio on February 21, 2025, and closed for evaluation on April 30, 2025. The German questionnaire achieved significantly higher response rates, with 300 participants (265 met inclusion criteria) out of a total of 750 hits. The average duration was 6:22 minutes and the overall dropout rate was 60%. The English questionnaire received 173 responses, with around 58 participants (42 met inclusion criteria). The average duration here was 4:08 minutes and the dropout rate was 66%.

The data collected from the online survey using Empirio was exported to Microsoft Excel and subjected to descriptive analysis there. Here, the results of both questionnaires were combined so that they could be evaluated together. These were then presented graphically.

For a more detailed analysis of the results, correlations were calculated to highlight group differences and statistical significance. To this end, cross tables were first created to differentiate the participants into groups that did not agree with the statement ("0") and those that agreed ("1"). This resulted in the participant values ("n") and the percentage distribution of each group. Based on the observed responses within each group, the corresponding percentage distributions were calculated accordingly. The total number of participants will be indicated with "N". "m" indicates the number of responses in multiple-choice questions, which may exceed the number of respondents since individuals can select more than one option

To ensure that groups with higher participant numbers did not distort the final results, the percentage distribution of the expected and actual values was further analyzed using the chi-square test. A chi-square test is applied when examining whether there is a statistically significant association between two categorical variables.

The chi-square test was used to calculate and determine the significance of the results ("p"). To this end, the observed and expected values were compared. The following classification of p-values explains the corresponding significance level:

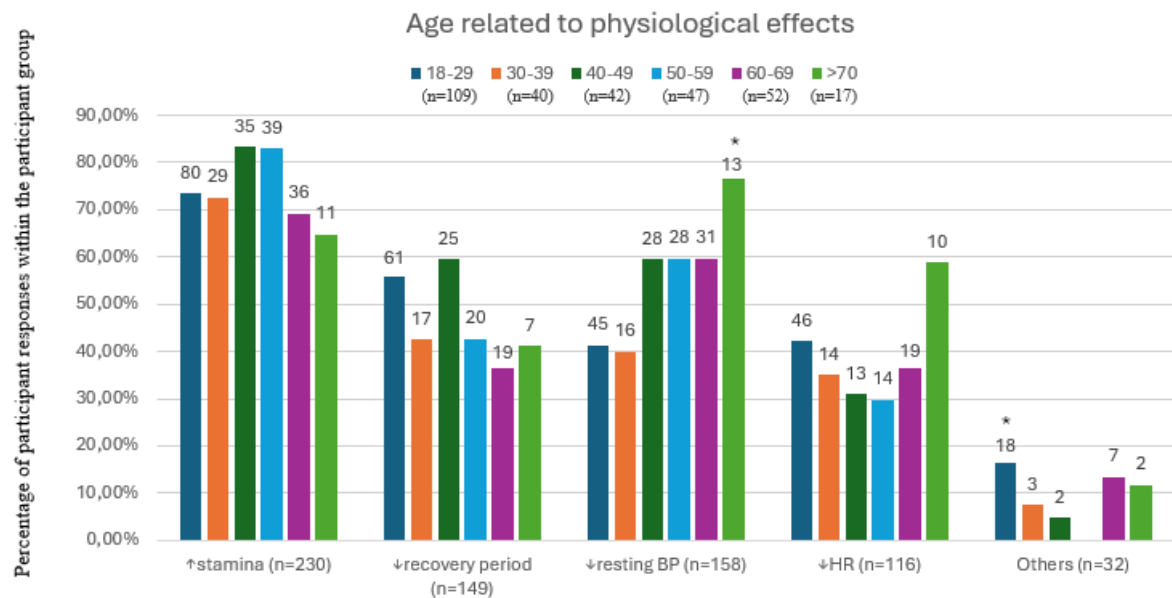
- $p \geq 0.05$ = insignificant
- $p < 0.05$ = significant (*)
- $p < 0.01$ = highly significant (**)
- $p < 0.001$ = very highly significant (***)

In order to understand the diagrams of the group comparisons, a more detailed explanation is provided below using the example of Figure 18 "Age related to physiological effects." Many of the diagrams follow the same pattern. The title of the diagram names the two comparison groups that were correlated with each other. The legend refers to the first comparison group, in this case "Age," and divides it into the corresponding subgroups, i.e., age groups. "n" in the legend is the total number of participant responses within the respective group is given. This includes individuals who did not report experiencing the given effect, thereby providing a more comprehensive basis for evaluation and interpretation of the chart. The respective groups are represented in the diagram with different colors, and the individual number of participants who agree with the statement is indicated at the top of each bar. On the X-axis, the physiological effects are clustered into five groups and described below with keywords such as "stamina." The arrow indicates an increase or decrease. The number of overall positive responses in each category is indicated, e.g., for stamina $n = 230$, while on top of the bar the number of each age group is indicated (from 0–80).

The Y-axis shows the adjusted percentage distribution of the respective subgroup. This allows the values to be compared across all age groups without overshadowing effects from large numbers. The largest group, with 109 participants, is the 18–29 age group (dark blue), while participants > 70 (light green), are represented by 17 participants.

The statistical significance is also indicated with asterisks above the bar and the number of responses.

Example of Figure 18 “Age related to physiological effects”.



An ethics vote was not required for this survey, as it is anonymous and does not allow any conclusions to be drawn about personal data. Furthermore, no patients from clinics were included and no interventional measures were taken.

5. Presentation of results

The following section presents the results of the survey. First, the participants' responses are presented in relation to demographic characteristics, training behavior, risk awareness, and health management. In the next section, correlations are drawn that combine and analyze several questions. The results are presented in text form and, in some cases, using specific diagrams. These are labeled and explained accordingly.

5.1 Demographic Characteristics of the Sample

The survey begins with demographic characteristics and refers to all participants, a total of 358. These were presented graphically in pie chart form. The 18–29 age group accounted for the highest proportion ($n = 139$, 39%). This was followed by the two groups aged 50–59 ($n = 55$, 15%) and 60–

69 ($n = 54$, 15%), and the groups aged 30–39 ($n = 45$) and 40–49 ($n = 47$), each with 13%. Those aged 70 and over formed the smallest group with 5% ($n = 18$). (Figure 1)

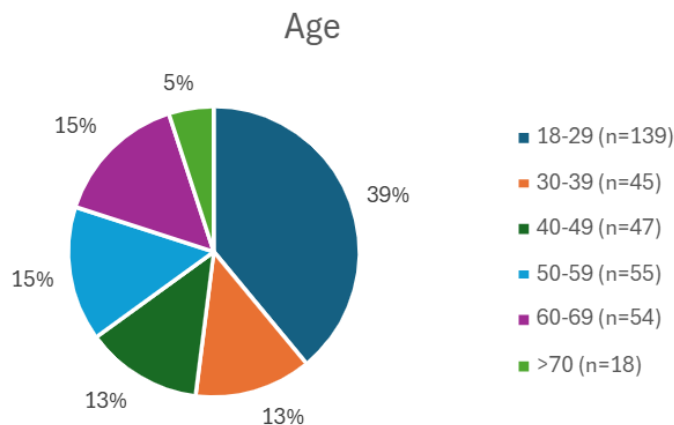


Figure 1: Age distribution (N = 358)

The gender distribution was very similar between men ($n = 174$, 48,6%) and women ($n = 182$, 50,8%), with a slightly higher proportion of women. Only two diverse participants took part (0,6%) and, due to the small number, are not included in gender-specific evaluations. (Figure 2)

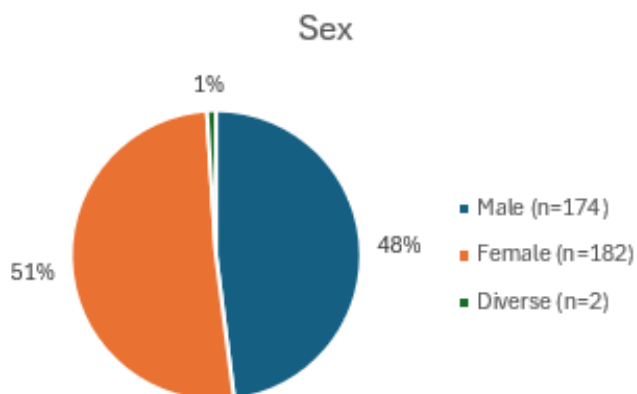


Figure 2: Sex (N = 358)

In terms of occupation, the "employed" group made up the largest proportion of respondents with 195 participants (54%). The other two groups were "students" ($n = 110$, 31%) and "retired" ($n = 53$, 15%).

In terms of height and weight, most of the participants were between 160 and 180 cm ($n = 241$, 68%). The most common height category was 170-180 cm ($n = 126$, 36%), followed by 160-170 cm ($n = 115$, 32%). (Figure 3)

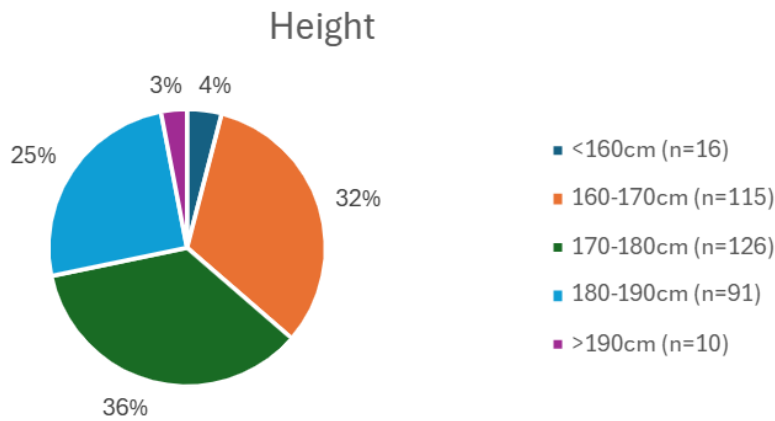


Figure 3: Height (N = 358)

In terms of weight, the data was most evenly distributed across the categories 60-70 kg ($n = 110$, 31%) and 70-80 kg ($n = 97$, 27%). (Figure 4) A chi-square test did not reveal any significant distributions.

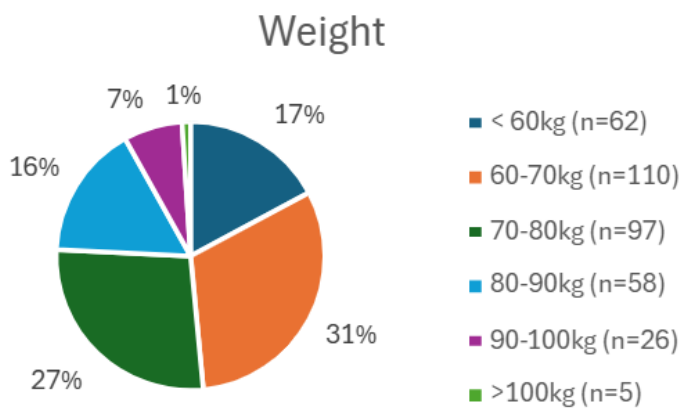


Figure 4: Weight (N = 358)

5.2 Main Sport

The questionnaire then collected data on the main sporting discipline. Participants could choose between the endurance sports of running, cycling, swimming, and triathlon, or select "None." A total of 14% ($n = 51$) stated that they did not regularly participate in any of these sports. For these participants, the questionnaire ended after the demographic information was collected. The remaining sample thus comprised 307 individuals. Among the endurance athletes who took part in this survey, "running" was by far the most frequently mentioned main discipline ($n = 208$, 58%), followed by cycling ($n = 46$, 13%), triathlon ($n = 31$, 9%) and swimming ($n = 22$, 6%). (Figure 5)

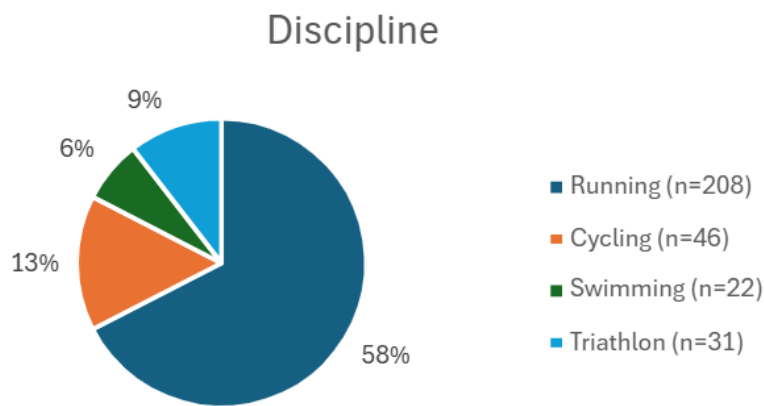


Figure 5: Discipline (N = 358)

5.3 Training Behavior

In terms of training level, 87% ($n = 266$) stated that they were at a "recreational" to "intermediate" level. The remaining 13% represented the "competitive" group.

