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Faculty of Physical Education and Sports

DIPLOMA THESIS

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Exploring Heart Rate Recovery as an Aerobic Fitness Indicator in Elite Athletes

Diploma thesis

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Declaration:

I declare that I have independently processed the final (master's) thesis and that I have cited all used sources of information and literature. This thesis or its significant part has not been submitted for obtaining any other academic degree.

In Prague: _______________ Signature: _______________

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Abstract

Title: Exploring Heart Rate Recovery as an Aerobic Fitness Indicator in Elite Athletes.

Aim: The purpose of this study was to determine the relationship between HRR and aerobic fitness in elite youth and adult elite athletes.

Methods: A total of eighty-two (n=82) participants volunteered to participate in the study with seventy-six well-trained soccer players (n=76) and six well-trained triathletes (n=6) according to age and type of sports divided into Group Youth soccer players (15.6±0.8 yrs) n=19 (Group Y); Group Adult soccer players (23.8±2.8yrs) n=57 (Group A)and Group Triathletes(16.6±1.2 yrs) n=6 (Group T). Soccer players were all from the Czech First League and triathletes are performing in top-level competition. All participants underwent anthropometric measurements and performed a maximal cardiopulmonary exercise test on a treadmill to determine maximal oxygen uptake (V̇O2max), oxygen consumption at the second ventilatory threshold (VO2VT2), percentage of VO2max at the second ventilatory threshold (%VO2maxVT2), maximum heart rate (HRmax), Heart rate recovery after 1^{st}, 2^{nd}, 3^{rd} minute, respectively (HRR 1min, HRR 2min, HRR 3min).

Results: The youth soccer group showed significantly higher HRR 1min ($P<0.05$) and VO2max in relative value ($P<0.05$) compared to the adult soccer group. The triathlete group showed a significantly lower %VO2maxVT2 ($P<0.01$) than both soccer groups. The correlation between HRR 2min, HRR 3min and VO2VT2 only could be found in the youth soccer group ($r=-0.517$, $P<0.05$; $r=-0.552$, $P<0.05$). The correlation between HRR 3min and %VO2maxVT2 could be found both in the youth soccer group ($r=-0.508$, $P<0.05$) and the triathlete group ($r=-0.845$, $P<0.05$).

Conclusions: The results of this study do not support HRR as a significant indicator of aerobic fitness in elite soccer players and triathletes. However, HRR may be considered in an individual's aerobic fitness diagnostics as a unique indicator related to cardiovascular fitness and recovery.

Keywords: Ventilatory threshold, Maximal Oxygen Uptake, Triathlon, Soccer, Football

LIST OF ABBREVIATIONS

MHR: Maximal Heart Rate

HRR: Heart rate recovery

HRR 1min: Heart rate decreases in 1 minute after exercise.

HRR 2min: Heart rate decreases in 2 minutes after exercise.

HRR 3min: Heart rate decreases in 3 minutes after exercise.

HRR1: Average Heart Rate in 1 minute

VT: Ventilatory Threshold

VT1: The first Ventilatory Threshold

VT2: The second Ventilatory Threshold

VO2max: Maximal Oxygen consumption

VO2VT2: Volume of Oxygen consumption at VT2

%VO2maxVT2: Percentage of VO2max at VT2

VCO2: Volume of Carbon dioxide produced.

VO2: Volume of Oxygen consumed.

VE: Minute ventilation

BMI: Body mass index

ANS: Autonomic nervous system

CONTENTS

1. INTRODUCTION

Soccer is one of the most popular sports in the world and is a globally beloved sport played by millions. A soccer match contains high/maximal-intensity activities like sprinting and running combined with low-intensity activities like walking and jogging (Bradley et al., 2013). To have a better performance in competition, soccer players need to develop both anaerobic capacity and aerobic capacity (Colosio et al., 2020). For the anaerobic level, we could observe the peak power output and other functional tests (Jumping test, Repeated Sprint Ability, anaerobic threshold, etc.). For the aerobic level, VO2max (Maximal Oxygen Consumption) and some field tests (Yo-Yo Intermittent Recovery Test, the Beep Test, etc.) are the most common measurements for accessing aerobic fitness. However, these tests should be done while training, they could not provide an immediate response to the coach to assess players' status during a match or training.