3-4 days per week was mentioned by 41% ($n = 127$) of the participants, followed by 1–2 days (38%; $n = 117$). Only 21% ($n = 63$) trained more than four times per week (Figure 6).

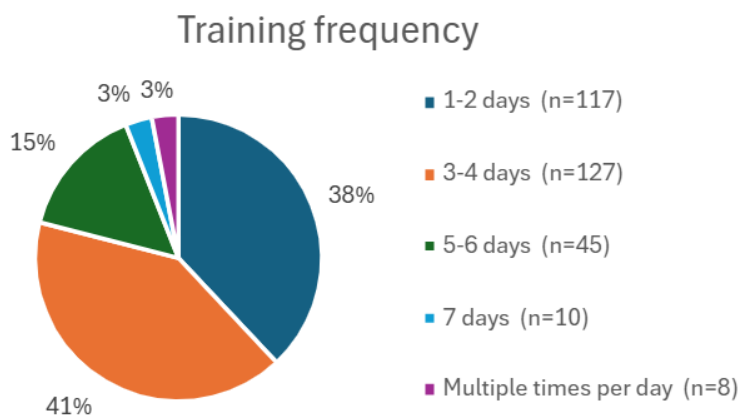


Figure 6: Training frequency (N = 307)

The average training duration per session was between 30 and 60 minutes for the majority (51%; $n = 158$), followed by 1–2 hours (41%; $n = 125$). Only 4% ($n = 13$) trained for less than 30 minutes, and 4% ($n = 11$) trained for more than two hours.

The intensity of the training sessions as perceived by the participants themselves was predominantly rated as moderate (71%; $n = 215$). (Figure 7)

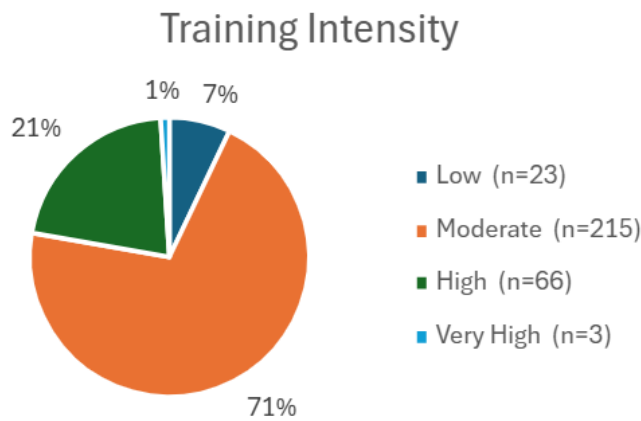


Figure 7: Training intensity (N = 307)

5.4 Training Goals

To determine training goals, five key motives were rated on a scale from 1 (strongly disagree) to 5 (strongly agree). The goal of "improving health" received the highest approval rating at level 5, with 60% ($n = 184$). "Improving endurance" ($n = 148$, 48%) and "increasing athletic performance" ($n = 146$, 48%) also received high approval ratings. No respondent assigned the rating '1' to „endurance“. "Weight management" ($n = 84$, 27%) and "participation in competitions" ($n = 104$, 24%) received lower approval ratings.

5.5 Training Monitoring and Physiological Effects

219 respondents use technical aids to monitor their training. Smartwatches ($n = 89$, 29%) and fitness trackers ($n = 86$, 28%) were most frequently reported, followed by HR monitors ($n = 69$, 22%). Around 29% ($n = 88$) stated that they did not use any monitoring devices (Figure 8).

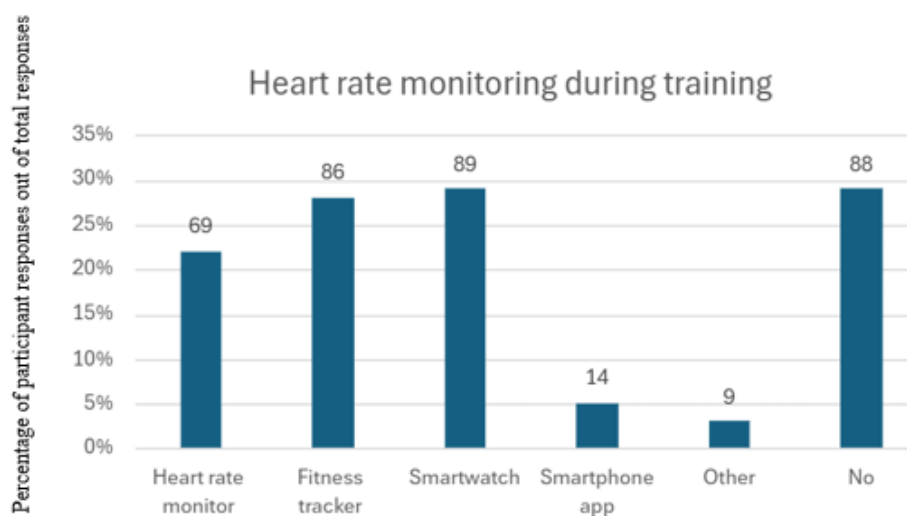


Figure 8: Heart rate monitoring during training (N = 307, m=355)

Awareness of HR zone training varied. 32% ($n = 99$) trained predominantly in zone 3. Around 30% ($n = 91$) had no knowledge of zone training. (Figure 9)

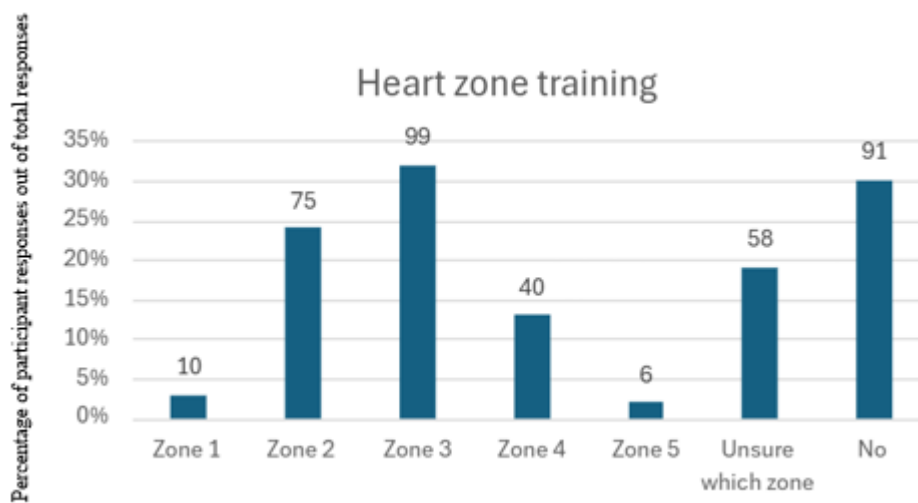


Figure 9: Heart zone training (N = 307, m=379)

Of the subjective physiological changes reported, 75% ($n = 230$) reported increased endurance, 51% ($n = 158$) reported lower resting blood pressure, and 49% ($n = 149$) reported a shorter recovery time. A further 38% ($n = 116$) observed a reduced resting HR. Only 10% ($n = 32$) reported other physiological changes. Pathological symptoms were perceived significantly less frequently. 25% ($n = 80$) cited dehydration as the most common symptom. 43% ($n = 132$) had no symptoms during or after endurance training. Other reported complaints included shortness of breath, cardiac arrhythmia, fatigue, dizziness, and headaches ($n = 38$ – 57 ; 12–19% each). Chest pain ($n = 16$; 5%) and other symptoms ($n = 11$; 4%) were reported least frequently. 38% ($n = 117$) did not experience any of these symptoms, 29% ($n = 90$) experienced them rarely, and 25% ($n = 77$) occasionally.

A total of 80% ($n = 246$) integrated active recovery, such as stretching and light activity, into their training. (Figure 10)

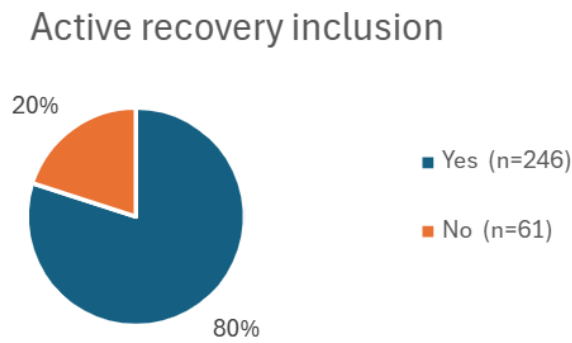


Figure 10: Active recovery inclusion (N = 307)

5.6 Risk Perception and Medical Care

Participants were asked about their risk awareness and whether they were aware of the cardiovascular risks associated with long-term endurance training. Only 36% ($n = 110$) answered positively, while 64% ($n = 197$) were not aware of these risks. (Figure 11)

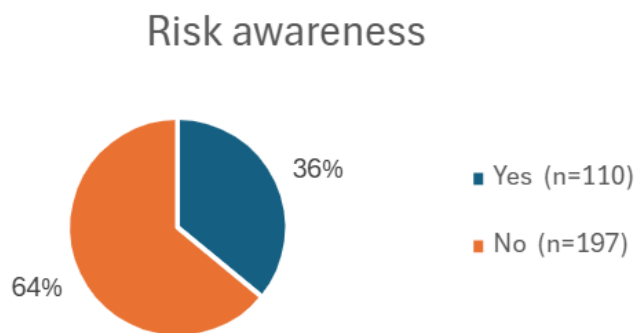


Figure 11: Risk awareness (N = 307)

58% ($n = 178$) associated long-term endurance training with the possibility of cardiac enlargement, 27% ($n = 82$) cited "other risks," 23% ($n = 72$) saw an increased risk of SCD, while 16% ($n = 48$) mentioned arrhythmias. High blood pressure ($n = 23$, 7%) and coronary calcification ($n = 9$, 3%) were rarely mentioned. (Figure 12)

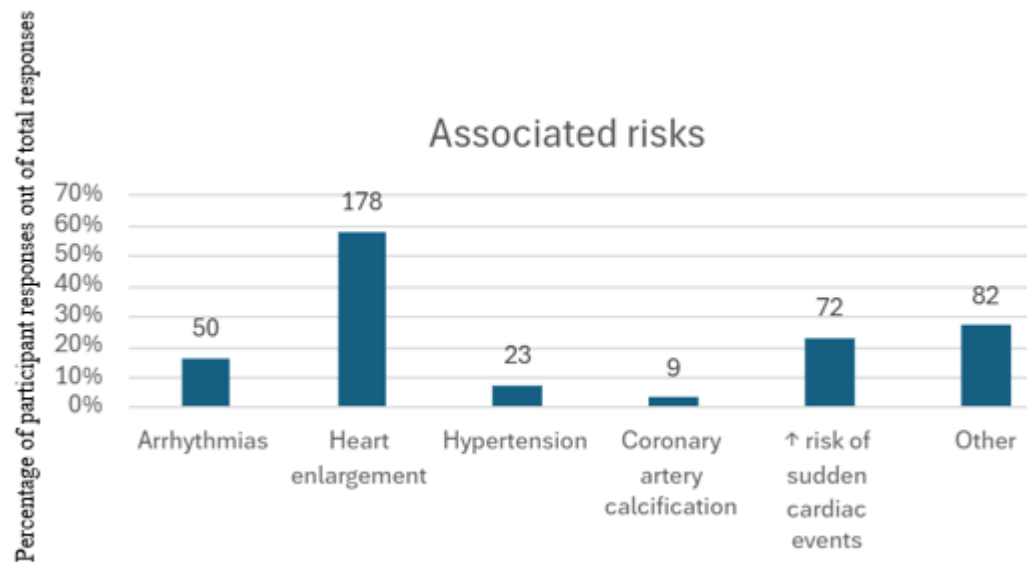


Figure 12: Associated risks (N = 307, m=414)

Participants were then asked about regular monthly tests regarding risk factors. 51% ($n = 157$) stated that they did not regularly check relevant blood values such as blood pressure, cholesterol, or blood sugar. In contrast, 41% ($n = 125$) regularly checked their resting HR, and 23% ($n = 71$) checked their blood pressure. Cholesterol and blood sugar were only checked by 4% ($n = 13$) in each case.