Thus, with the popularity of smart wearable devices, monitoring and collecting heart rates in real-time has become simple and non-invasive, which can be accepted by both professional teams and the public. This thesis will focus on exploring heart rate recovery as an indicator to assess aerobic fitness in elite athletes.

2. OVERVIEW OF THEORETICAL KNOWLEDGE

2.1 Heart Rate Parameters

2.1.1 Heart Rate monitoring

To the best of our knowledge, Heart Rate Monitoring has been invented for evaluation of the physiological load since the 1960s (Seliger ,1968). Traditional methods of measuring heart rate response during different sports activities involved continuous electrocardiogram (ECG) recordings that were transmitted via short-range radio telemetry. There is increasing concern that the activities in soccer like Running, jumping, and sweating after high-intensity activities may cause poor contact with sensors during the measurement. In the early 1980s, wireless cardio monitoring technology was indicated, which allowed heart rate monitoring during playing situations, without the limitation of the previous ECG monitoring (Van Gool et al., 1983). Until the early 1990s, The HR monitor with a microcomputer was implemented which created a new method to monitor all players in one device through the software. More recently, the step-Polar Team2 HR system allows real-time HR monitoring and transits of the heart rate data to the software for further investigation (Teixeira et al., 2021).

2.1.2 Maximum Heart Rate (HR max)

Several studies investigating Maximum Heart Rate (HR max) have been carried out. There are three different equations to predict the HR max which are [HR max = age-220]; Tanaka et al. [HR max = 208 – (0.7*age)] and Nes et al. [HR max=211 – (0.64*age)]. However, Silva et al. (2012) compared these three equations with young soccer players and found out that it is recommended to use the Nes et al. [HR max=211 – (0.64*age)] equation to the MHR predicted which is most similar to the HR max observe comparing to other two equations. This finding could minimize the error of the predicted HR max (Diniz Silva et al., 2013).

2.1.3 Heart Rate Recovery (HRR)

Not only the real-time HR important but also post-exercise HR. In 1994, Imai et al. (1994) demonstrated two linear components of the decline in heart rate over a certain period of time after exercise: the first rapid decline followed by a slow decline. Therefore, the concept of

Heart rate recovery (HRR) was proposed and defined as the fall in HR during the first 60 seconds (HRR 1) after a bout of exercise exertion (Imai et al. 1994, Buchheit & Gindre, 2006) and other researchers characterized HRR as the rate of decline in heart rate over the initial 5-minute recovery period (Shetler et al., 2001, Yang et al., 2023). Still, based on investigations of Yang et al., (2023) and Suzic Lazic et al. (2017), HRR 1-3min has the greatest improvement in the model's prediction of aerobic capacity. Therefore, in this research, HRR 1min and the following minutes (HRR 2min and HRR 3min) up to 3 minutes will be used to define HRR.

HRR 1min = MHR – HRR1

HRR 1min: Heart rate decreases in 1 minute after exercise.
MHR: Maximal Heart Rate
HRR1: Average Heart Rate in 1 minute

Thanks to Cole et al (1999), investigating heart-rate recovery following exercise could serve as a predictor of mortality. Therefore, more and more researches were done to identify the association between parasympathetic reactivation reflected by HRR and cardiovascular disease (CVD) (Goldberger et al., 2006). The parasympathetic nervous is a branch of the autonomous nervous system (ANS), cooperating with another branch of the nervous, the sympathetic nervous. These two nervous branches work in opposition to maintaining body activities such as increasing the heart rate by activating the sympathetic branch and inhibiting the parasympathetic branch, which is similar to the mechanism of HRR that parasympathetic reactivation and sympathetic inhibition (Borresen & Lambert, 2007) (Goldberger et al., 2006). HRR is a powerful and independent predictor of cardiovascular and all-cause mortality in healthy adults, in those with CVD and diabetes (Durmić et al., 2019). However, it is also a useful indicator of aerobic fitness, Daanen et al., (2012) reported that HRR has the potential to become a valuable tool for monitoring changes in training status in athletes. Fast HRR is associated not only with better athletic performance but also with cardiac functional adaptation to physical activities of various durations and intensities (Vahia et al., 2019). According to Nishime et al. (2000), During exercise echocardiography during which there is no cool-down period, a HRR of ≥18 beats/min within the first minute is considered normal. The average HRR in athletes in the first minute is 26 ±13.8(bpm), the second minute is 57.6±4.8(bpm) and the third minute is 81.3±11.3(bpm) (Suzic Lazic et al., 2017).

2.1.4 Heart rate recovery applied in triathletes and endurance athletes

In recent years, there has been an increasing amount of literature on HRR in triathletes and endurance athletes. Stöggl & Björklund, (2017) performed a comparison between low-volume high-intensity interval training (HIIT) and a combination of low-intensity and high-intensity training (POL) and found that HIIT could improve the neuromuscular status and thus acute HRR in well-trained triathletes. Other studies have considered this relationship, Aubry et al., (2015) HRR is sensitive to functional overreaching though faster HRR is not associated with improved physical performance in well-trained triathletes. Considering the sex difference factor, Hottenrott et al., (2021) compared the different sex triathletes' recovery from HIIT by HRR. 11 females (32.1±9.7yrs) and 11 males (33.2±9.9yrs) triathletes were tested after HIIT training protocol with Wingate test and recorded the HRR. This study showed that women triathletes have a slower HRR than males because of sex differences in autonomic function and vagal reactivation following maximal exercise.

Dixon (1992) observed accelerated HRR with higher resting high-frequency vagal components in running endurance athletes and thus proved endurance training could affect their neurocardiac system. Seiler et al., (2007) discovered 9 highly trained athletes who applied different exercise protocols varying in intensity and duration and found that autonomic recovery is delayed when exercise is performed above VT1, which means exercise intensity could affect the ANS.

Lamberts et al., (2009) studied the relationship between HRR and high-intensity training. They invited 14 well-trained cyclists to perform a high-intensity training program in 4 weeks and compared the respiratory gas and HRR. In the end, they reported that high-intensity training can improve HRR. Further, they did a further investigation of the use of HRR as a Grouping metric that divided 14 well-trained cyclists into continues had an increase in HRR(G_{incr}) and a decrease in HRR(G_{decr}) and performed the same high-intensity training in 4 weeks and comparing their HRR after training. This study found that athletes with higher HRR could improve more in endurance performance. Thus, HRR is sensitive to changes in the training status and has the potential to monitor changes in endurance performance in well-trained cyclists.

Lee and Mendoza (2011) based on Lambert's discovery, investigated how low-intensity exercise of different durations affects HRR. 20 healthy male adults were separated randomly into 2 groups to perform the same volume and low-intensity but in 16x30min exercise sessions or 8x1hour exercise sessions and comparing the HRR and VO2max. They found a significant correlation between HRR and both physical activity and VO2max, suggesting that HRR may be a better marker of aerobic fitness in well-trained endurance athletes.

Suzic Lazic et al. (2017) did a large group experiment with 274 elite male athletes in 137 adolescents(14y-18yrs) and 137 adults (≥18yrs). Both two groups of participants performed maximal cardiopulmonary exercise testing on a treadmill and monitored heart rate decline from peak heart rate to the heart rate of 1/2/3 minutes after cessation exercise (HRR 1min, HRR 2min, HRR 3min) and VO2max. This study reported a precise indicator indicating that different times of HRR should be considered for different functions. They found that HRR 3min could serve as an index of aerobic capacity, regardless of age. However, a higher value should be placed on HRR 1min in older athletes.

Bentley et al., (2020) investigated the effects of chronic endurance training by HRR following maximal exercise in 36 (53 ± 5yrs) middle-aged endurance athletes and 19 (56 ± 5 yrs) physically-active individuals. The study found that endurance athletes had greater HRR compared to physically active individuals due to lower resting HR in endurance athletes.

Dupuy et al., (2022) tested 12 untrained prepubertal children(12.3 ± 1.6yrs) and 14 untrained men(21.8 ± 2.2yrs) and 16 well-trained adult male endurance athletes(24.5 ± 4.8yrs) maximal run field test and immediately recorded HRR for 5 minutes. This study showed that untrained prepubertal children have the same decrease as well-trained adult endurance athletes in HRR. It is said that exercise training can counteract the decline in HRR, parasympathetic reactivation, and metabolic health after exercise because of growth and maturation.