Cardiac imaging procedures in the last five years were reported by the respondents as follows: ECG (44%; $n = 136$), stress ECG ($n = 113$, 37%), echocardiography ($n = 84$, 27%), cardiac MRI and CT ($n = 11$, 4% each). 38% ($n = 117$) had not undergone any of these procedures.

A personal history of cardiovascular disease was reported by 7% ($n = 22$), 33% ($n = 102$) reported a family history, while 47% ($n = 143$) had no history and 17% ($n = 51$) were unaware of any history. (Figure 13)

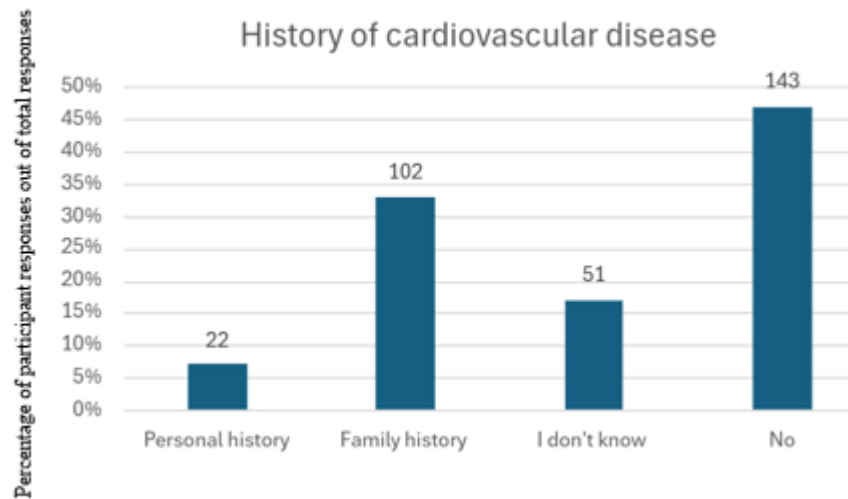


Figure 13: History of cardiovascular disease (N = 307, m=318)

58% visited their family doctor regularly, 33% ($n = 104$) annually and 25% ($n = 76$) every 2–3 years. One third ($n = 98$) consulted medical professionals only when they had symptoms. (Figure 14).

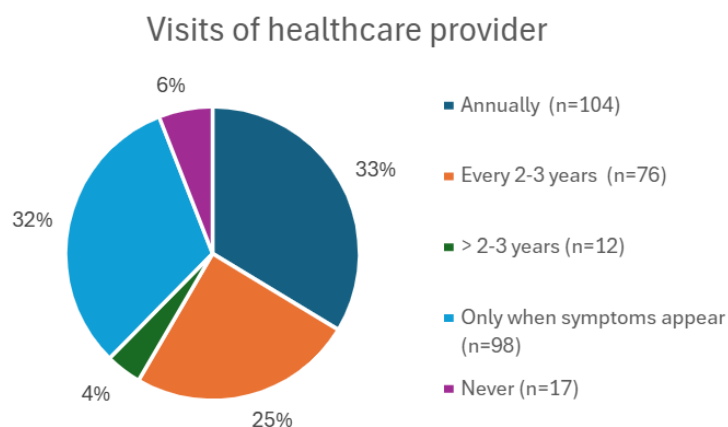


Figure 14: Visits to healthcare providers (N = 307)

Only 6% ($n = 17$) were ever advised to adjust their endurance training due to cardiovascular stress.

5.7 Subjective perception of exertion and level of information

80% ($n = 246$) felt that their training was manageable. 19% ($n = 58$) felt occasionally overwhelmed, and only 1% ($n = 3$) felt frequently overwhelmed.

In addition, 65% ($n = 198$) expressed no concerns about cardiovascular risks in relation to their training. (Figure 15)

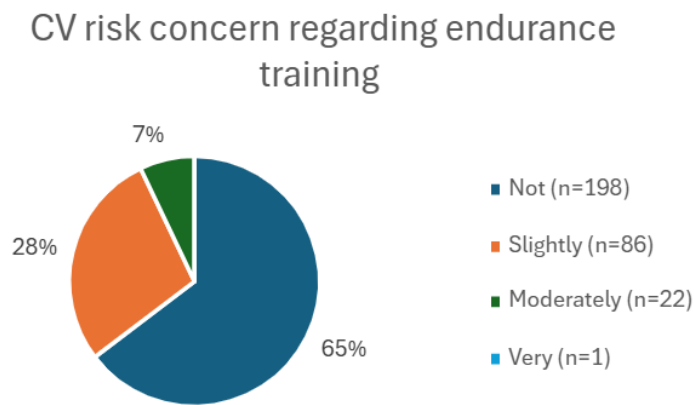


Figure 15: CV risk concern endurance training (N = 307)

The most common sources of information on cardiovascular risks in endurance training were the internet ($n = 122$, 40%), medical professionals ($n = 97$, 32%), friends ($n = 64$, 21%), and trainers ($n = 46$, 15%). Social media ($n = 24$, 8%), YouTube ($n = 31$, 10%) and "Other" ($n = 28$, 9%) were used significantly less frequently. 34% ($n = 104$) stated that they did not seek any information. Multiple answers were possible (Figure 16).

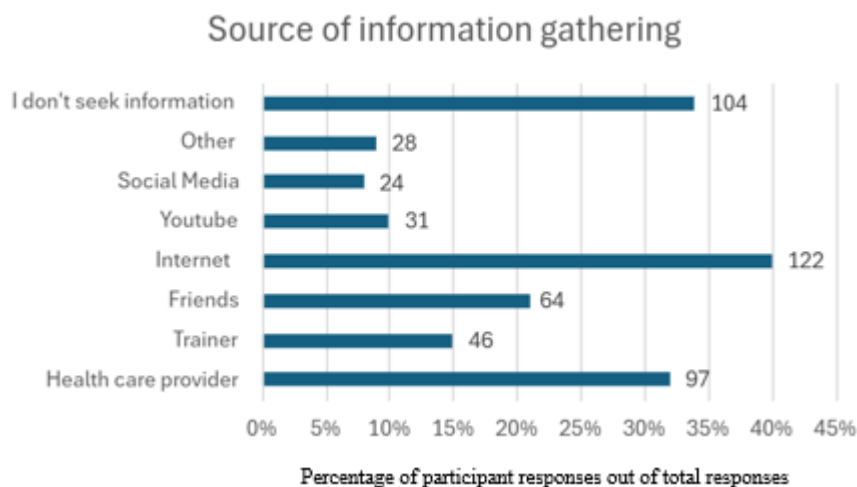


Figure 16: Source of information gathering (N = 307, m=516)

Despite the wide range of information available, only 36% ($n = 111$) felt sufficiently informed. 64% ($n = 196$) felt inadequately informed.

5.8 Training Control and External Guidance

The vast majority of participants trained without external guidance ($n = 237$, 77%). 103 people (30%) were accompanied by trainers or medical professionals. (Figure 17)

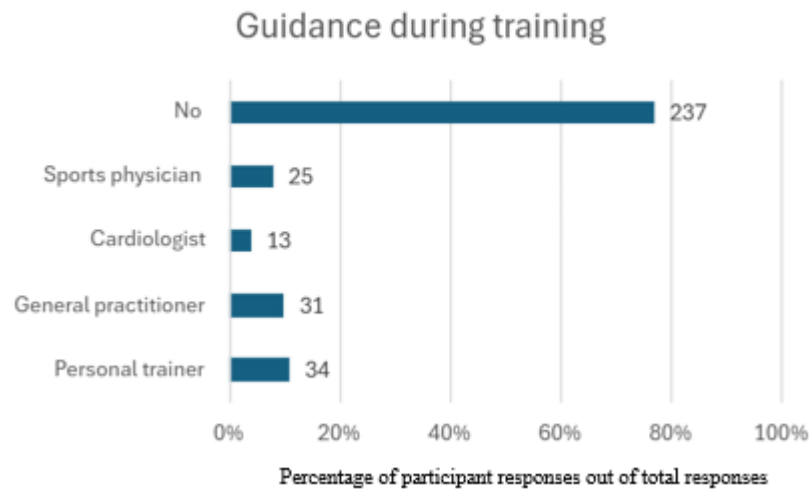


Figure 17: Guidance during training (N = 307, m=340)

5.9 Correlation of different Group Characteristics

First, a comparison was made between six age groups and potential physiological changes. A chi-square test was performed to evaluate possible statistical correlations. The possible answers were based on multiple choices and refer to a sample of 307 participants.

Significant differences were found in two areas in particular: The group of over 70-year-olds reported a significantly higher incidence of a reduction in resting blood pressure (76%, $p = 0.01$). In addition, the 30–59 age group reported noticeably fewer "other" physiological effects (0–7.5%, $p = 0.03$).

No significant differences between the age groups were found for all other parameters ($p > 0.05$). (Figure 18) A detailed explanation of how the diagrams were interpreted can be found in the methods section. (Page 29)

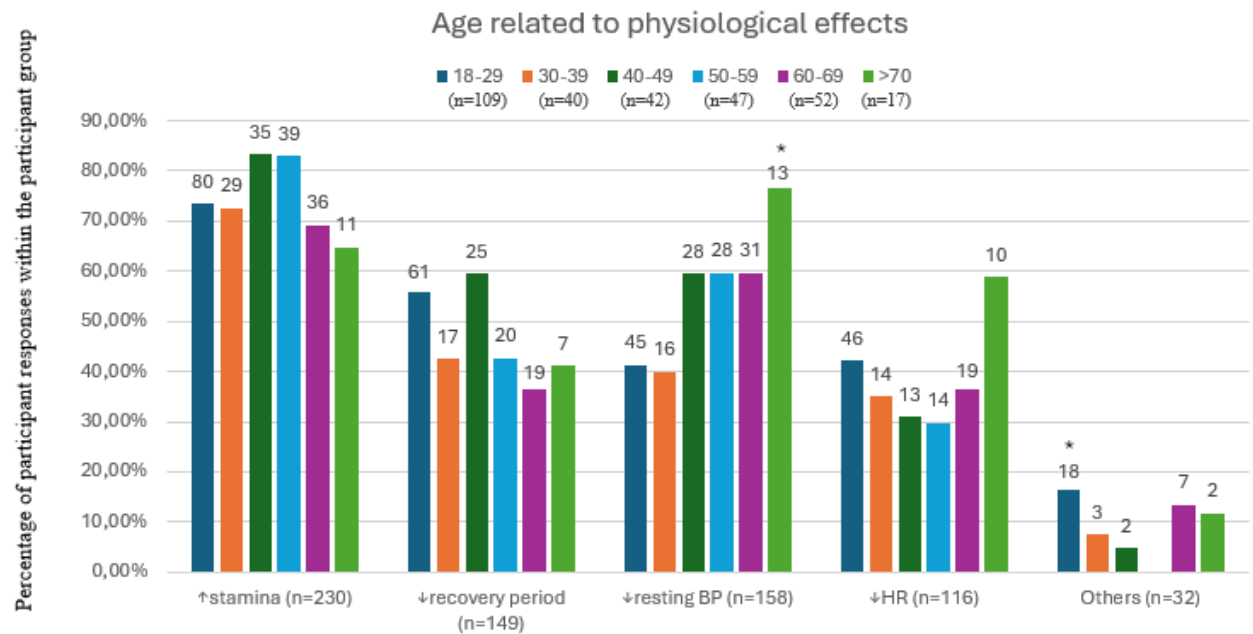


Figure 18: Age related to physiological effects (N = 307)

In Figure 19, the same age groups as before were compared with regard to potential pathological effects. Statistically significant differences were found primarily in the 18–29 age group, particularly in the symptoms of chest pain ($p = 0.01$) and rapid or irregular heartbeat ($p = 0.02$). Highly significant differences were found for shortness of breath ($p = 0.0003$) and headaches ($p = 0.0002$). The results were highly significant for dizziness ($p = 2.87 \times 10^{-7}$) and dehydration ($p = 6.38 \times 10^{-8}$). The statement "symptom-free" also showed a highly significant difference ($p = 2.14 \times 10^{-10}$), with only 17.4% of 18-29-year-olds reporting this condition.

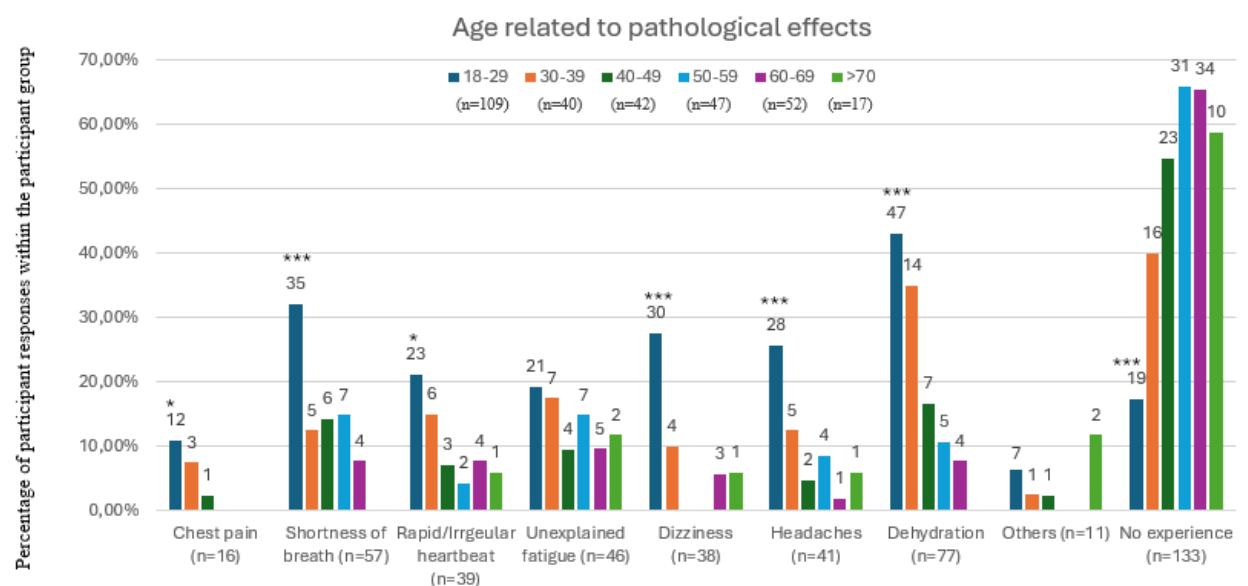


Figure 19: Age related to pathological effects (N = 307)

Figure 20 shows the comparison between male and female participants in terms of physiological effects.

The study revealed notable outcomes among male participants, including reduced resting blood pressure (60%, $p = 0.002$) and decreased HR (47%, $p = 0.0005$).

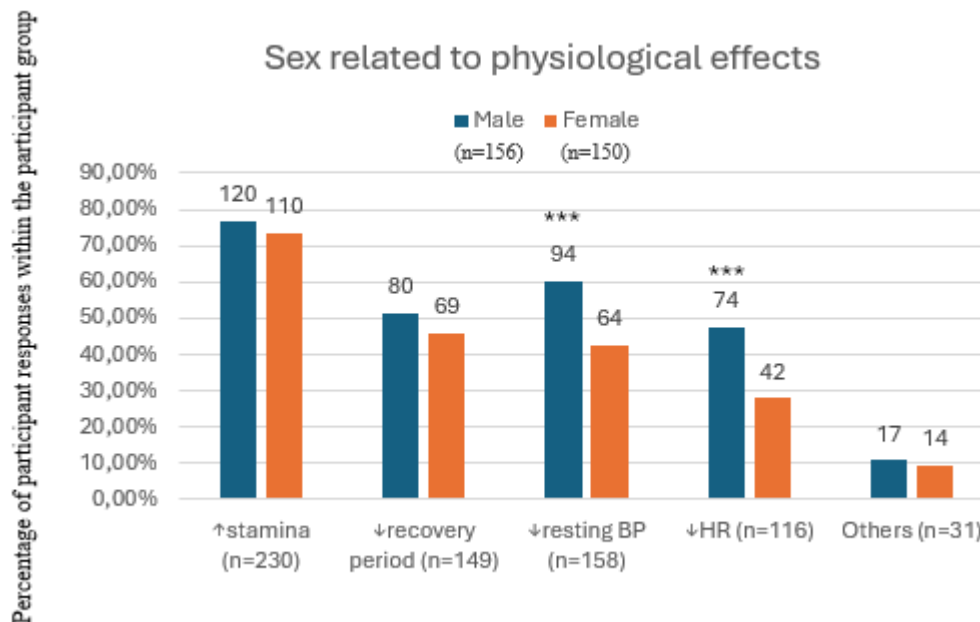


Figure 20: Sex related to physiological effects (N = 307)

With regard to gender-specific differences in pathological effects, only chest pain was significant in women, at around 8% ($p = 0.02$). (Figure 21)

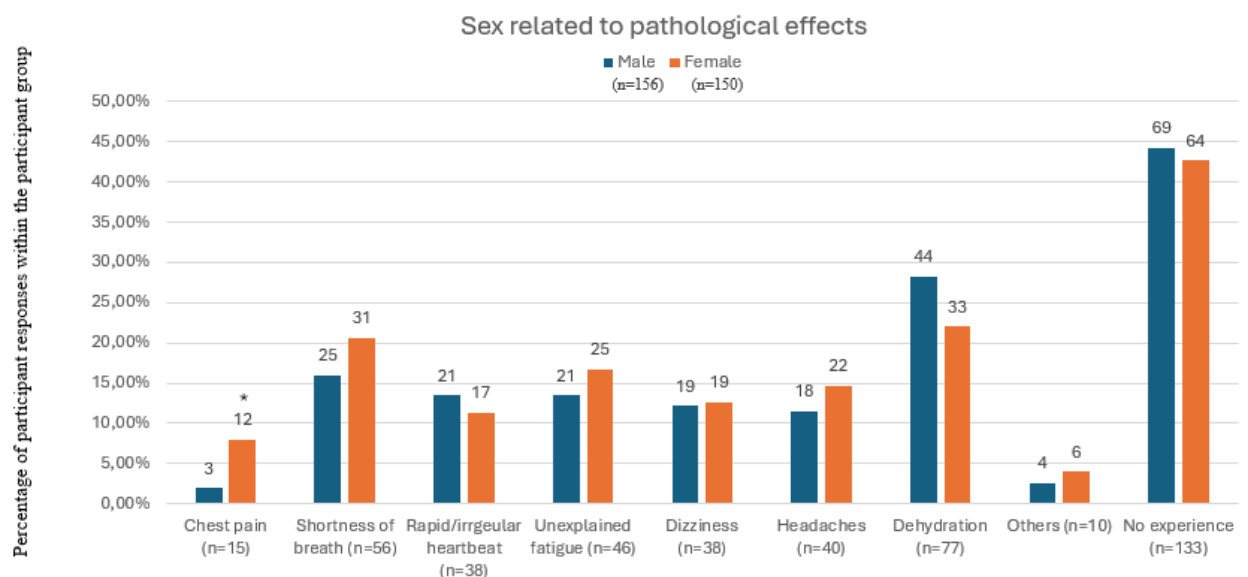


Figure 21: Sex related to pathological effects (N = 307)

The various disciplines also showed little significance in terms of physiological and pathological effects. Only a lower HR in triathletes (58%) was significant ($p = 0.04$). (Figures 22, 23)

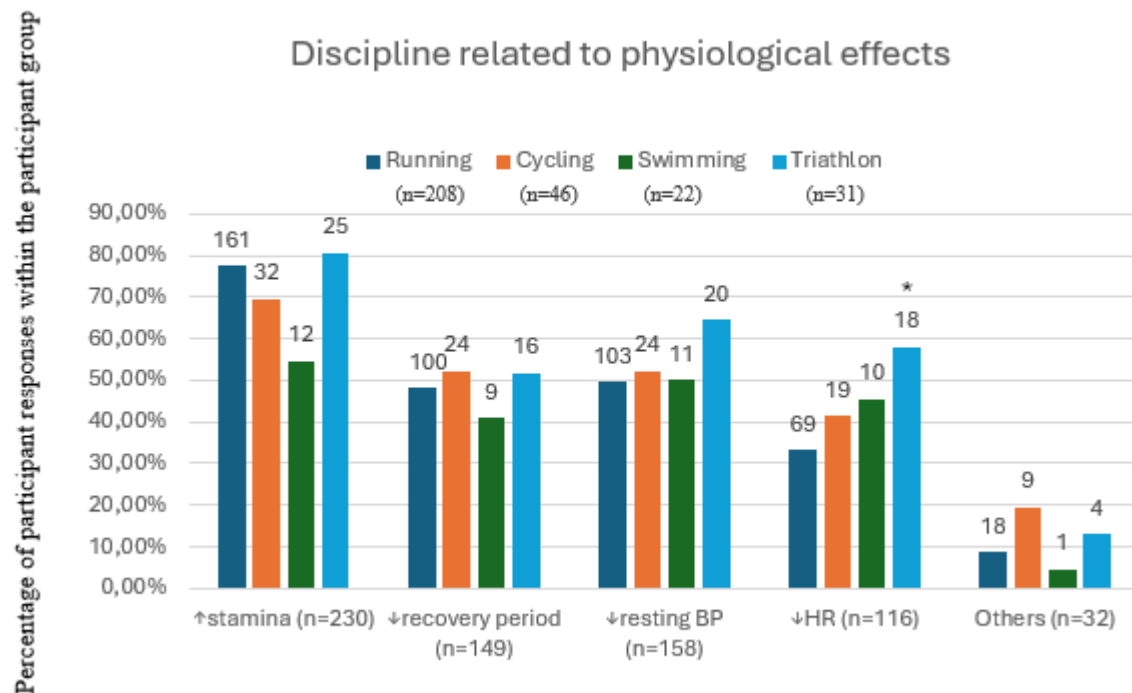


Figure 22: Discipline related to physiological effects (N = 307)

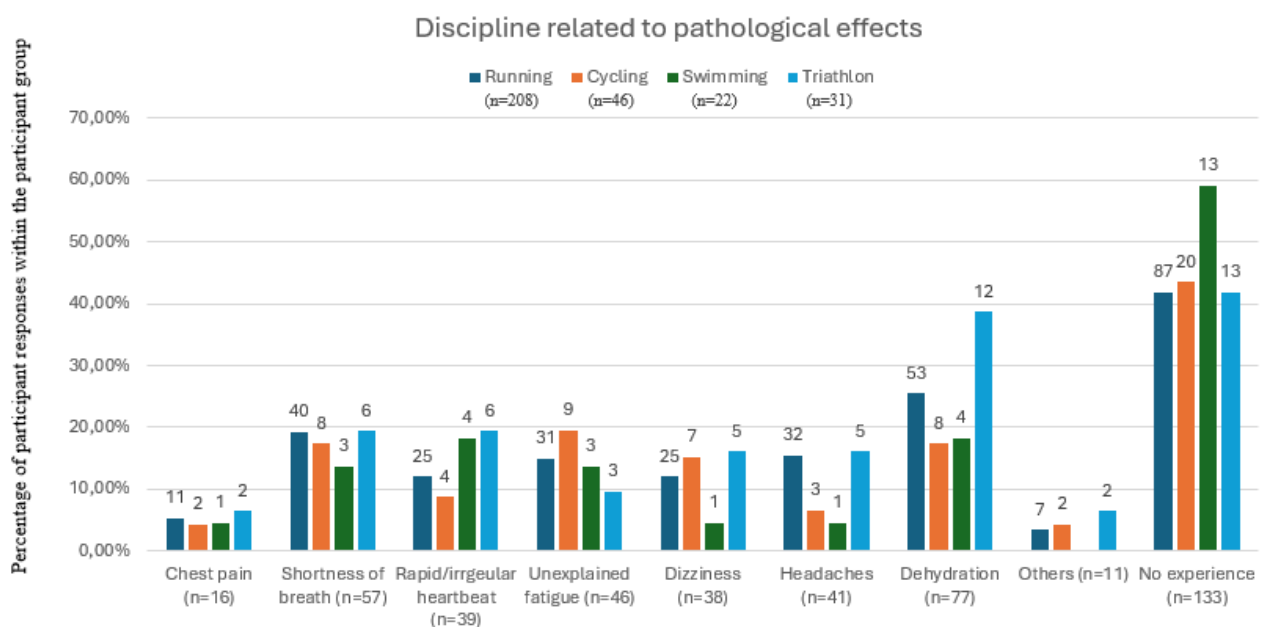


Figure 23: Discipline related to pathological effects (N = 307)

The distribution of physiological effects depending on performance level is shown in Figure 24. A clear step-like trend can be seen: participants with a recreational activity level consistently had the lowest percentages, followed by the intermediate group, while the highest values were observed in

the competitive group. This gradation was statistically significant in the following areas in particular: In terms of reduced recovery time, 61% of the highest-performing competitive group reported this effect ($p = 0.002$). A reduction in resting HR was observed in 73% ($p = 2.38 \times 10^{-7}$), and 59% reported a reduced HR ($p = 1.74 \times 10^{-5}$).