Bandsode & Joshi, (2022) invited 47 well-trained male swimmers(18-30yrs) to perform a Treadmill test and discover the relationship between HRR and Fatigue by Borg-based RPE and VO2max. The result shows an indirect correlation between HRR and fatigue, whereby an increase in HRR with a decrease in fatigue levels. Additionally, a direct relationship was observed between HRR and VO2max, indicating that enhancements in HRR correspond with improvements in VO2max.

Overall, these studies highlight the need for the investigation of HRR, which is influenced by exercise intensity and training status in endurance athletes. Most of the research on triathletes has focused on the effects of training protocol on HRR. Higher-intensity exercise can delay HRR, while training can improve it. HRR correlates with aerobic fitness and fatigue levels, with potential associations for training optimization and performance monitoring in athletes of different ages.

2.1.5 Heart rate recovery applied in soccer players

HRR applied in soccer is controversial. Based on Rave et al., (2018) investigation, Half of the European soccer clubs did not use HRR for training monitoring because they didn't find any scientific evidence in past research.

However, there are several studies investigating HRR applied to soccer players. Buchheit et al., (2010) demonstrated Day-to-day HRR after a 5-min submaximal run and recorded HRR for 5minute in the sitting position in 18 (under 15yrs) and 15 (under 17yrs) soccer players over 3 weeks of competition camp. U15 players have faster HRR than U17 and HRR is correlated to maximal aerobic speed. Buchheit et al., (2011) did a further investigation of post-exercise hemodynamic and autonomic response in 55 highly trained young male soccer players(12-18yrs) divided by maturation level (Peak height velocity, PHV). All the participants performed a running test on a treadmill until exhausted and recorded HRR and Parasympathetic metrics. This study shows that pre-PHV players have a faster HRR than others because of lean muscle mass, blood acidosis and intrinsic parasympathetic function but not maturation.

The study by Doncaster et al. (2019) invited a group of youth (12-14yrs) well-trained soccer athletes to have a 6-minute Yo-Yo IR1 test and record the HRR for 3min and suggested that HRR measures are pertinent for evaluating training-induced changes in soccer players' aerobic fitness.

A recent study by Kulothungan et al., (2019) tested 15 female endurance-trained soccer players(18-25yrs) to perform an immediate cessation of Cooper twelve-minute run/walk test and recorded HRR for 5min. This study reported that higher aerobic capacity could be expected to have faster HRR, and aerobic exercise could accelerate HRR. Thus, HRR has an acute response to aerobic exercise in female soccer players.

Kurtay et al., (2021) invited 25 male soccer players(16yrs) to perform a Yo-Yo Intermittent Recovery Level 1 test and measured aerobic endurance level and MHR and HRR in 2 minutes (HRR 1min, HRR 2min) and compared after a 9-week training program in the competition period. This study showed that this training program could affect the HRR 1min and aerobic endurance levels in U16 soccer players.

Beyaz (2021) involved 67 male soccer players from three different teams to have the VO2max test and recorded the VO2max and anaerobic threshold. He found that there is a statistically significant difference between teams in HRR and anaerobic threshold but not in VO2max in Turkish soccer teams.

More recent attention has focused on the provision that Mandroukas et al.,(2021) invited 126 young soccer players (12-16yrs) to determine the effect of soccer training on aerobic capacity between trained and untrained adolescent boys and reported that soccer training has a positive effect in the central cardiovascular system with higher VO2max in trained group comparing with the untrained group.

The studies presented thus far provide evidence that HRR correlates with aerobic fitness in youth players and show the acute response to aerobic exercise in females and status changes in males. Differences exist between teams in HRR and anaerobic threshold. Soccer training positively impacts aerobic capacity in adolescents. Thus, HRR has the potential to assess fitness and training effects in soccer.

2.2 Aerobic Fitness Variables

2.2.1 Oxygen consumption

Oxygen is the key factor in the analysis of aerobic fitness. Measuring oxygen consumption could determine an individual's ability to transmit oxygen to the whole body during exercise. Generally, cardiopulmonary tests are used for measurement through a treadmill or a bike which requires individual walking, running, or riding with a facemask or Hans-Rudolph mouthpiece to record the volume and composition of oxygen and carbon dioxide in every single breathing including one-time inhale and one-time exhale. Additionally, another wearable device called muscle oxygen saturation (SmO2) can indirectly measure muscle oxygen utilization by monitoring the balance between oxygen delivery and oxygen consumption in skeletal muscle tissue by near-infrared spectroscopy (NIRS).