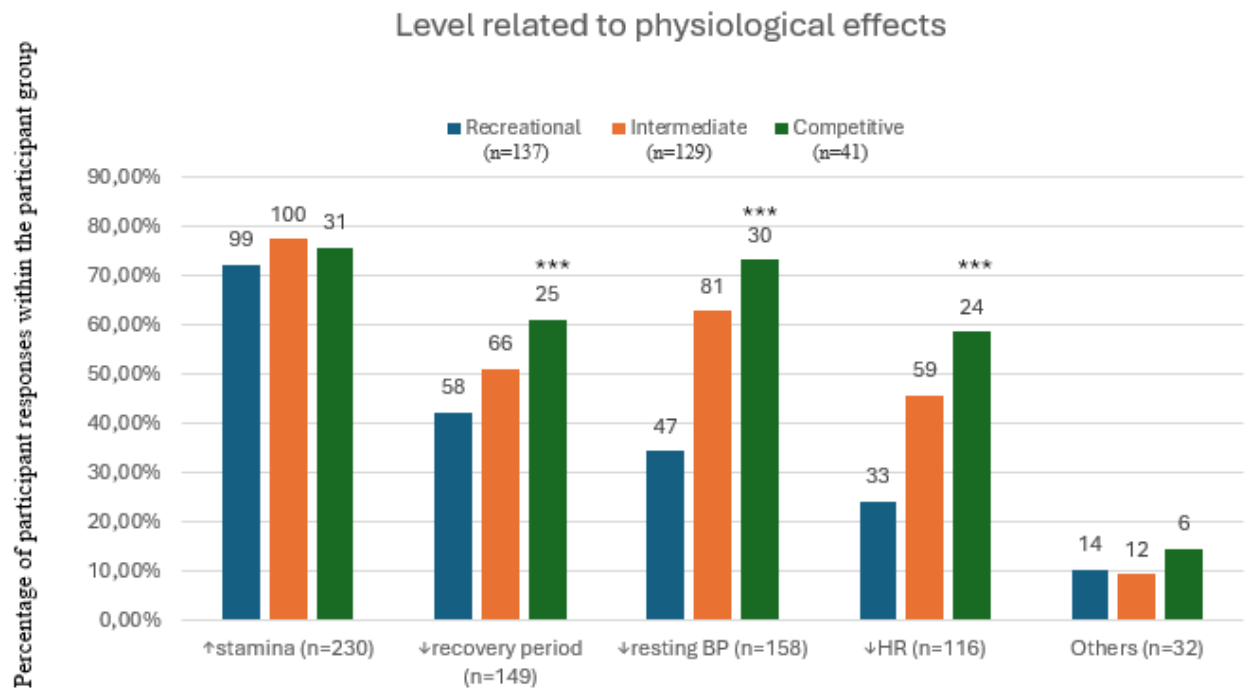


Figure 24: Level related to physiological effects (N = 307)

Figure 25 shows the distribution of pathological effects depending on performance level. While a significant proportion of competitive athletes (22%) reported headaches ($p = 0.02$), shortness of breath was particularly common in the recreational group. The proportion there was 28%, which was a highly significant difference ($p = 0.0006$).

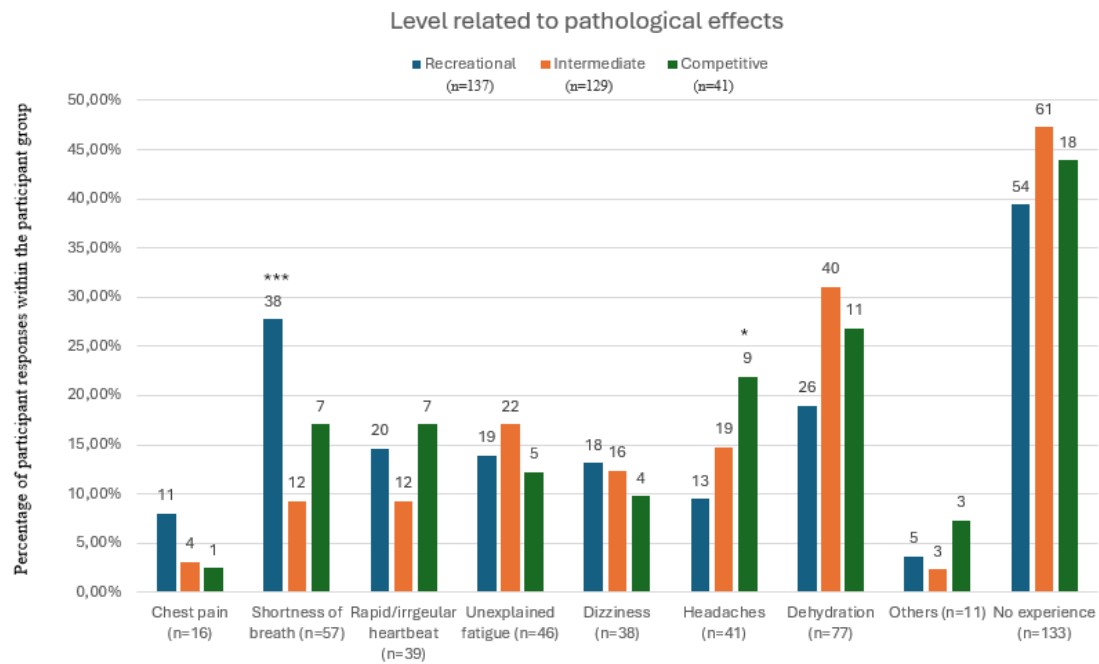


Figure 25: Level related to pathological effects (N = 307)

Figure 26 shows the relationship between training duration (experience in years) and the reported physiological effects. A significant difference was found in the statement "increased stamina": the group with 1–2 years of experience had the lowest value at 60% ($p = 2.80 \times 10^{-18}$). Conversely, participants with more than 10 years of training experience most frequently reported a lower resting HR (62%, $p = 0.001$), which was also statistically significant.

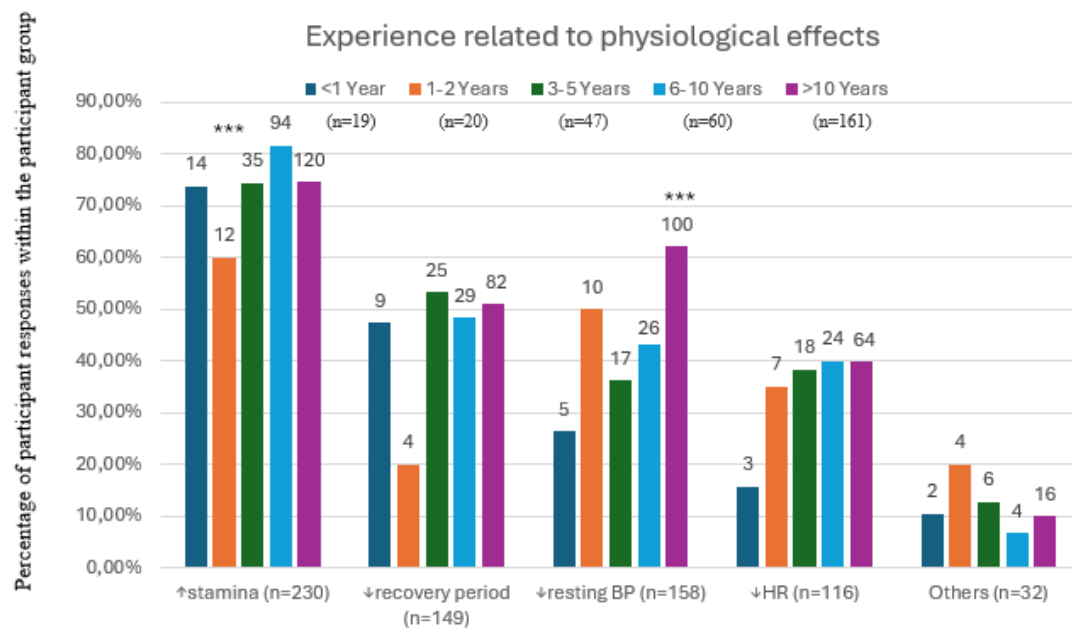


Figure 26: Experience related to physiological effects (N = 307)

Figure 27 shows the frequency of pathological effects depending on training experience. Striking here is the group with less than one year of training experience, which reported significantly higher rates of several symptoms: Chest pain occurred in 26% ($p = 0.0001$), shortness of breath in 53% ($p = 7.93 \times 10^{-5}$), rapid or irregular heartbeat in 32% ($p = 0.047$), and dizziness also in 32% ($p = 0.002$). In addition, the group with 3–5 years of experience stood out due to a high frequency of headaches (37%, $p = 1.73 \times 10^{-5}$) and dehydration (45%, $p = 0.01$). No noticeable or significant differences were found in the other experience groups ($p > 0.05$).

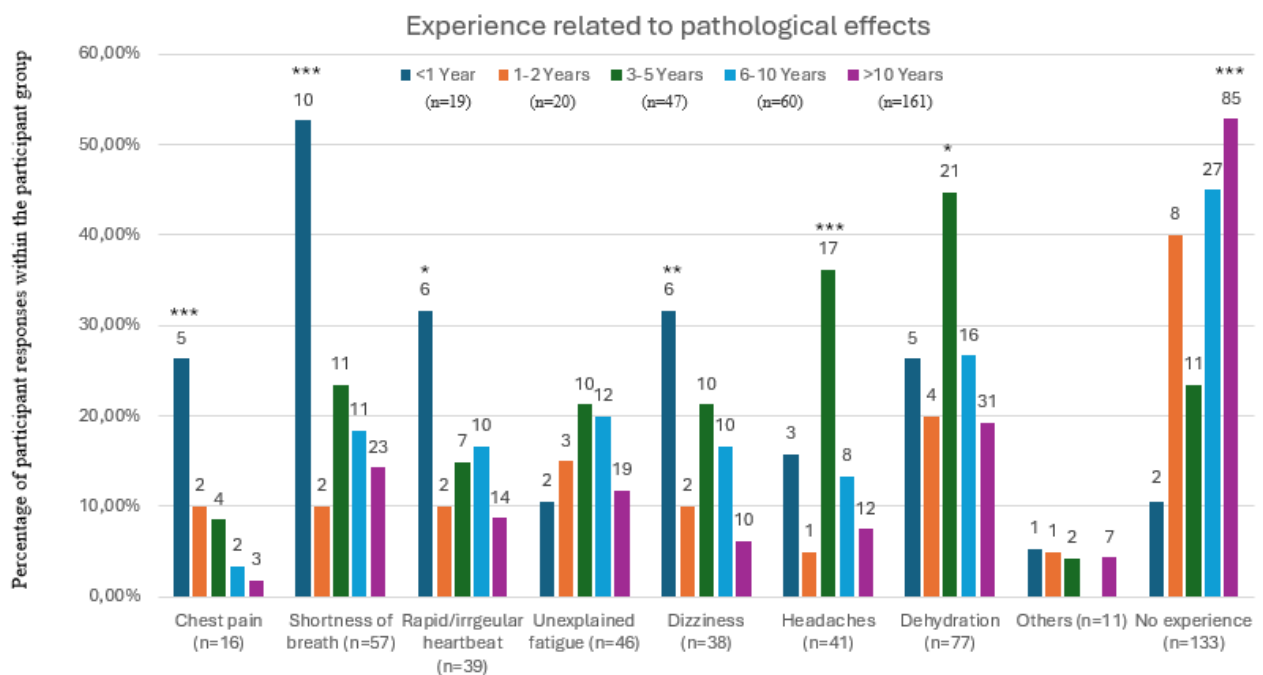


Figure 27: Experience related to pathological effects (N = 307)

The following Table 1 clearly illustrates the significance in relation to training experience, duration, frequency, and intensity, as well as the physiological and pathological effects. Most of the reported effects (in total 9) were found to be significantly related to experience. With regard to the duration of the training sessions, the group that trained between 1-2 hours reported the most frequent improvements in endurance ($n = 103$, 82%, $p = 0.0065$) and lower BP ($n = 83$, 66%, $p = 1.93348 \times 10^{-5}$). Other physiological effects were significantly more noticeable in the group that trained for more than 2 hours ($n = 4$, 36%, $p = 0.028$), while the group that trained for less than 30 minutes reported shortness of breath ($n = 7$, 54%, $p = 0.0021$). Training frequency showed significant results, especially in the group that trained 1-2 days in terms of resting HR ($n = 48$, 41%, $p = 0.00199$) and HR ($n = 25$, 21%, $p = 3.67998 \times 10^{-7}$), which were comparatively the lowest. Pathological experiences such as chest pain ($n = 12/1$, 10-12.5%, $p = 0.03$) and shortness of breath ($n = 31/2$, 25-26.5%, $p = 0.0286$) were reported primarily by the groups that trained 1-2 days or several times a

day. Finally, training intensity showed pathologically significant effects only at very high intensity in the areas of chest pain ($n = 2$, 66%, $p = 0.0465$), headache ($n = 3$, 100%, $p = 0.0003$), and other ($n = 1$, 33%, $p = 0.0468$).