2.2.2 Maximal Oxygen Consumption (VO2max)

VO2max is also called maximal oxygen consumption, which is the rate of an individual's ability of body consumption and utilization of oxygen during maximal exercise and is also used to indicate aerobic capacity (Bassett, 2000). This is significant for athletes to maximum utilize energy to be produced aerobically. VO2max could be approximately calculated with Heart rate, which is dividing one's maximal heart rate by one's rest heart rate and multiplying by 15.3 (Habibi et al., 2014). The average of the soccer player's Vo2max is from 58 to 66 ml.kg-1.min-1 (Da Silva et al., 2011). Sergej et al., (2011) and Suzic et al., (2017) suggested that higher aerobic capacity (VO2max) could be better adapted to maximal exercise and could be more prone to a rapid decrease in Ultra-short-term HRR (Algrøy et al., 2011).

2.2.3 Ventilatory Threshold (VT)

From a practical point of view, the first and second ventilatory thresholds are usually used to differentiate exercise intensity (Kaufmann et al., 2023). The first Ventilatory Threshold (VT1) as well as the Gas exchange threshold, VT1 is defined as the intensity at the beginning of an increase in VE/VO2 without a concomitant increase in VE/VCO2 (Algrøy et al., 2011; Froelicher & Myers, 2006).

The second Ventilatory Threshold (VT2), also called the Respiration Compensation Point, is characterized by the intensity at a significant increase in ventilation (VE) or observed an increase in VE/VCO2 and is often associated with the onset of metabolic acidosis (Poole et al., 2021). This threshold can be determined through various methods, including the analysis of respiratory frequency (James et al., 1989) and the monitoring of respiratory gas exchange variables such as respiratory exchange ratio (RER), VE/VO2 and VE/VCO2 (Bhambhani, 1985). Hebestreit et al., (2000) found that the Ventilatory threshold is a valid marker of aerobic capacity and a useful measure of aerobic fitness. Seiler et al., (2007) discovered that autonomic recovery is delayed when exercise is performed above VT1, which means the ventilatory threshold could affect the ANS. Later, Algrøy et al., (2011) applied VT to distinguish exercise intensity and reported that the soccer players' intensity distribution during in-season training was similar: 71% ≤ VT1, 21% between VT1 and VT2, and 8% ≥ VT2.

2.2.4 Percentage of VO2max at VT2

A percentage of VO2max is usually used to describe the intensity of exercise (Mann et al., 2013). Every individual has a different level of Oxygen consumption. The position of VT relative to VO2max is used to represent the thresholds for different individuals. This study introduces a new indicator to describe the VT position using the percentage of VO2max, the Percentage of VO2max at VT2 (%VO2maxVT2). This indicator aims to minimize the impact of individual differences in aerobic capacity by providing a standardized measure that reflects the relationship between VT2 and maximal oxygen consumption during exercise which better describes the position of VT2 and make it comparable.

$$\%\text{VO2maxVT2} = \frac{\text{VO2VT2}}{\text{VO2max}} * 100\%$$

VO2VT2: Volume of oxygen consumption at the second Ventilatory Threshold (VT2)

VO2max: The highest volume of oxygen consumption in intense exercise

3. PURPOSE OF STUDY

Previous studies have indicated a relationship between heart rate recovery (HRR), endurance performance, and aerobic capacity in well-trained endurance athletes. These previous studies suggest that HRR may be modifiable through adjustments in exercise intensity or training methods. Several studies on soccer players show the resemblance results that HRR is also related to aerobic fitness and has a faster decrease in younger athletes. So far, however, there has been little discussion about the relationship between HRR and the second ventilatory threshold (VT2). Previous studies have shown a clear connection between HRR and endurance performance, as well as aerobic capacity, there is a significant gap in exploring the correlation specifically with VT2. By exploring this unknown area, this study aims to determine the potential relationship between HRR and VT2 so as to enhance our understanding of biological markers in athletic aerobic fitness.

3.1 Objective

The objective of this research is to determine the relationship between HRR and aerobic fitness in elite youth and adult elite athletes.