Table 1: Specification of the statistical significance of training volume in relation to physiological and pathological effects (N = 307)

Training Volume	Physiological Effects					Pathological Effects								
	Stam.	Rec.	BP.	HR.	Other	Chest	Breath.	Beat.	Fatigue	Dizzi.	Head.	Dehyd.	Other	No
Experience	***		**			**	***	*		**	***	*		**
Duration	**		***		*		**							
Frequency			**	***		*	*							
Intensity								*			**		*	

- $p \geq 0.05$ = insignificant
- $p < 0.05$ = significant (*)
- $p < 0.01$ = highly significant (**)
- $p < 0.001$ = very highly significant (***)

Figure 28 shows the relationship between the participants' primary training goals and the occurrence of physiological effects. For practical reasons, these goals and effects were summarized and considered as an overall picture. In addition, only the group of “5” who rated the corresponding goal as the strongest were considered. The performed chi-square test revealed a highly significant association between all training goals and physiological effects experienced ($p = 1.27 \times 10^{-5}$). The group that stated competitions as their primary goal was particularly striking: at 60%, they reported corresponding physiological changes most frequently. On the other hand, the groups with the primary goal of "weight management" ($n = 149$, 41%) and "overall health" ($n = 397$, 43%) reported these effects the least.

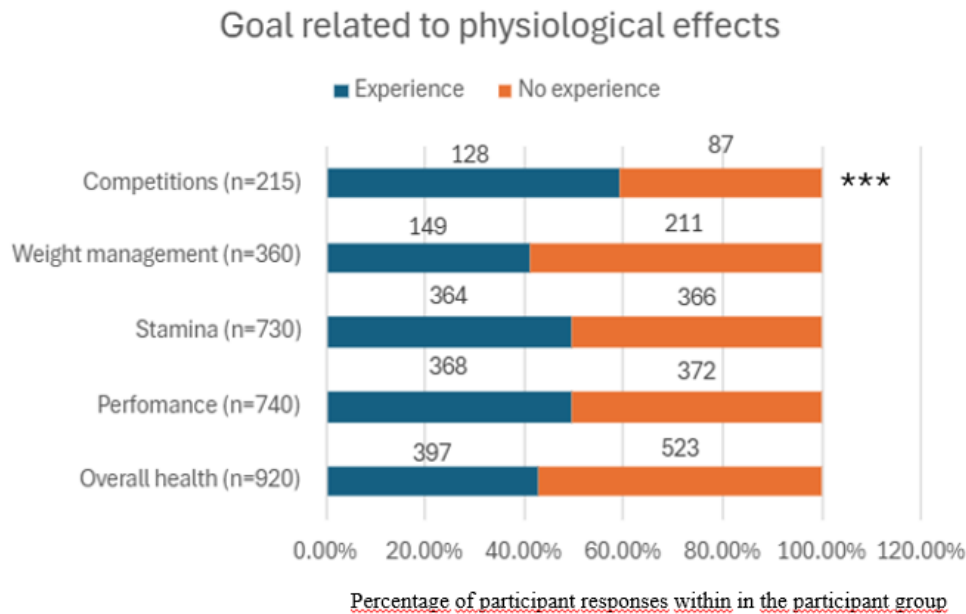


Figure 28: Goal related to physiological effects (N = 307)

However, no significant differences remained in terms of an overall assessment of the pathological effects. (Figure 29)

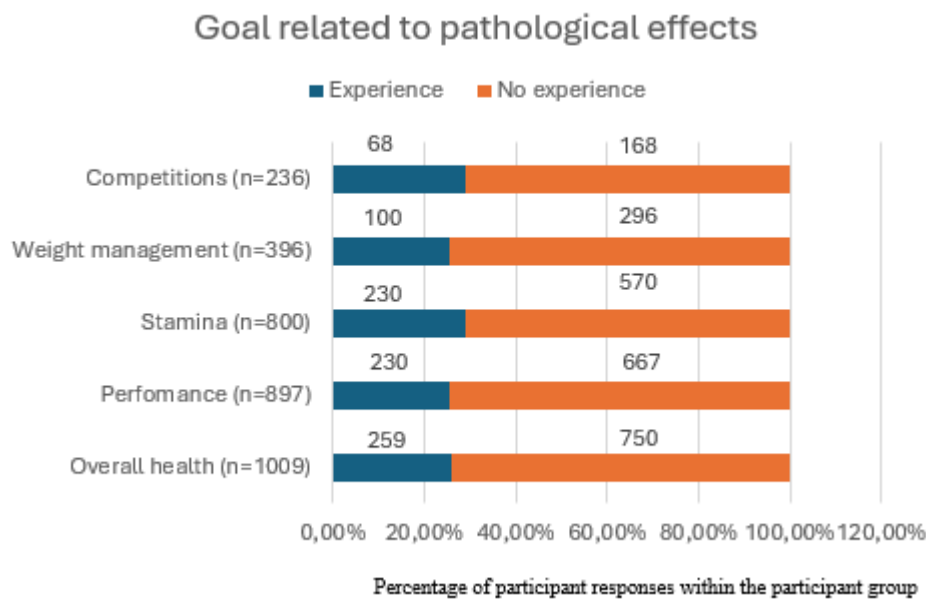


Figure 29: Goal related to pathological effects (N = 307)

Figure 30 shows a comparison between participants with and without knowledge of the zone training principle, categorized into "knowledgeable" vs. "unknowledgeable". The group of "knowledgeable" included all those who selected at least one training zone (zones 1–5) or "unsure but specified a zone."

The results were statistically re-evaluated as percentages using the chi-square test. The figure shows only those areas in which significant differences occurred, both physiological and pathological.

On a physiological level, two effects occurred exclusively among experts and with high statistical significance: a lower resting HR (62%, $p = 4.17 \times 10^{-7}$) and a reduced HR (45%, $p = 5.78 \times 10^{-5}$).

In terms of pathological symptoms, experts also showed a significantly higher incidence of dehydration (30%, $p = 0.02$), as did "others" (16%, $p = 0.01$), shortness of breath (27%, $p = 0.007$) and headaches (23%, $p = 0.004$).

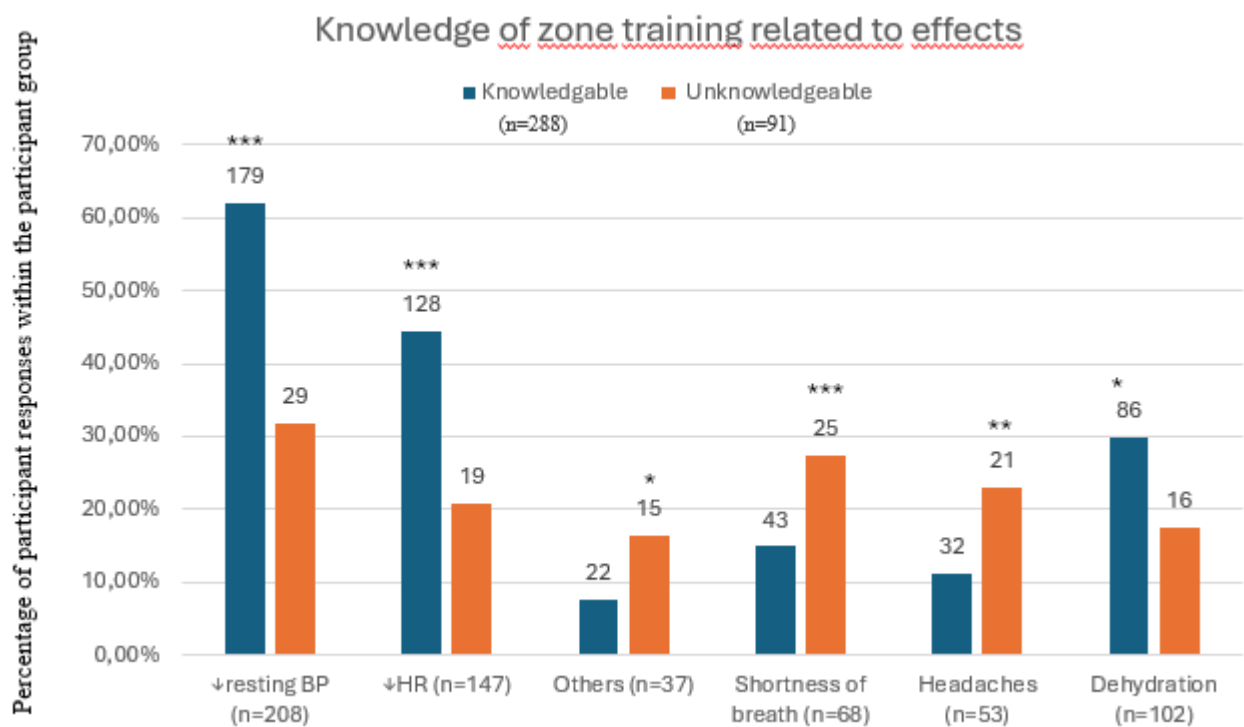


Figure 30: Knowledge of zone training related to effects (N = 307)

6. Discussion

After the presentation of the survey results, this chapter critically analyses the collected data in the context of current scientific literature. The goal is twofold: to assess the methodological strengths and limitations of the study, and to identify the practical implications of the findings for cardiovascular risk prevention and future research.

6.1 Discussion regarding Methodology

The methodology of the survey can be divided into structure and results. First, the structure is examined. With 30 questions, the survey outlines the areas of demographic distribution, training behavior, risk awareness, and health management. Standardized single and multiple-choice response formats simplified data collection and facilitated quantitative comparability, though at the cost of individual response depth. To ensure a broad representation of the target population, participants across different age groups, sexes, and performance levels were included. In order to generate a comprehensive data pool, the online survey was conducted in English and German. Distribution via online platforms, personal contacts, and letters to 80 sports clubs introduced a potential selection bias. The accessible population likely overrepresents health-conscious, digitally active athletes. Certain clubs denied the distribution of the survey which further restricted access. A key limitation of the present study lies in its recruitment approach. By targeting active endurance athletes, those who discontinued training due to adverse health events are systematically absent from the sample. This particular selection bias directly affects the interpretability of the findings. Positive physiological outcomes are likely overestimated, while reported symptom rates and knowledge gaps should be considered conservative estimates rather than true population values. A health-engaged sample performing above average on risk awareness makes the documented gaps, particularly the 3% CAC recognition rate, more striking, not less.

A total of 307 fully completed questionnaires were included in the evaluation. Empirio and Excel were used as tools for descriptive representations and group correlations via the chi-square test. It must be noted that the cross-sectional design of this study allows for the identification of associations, but does not permit causal conclusions to be drawn from the data. Summarizing the data from two questionnaires and manually coding it in Excel was time-consuming and should be improved using dedicated software in future studies. The evaluation allows a direct comparison of two categorical parameters in which the data is distributed nominally or ordinally. This was applicable to the present data set, but no causal relationships can be derived from it. The study focuses on cardiovascular changes and risks. Future research should combine longitudinal designs with objective cardiovascular measurements and recruit from clinical populations to capture high-risk individuals systematically absent from active-athlete samples.

6.2 Discussion of the Results

6.2.1 Age and Gender

The 18 to 29-year-old age group was by a substantial margin the most symptomatic group in the entire sample, with only 17.4% reporting being symptom-free ($p = 2.14 \times 10^{-10}$). Chest pain ($p = 0.01$),

rapid or irregular heartbeat ($p = 0.02$), shortness of breath ($p = 0.0003$), and headaches ($p = 0.0002$) were significantly more prevalent, while dizziness ($p = 2.87 \times 10^{-7}$) and dehydration ($p = 6.38 \times 10^{-8}$) reached very high statistical significance. These symptoms are clinically non-specific and consistent with multiple non-cardiovascular causes, including dehydration and nutritional deficits. This argues against a structural cardiac explanation and points toward a functional, load-related origin. NFOR represents the most plausible explanation, arising from excessive training load relative to recovery capacity in athletes lacking structured guidance (35).

This age-dependent pattern also maps onto an established risk differentiation in the literature. Young athletes below 35 years face structurally driven SCD risk from congenital conditions such as HCM and channelopathies, pathologies that are frequently asymptomatic and undetectable by standard resting examination (3). The present survey shows a contrasting picture for this age group. Rather than reflecting structural cardiac pathology, the symptom burden in the 18–29 age group, the largest subgroup in this sample ($n = 139$), was dominated by acute functional complaints consistent with load mismanagement and insufficient recovery. This discrepancy between the literature's emphasis on structural risk in young athletes and the functional symptom pattern observed here most plausibly reflects a fundamental difference in study populations (3,10). The existing literature is predominantly derived from competitive and elite athletes, whereas this sample consists largely of recreational participants training without structured guidance.

In contrast, the 50 to 69-year-old groups reported being symptom-free significantly more often, which could reflect genuine physiological adaptation through years of structured training. However, this must be interpreted cautiously given the dissociation between symptom freedom and subclinical coronary pathology documented in imaging studies (10,21). Older veteran athletes accumulate a different, cumulative risk profile including CAC, MF, and AF that is not captured by self-reported symptoms (10,21). These two distinct risk profiles, acute functional overload in younger recreational athletes versus silent structural remodeling in older experienced athletes, demand correspondingly distinct prevention strategies and should not be mixed in public health messaging.

The gender-specific findings of this study are of particular interest. Traditionally, male athletes are identified as the primary risk group for SCD (33). However, female participants in this survey reported chest pain more frequently ($n = 12$ vs. $n = 3$, $p = 0.02$). This difference reached statistical significance and, while hypothesis-generating rather than confirmatory given the small absolute numbers, represents a clinically relevant finding. Male participants showed significantly more physiological adaptations, including reduced resting blood pressure (60%, $p = 0.002$) and decreased HR (47%, $p = 0.0005$), which may reflect biological differences or more performance-oriented training strategies in men. Taken together, these sex-specific patterns are consistent with emerging

evidence that female cardiovascular risk in endurance sport is systematically underestimated. Elite female endurance athletes have been shown to face a substantially elevated risk of AF compared to matched controls, a risk only uncovered through dedicated sex-stratified longitudinal study designs (25). Additionally, women with cardiovascular symptoms are more frequently subject to delayed or missed diagnoses compared to men, which may contribute to the underrepresentation of female cardiovascular risk in the existing literature (34).

6.2.2 Discipline

The survey shows no major differences in the physiological and pathological outcomes between the individual endurance disciplines of running, cycling, and swimming. The literature has addressed studies that show discipline-specific cardiovascular adaptations, these are not apparent from the results of the present study (19,20,22,23). The most plausible explanation is insufficient statistical power. Furthermore, the predominantly moderate training intensity reported by 71% of participants suggests that the hemodynamic demands required to produce measurable discipline-specific adaptations were rarely reached in this sample. With running accounting for 58% of participants, between-group comparisons lack the sample sizes required to detect discipline-specific effects. Furthermore, discipline-specific cardiovascular adaptations tend to emerge primarily in high-volume, high-intensity training contexts, which are underrepresented in this cross-sectional cohort reflecting all performance groups. It should be noted that the present study assessed training frequency as an indirect measure of training load, but did not differentiate between vigorous and very vigorous exercise intensity. Given that recent evidence identifies exercise intensity rather than volume as the primary driver of coronary atherosclerosis progression, future studies should include more precise intensity quantification to better capture this clinically relevant distinction (27). The absence of differences is therefore less surprising and itself consistent with a predominantly recreational sample.

The 31 triathletes showed no significant differences compared to other disciplines in terms of pathological effects. The only significant finding was a higher prevalence of lower resting HR in triathletes (58%, $p = 0.04$), which is a physiological rather than a pathological finding. It likely reflects their higher total training volume across three disciplines. It was important to include triathlon in the survey in order to compare possible similarities and differences in comparison with the individual disciplines. Since other studies have associated larger events such as half marathons or marathons with a higher risk of pathological effects, the investigation of these combination athletes in triathlon is of particular importance (10). Given the higher total training volume across three disciplines, triathletes may be more susceptible to training-associated cardiovascular adaptations and pathological findings. This is consistent with the dose-dependent relationship between exercise volume and adverse cardiac remodeling described in the literature (10,12). The results of this survey

show more pathological effects in triathletes, but these remain statistically insignificant, which is most plausibly attributable to the limited number of 31 respondents. It should also be noted that triathlons only describe sport with the sub-disciplines running, cycling, and swimming. It encompasses a wide range of distances, from shorter sprint formats to the demanding Ironman distance of 226 km, each associated with distinctly different training volumes and cardiovascular demands. A more detailed survey stratified by discipline and competitive distance would provide more information and enable a more differentiated analysis. Future studies should be stratified by discipline with adequately powered subgroups.

6.2.3 Training Management

A key finding of this study is the significant correlation between training level and training volume and positive physiological adaptations. It should be noted that the classification of training level was made subjectively by the participants, which can lead to distortions between subjective and objective stress intensity. However, the results show that physiological parameters such as reduced recovery time, lower resting HR, and HR gradually improve with increasing training levels. These physiological adaptations align with established cardiovascular training responses documented in the literature (15). With regard to pathological effects, there were no significant differences between the groups, except for shortness of breath and headaches. Shortness of breath was significantly more prevalent in the recreational group (28%, $p = 0.0006$), while headaches were more frequently reported by competitive athletes (22%, $p = 0.02$). The higher rate of shortness of breath in recreational athletes most plausibly reflects an insufficient aerobic base and inadequate pacing, consistent with the FOR pattern observed in less experienced athletes (35). The elevated headache prevalence in competitive athletes may reflect higher cumulative training load, dehydration, or insufficient recovery in a group pursuing performance-oriented goals. Neither finding is sufficiently specific to indicate structural cardiac risk, but both serve as indicators of suboptimal training management that should be addressed through structured coaching. A more detailed analysis of the level, training volume, and experience would be important here. Evidence suggests that at very high training volumes, the cardiovascular benefits of exercise begin to diminish and pathological effects may emerge, particularly in susceptible individuals (10,12).

The training can be divided into training experience, duration, frequency, and intensity. With increasing training experience, physiological adaptations have a positive effect, above all improved endurance and lower resting HR (15). The survey results support this, as participants with at least six years of training experience reported significantly fewer pathological symptoms, and 52% of those with more than ten years reported being symptom-free. This apparent protective effect requires critical interpretation. While the data suggest that greater training experience is associated with fewer

adverse symptoms, two alternative explanations must be considered. The first is genuine physiological adaptation: with years of structured training, athletes develop improved recovery management and autonomic regulation, which may reduce symptom burden (35). The second is the survivor bias: the experienced cohort represents those who tolerated training loads without disqualifying adverse events, as those who developed arrhythmias, OTS, or cardiac symptoms are likely absent from this sample. However, as discussed in Section 6.2.1, symptom freedom in older experienced athletes does not indicate reduced structural cardiovascular risk. The risk profile shifts from functional to cumulative structural pathology, which is not detectable through self-reported symptoms alone and therefore requires longitudinal studies with objective imaging for meaningful conclusions in this cohort (21).

Connected with the duration of the training sessions, improved physiological parameters were reported more frequently with longer training duration. At the same time, no statistical significances were found among participants with increased duration, but those with shorter training duration reported more a shortness of breath.

The training frequency data reveals a pattern consistent with the U-shaped dose-response relationship between exercise volume and cardiovascular risk (10,12). The 3 to 6 day group reported the lowest chest pain rates (0–1.5%), while both the 1 to 2 day group (10%) and those training daily or more (10–12.5%) showed markedly higher rates. This is consistent with the finding that both insufficient and excessive exercise carry elevated cardiovascular risk (10,12). Training too frequently or too infrequently therefore appears suboptimal, which can be explained by insufficient training load on the one hand and shortened recovery times on the other. The 3 to 6 day window most plausibly represents adequate stimulus combined with sufficient recovery time, providing observational support for structured, progressive training as a cardiovascular protective principle.

The training intensity data shows no significant differences in terms of physiological adaptations. However, the group with very high intensity stands out in terms of negative effects such as increased HR, headaches, or other complaints. Given the very limited sample size, with only three participants, the observed statistical significances must be interpreted with caution and cannot be considered representative. Nevertheless, the observed pattern aligns with findings reported in the existing literature. These suggest that very high exercise intensities are associated with an increased risk of adverse cardiovascular effects, particularly in susceptible individuals (10,12).

6.2.4 Training Goals and Zone Training

Another aspect concerns training planning, or more precisely, the participants' goals. The literature does not provide any precise guidance on the advantages and disadvantages of specific goal setting.

Previous studies have not reached a consensus on whether professional competitive athletes are more frequently affected by negative effects than recreational athletes. SCDs are more common in recreational athletes, while OTS is more prevalent in competitive athletes (10,35). This survey's findings did not indicate any substantial disparities in goal setting with respect to adverse effects experienced. Notably, participants who rated competitive participation as their primary training goal reported the highest rates of physiological adaptations, a finding that reached very high statistical significance. Further analysis of the raw data would be necessary to determine which age and gender groups were primarily addressed and to correlate this with training volume. The distribution of training objectives would also be a subject of interest for future studies. Given that subjects were requested to specify on a scale which objectives they were most likely to prioritize, it would be intriguing to observe the degree to which distinct objectives impact training strategy and the corresponding outcomes.

Another parameter is zone training, or knowledge of it. Zone training is a complex training model that is defined and applied in many different ways. To standardize the questionnaire, the most widely used 5-zone model was used (5,37). Of all respondents, 70% were familiar with this term and concept. This is reflected above all in the reported adaptations. 62% reported a lower resting HR and 44% reported a lower HR when they were aware of zone training, compared with 32% and 21% among participants with no knowledge of zone training. Moreover, the knowledgeable group reported shortness of breath in 15% of cases and headaches in 11% of cases, compared with 27% and 23% in the uninformed group. These are among the strongest associations in the entire dataset, carrying high to very high statistical significance.

Due to the cross-sectional design, it cannot be determined whether these differences reflect a direct protective effect of zone-structured training or whether they are explained by other factors, such as training experience and health literacy. Multivariate analysis controlling for these variables would be a clear priority for future research. However, this study establishes independently a finding: the gap between zone training knowledge and its actual application. Of the 70% familiar with the concept, only 48.5% ($n = 149$) actively applied it, and 19% were uncertain which zone they were training in. This implementation gap has a plausible physiological consequence that the present data partially captures. The lower resting HR observed in the zone-knowledgeable group suggests that structured zone-based training is associated with more favorable cardiovascular adaptations compared to unstructured training approaches (37,41). The barrier to achieving this profile appears not to be informational but translational. Health psychology research describes it as the intention-behaviour gap, where health intentions account for on average only 28% of variance in actual behaviour (36).

Structured coaching support within athlete training environments, rather than information provision alone, is therefore indicated.

Zones 2 and 3 were most frequently cited as training zones, corresponding to light to moderate aerobic training. Zone 3 in particular has been associated with improvements in aerobic power and efficiency within THR models, which is consistent with the high statistical significance observed in this area (42). However, this stands in contrast to polarized training models, which deliberately minimize Zone 3 due to its unfavorable fatigue-to-adaptation ratio (37). In this study sample the high prevalence of Zone 3 training may reflect a suboptimal intensity distribution from a polarized training perspective, though its effectiveness within a threshold-based approach cannot be excluded. The high to very high statistical significance observed in relation to Zone 3 training in this sample should therefore be interpreted cautiously. It reflects an association between zone training knowledge and physiological adaptation, rather than a specific effect of Zone 3 intensity per se. Athletes who are aware of training zones and actively apply them may benefit from structured training principles in general, regardless of which specific zone predominates. Whether the observed adaptations are attributable to Zone 3 training specifically, or to the broader effect of structured training guidance, cannot be determined from the cross-sectional design.

The more extreme zones, such as 1 and 5, are less meaningful due to the low number of participants. This raises the question of whether differences in outcomes and risk awareness exist between participants who have knowledge, those who actively implement it, and those who neither have nor implement it. A more specific analysis of the different zones should be relevant for future studies.

6.2.5 Recovery

In addition to the implementation of zone training, the question of active recovery and stretching was also asked. The importance of adequate recovery for maintaining training-induced cardiovascular adaptations and preventing maladaptation is well established in the literature (15,24). A total of 80% of participants reported incorporating active recovery into their training, which may reflect increased awareness of regenerative processes and education in this area. This should be interpreted cautiously, as self-reported incorporation does not verify the quality or consistency of implementation. Furthermore, no correlation between recovery behavior and physiological or pathological outcomes was established in this survey, which represents a methodological gap that future studies should address directly. Notably, 68% of participants actively sought information about endurance sports from various sources. A direct connection between information-seeking behavior and training outcomes cannot be established from the present data, as no specific question was asked about the reasons and goals for seeking information.

6.2.6 Information Behavior and Risk Perception

One key question addressed in this study focused on the risks associated with endurance training. The survey results show that awareness of the various risks varies considerably. Cardiac enlargement was most frequently associated (58%), while other life-threatening risks such as arrhythmias (16%) and sudden cardiac events (23%) were mentioned less frequently. In particular, only 9 of the participants (3%) were familiar with CAC in this context. A total of 27% gave the answer "Other", which suggests that other relevant risk factors were not recognized or could not be named.

This significant knowledge gap is particularly concerning, as even health-motivated young athletes remain susceptible to serious cardiovascular risks such as arrhythmias, progressive coronary pathology, and SCD (3,10). Recent evidence consistently documents elevated coronary plaque burden in long-term endurance athletes, including more non-calcified and potentially vulnerable plaques, in the complete absence of symptoms (21,27). That 66% of this survey's participants actively sought health information, yet only 3% were aware of CAC, indicates that the problem is not motivational but informational. Clinical risk findings remain confined to specialist literature while general sports media frames endurance sport almost exclusively in terms of benefit. Reasons for these gaps in knowledge may include a lack of specific information gathering, a limited public awareness of the cardiac conditions mentioned, and a general tendency toward selective perception of health-promoting aspects without critical reflection on the associated risks. A participant with a low to moderate level of training may expect fewer health risks and therefore seek less specific information in this area. This assumption is supported by the literature, which links increased training behavior with more risks (10).

The low awareness of SCD risk (23%) requires proportionate contextualisation. The absolute SCD incidence in endurance athletes is low, and low general awareness does not constitute an immediate public health emergency (3,33). What makes the gap clinically significant is the nature of the underlying pathologies. The structural anomalies responsible for most SCDs in young athletes are frequently asymptomatic and undetectable by standard resting examination (3,15). A substantial minority of respondents reported chest pain and irregular heartbeat, symptoms which, if exercise-induced and persistent, warrant specialist evaluation. The key message is not to cause alarm, but to promote structured symptom awareness. Athletes should know which symptoms are warning signs, what to do when they occur, and that a normal resting examination does not exclude serious underlying pathology.

A related pattern emerges from the results regarding risk concerns, as 35% of respondents expressed slight to moderate concerns. Despite this, 64% stated that they did not feel sufficiently informed about

the associated risks. This discrepancy between subjective information-seeking behavior and objective knowledge gaps highlights the need for improved and more targeted education, as well as scientifically based sources of information. The increasing number of cardiac events in recreational endurance athletes has drawn growing scientific attention to this issue (3). It should be emphasized that the absence of negative symptoms in survey results is not proof of the absence of potential cardiovascular risks.

6.3 Social and Health Policy Relevance

The knowledge gaps documented in the previous Section 6.2.6, particularly the 3% CAC awareness rate, have direct implications for public health and sports medicine practice.

General campaigns promoting the benefits of endurance sport are widely available, while targeted clinical risk communication reaching recreational athletes remains largely absent. Approaches that embed risk communication within established athlete touchpoints, such as sports medicine consultations, pre-event briefings, and coaching certification programs, are therefore likely to be more effective than broad information campaigns alone.

A more systematic integration of sports medicine competencies into coaching and trainer certification would represent a targeted and scalable measure. The association between zone training knowledge and reduced symptom prevalence in this study suggests that structured training guidance can simultaneously serve as a cardiovascular protective mechanism and an educational channel. In this context, wearable technologies represent a complementary tool. The present study documents that 71% of participants actively monitored their training using wearable devices such as smartwatches or fitness trackers, reflecting a substantial uptake of these technologies in recreational endurance sport. Wearables can support cardiovascular risk management through continuous HR monitoring, training load quantification, and early detection of physiological anomalies such as arrhythmias, all of which are relevant to the risk profiles documented in this study (5,38). However, their clinical value depends on structured implementation within a coached training environment, as data alone does not translate into behaviour change without appropriate guidance (5,39). It cannot be determined from this study whether such an approach would effectively address the implementation gap documented in Section 6.2.4. This should be examined in future dedicated research.

Overall, prevention rather than treatment should be the guiding principle. Wearable technologies can provide valuable support for individual risk assessment and training monitoring. However, they cannot replace pre-participation cardiovascular screening, particularly in older athletes with high training volumes.

6.4 Outlook and Recommendations for Future Research

This study provides original population-level evidence on training behavior, symptom burden, and cardiovascular risk awareness in recreational endurance athletes. The influence of individual factors such as body composition, personal medical history, and the specific diagnostic methods used by participants on the reported cardiovascular outcomes could not be examined within the scope of this study and should be addressed in future research.

The following four methodological priorities can be identified:

First, intervention studies evaluating structured training education programs are needed to establish whether the associations observed here reflect a causal pathway. In particular, the effect of coached zone training implementation on physiological outcomes and symptom prevalence should be examined, with the aim of developing evidence-based prevention protocols for recreational endurance sport.

Second, longitudinal designs with objective cardiovascular endpoints represent the minimum methodological standard for conclusions about health in veteran athletes. The dissociation between symptom freedom and subclinical coronary pathology means that symptom surveys alone cannot capture the cardiovascular trajectory of experienced athletes, and cardiac imaging endpoints should therefore be included as standard.

Third, sex-stratified analyses should be pre-registered as standard in future studies. The present findings contribute to the growing evidence that cardiovascular risk in female endurance athletes is systematically underestimated. Moreover, studies that fail to account for this may reinforce a male-dominated evidence base.

Fourth, recruitment from clinical populations, including athletes who have discontinued training due to adverse health events and patients presenting to sports medicine clinics, would address the systematic absence of high-risk individuals from active-athlete samples. This would enable more accurate estimation of adverse event rates in the broader endurance sport population.

In addition, qualitative supplementation through interviews or diary studies can help to better capture subjective experiences and individual coping strategies. International comparative studies examining country-specific differences in training culture, healthcare systems, and prevention services could also provide valuable insights.

7. Conclusion

Endurance sports are associated with numerous health benefits. They can strengthen the cardiovascular system, optimize physical fitness, and have a positive effect on general well-being. At the same time, recent studies show that both a lack of exercise and excessive training can be associated with health risks.

This study systematically investigated the physiological and pathological cardiovascular effects of endurance training through a cross-sectional online survey of 307 active endurance athletes. The central research question, whether a clearly definable threshold exists beyond which endurance training becomes cardiovascular harmful, cannot be answered definitively. The present data confirms that no universal threshold exists. Instead, risk emerges from the interaction of training volume, frequency, experience, age, sex, and health literacy, and must be evaluated on an individual basis.

A key finding of this study is the disproportionate symptom burden in the youngest age group. Athletes aged 18 to 29 years were significantly less likely to report being symptom-free than all other age groups ($p = 2.14 \times 10^{-10}$), with shortness of breath, dizziness, headaches, and dehydration among the most frequently reported complaints. This pattern points to acute training load mismanagement and insufficient recovery as primary drivers of adverse symptoms in inexperienced athletes, rather than cumulative structural cardiac risk. This study therefore provides evidence that risk communication in endurance sports requires a differentiated approach. Younger athletes require guidance on avoiding acute overreaching, while older high-volume athletes need targeted awareness of cumulative structural cardiovascular risks.

With respect to training frequency, this study identifies a non-linear, U-shaped relationship between weekly training days and symptom prevalence. Athletes training 3 to 6 days per week reported the lowest rates of chest pain (0 to 1.5%), while both very low (1 to 2 days: 10%) and very high training frequencies (daily or multiple times daily: 10 to 12.5%) were associated with markedly elevated symptom rates. This finding is consistent with evidence suggesting that both inactivity and extreme exercise volumes carry distinct cardiovascular risk profiles. The 3 to 6 day frequency window identified in this survey represents a concrete and actionable training guideline grounded in the study's own empirical data.

The gender-specific findings of this study are consistent with emerging evidence concerning female cardiovascular risk in endurance sport. While epidemiological data consistently identifies males as the primary risk group for SCD and exercise-associated AF, female participants reported chest pain more frequently than male participants ($n = 12$ vs. $n = 3$) and demonstrated lower rates of physiological adaptation such as lower resting HR. This study contributes to a growing body of

evidence suggesting that the cardiovascular risk burden of endurance training in women may be systematically underestimated and calls for sex-stratified analysis as a standard requirement in future endurance sport research.

With respect to risk awareness, this study documents a profound knowledge gap among active endurance athletes. Despite 66% of participants having actively sought information about training and health, only 3% identified CAC as an endurance-associated risk, and only 23% were aware of SCD. To the authors' knowledge, quantitative survey evidence on CAC risk awareness among active endurance athletes remains very limited in the literature. This finding therefore represents a relevant empirical contribution to this underexplored area, demonstrating that the most clinically significant long-term cardiovascular risks of endurance training, including CAC, AF, and MF, are virtually absent from athlete awareness despite occupying a central position in current sports cardiology literature. Closing this gap requires targeted, evidence-based public education that goes beyond general health promotion, and mandatory pre-participation health briefings at mass endurance events.

Knowledge of HR zone training was associated with significantly lower symptom prevalence across multiple categories, including shortness of breath (15% vs. 27%) and headaches (11% vs. 23%), confirming that structured training control is a modifiable protective factor. However, 21.5% of all participants trained without applying zone principles despite possessing conceptual knowledge, indicating a health literacy gap that wearable technology alone cannot resolve.

The primary limitation of this study is its cross-sectional, self-report design, which precludes causal inference and is susceptible to selection bias toward health-conscious, active athletes. The absence of objective cardiovascular measurements such as ECG, imaging, and biomarkers means that subclinical pathology, as documented in asymptomatic veteran athletes in recent imaging studies, cannot be detected. Future studies should combine longitudinal designs with objective biomarker data, sex-stratified cohorts, and targeted recruitment of athletes who have discontinued training due to health-related reasons, a population systematically absent from cross-sectional athletic surveys.

It can be concluded from the present study that endurance training must always be considered on an individual basis. The decisive factors are the interaction of personal characteristics, the quality of training management, and awareness of possible risks. The 3% CAC awareness rate documented in this study, combined with the statistically significant association between zone training knowledge and reduced symptom prevalence, points to structured educational interventions in sports medicine as a priority. Wearable technologies may support training monitoring and early symptom detection, but cannot substitute pre-participation cardiovascular screening, which remains essential particularly for older athletes with high training volumes.

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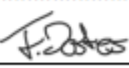
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9. Disclosure

9.1 Vilnius University Warranty

Vilniaus universiteto studijuojančiojo, teikiančio baigiamąjį darbą, GARANTIJA	WARRANTY of Vilnius University Student Thesis
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9.2 Declaration on the use of AI and Reference Management Software

Artificial intelligence (AI)-based language tools, specifically ChatGPT by OpenAI and Claude by Anthropic, were used in a limited and supportive manner during the preparation of this thesis. Their use was restricted to linguistic editing, improvement of academic phrasing, grammar correction, and formatting. AI tools also assisted in structuring selected sections and tables, as well as in creating distribution materials such as flyers for survey recruitment. AI tools were not used to generate scientific content, interpret study results independently, or draw methodological or clinical conclusions.

All scientific content was developed by the author. This includes the formulation of the research questions, the systematic literature review, the design and distribution of the cross-sectional online survey, the statistical analysis of the survey data, and the interpretation of findings regarding cardiovascular effects and risks of endurance training. Reference management and citation formatting were performed using Zotero (Corporation for Digital Scholarship, USA).

In accordance with the Guidelines on Artificial Intelligence Usage at Vilnius University (Senate Resolution No. SPN-54, 18 June 2024), the use of these tools is hereby disclosed.