3.2 Hypothesis

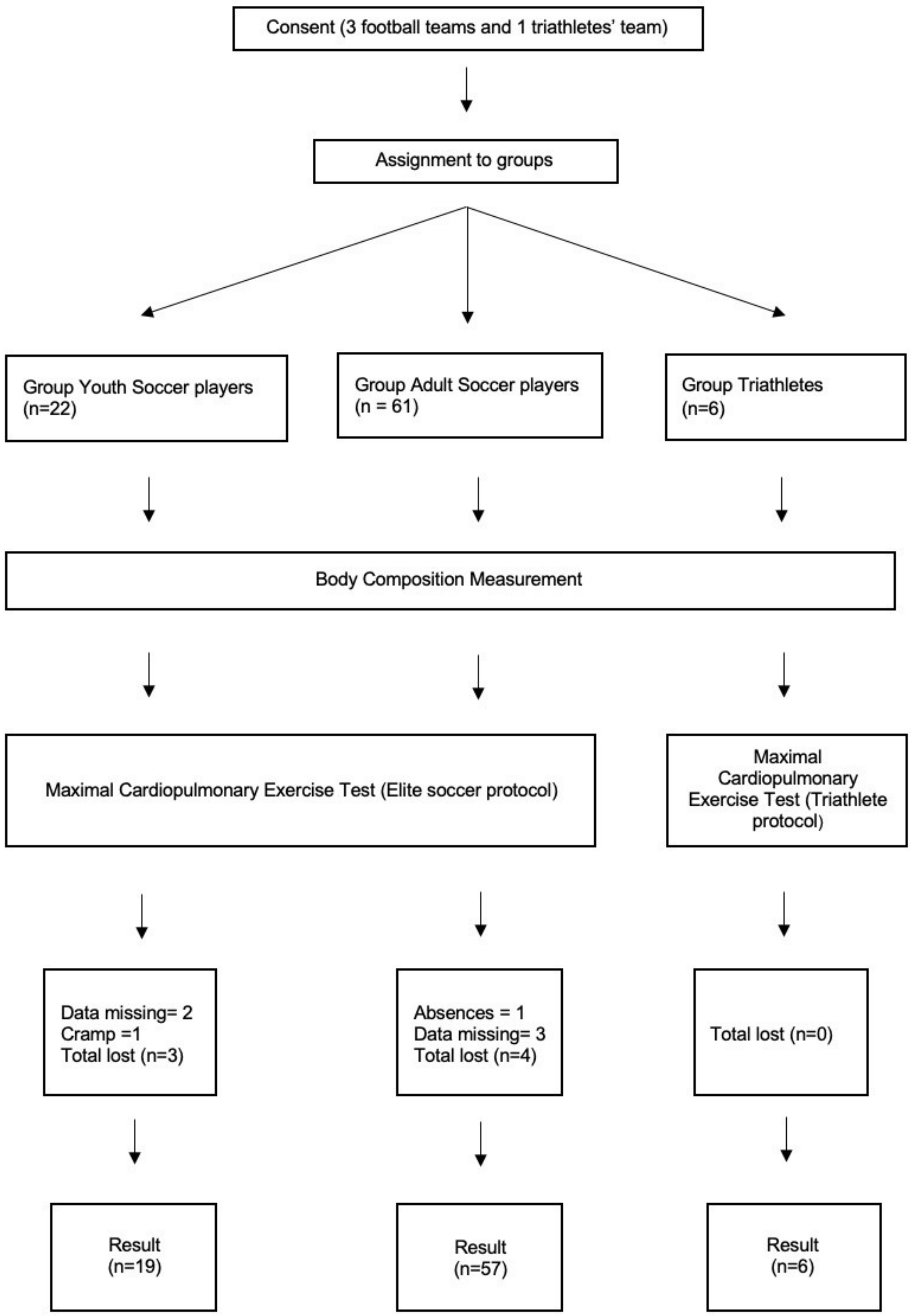
It is hypothesized that a significant correlation exists between heart rate recovery index (HRR 1min, HRR 2min, HRR 3min) and variables of aerobic fitness (VT2, %VO2maxVT2, VO2max) among elite athletes.

4. METHODOLOGY

4.1 Study design

This is a cross-sectional study involving 82 well-trained male athletes aged 16 to 28 years old. Figure 1 is the recruitment procedure and experiment protocol. Body composition measurements were taken before conducting the maximal cardiopulmonary exercise test. Participants underwent a 20-minute warm-up preparation, followed by a 5-minute warm-up run on a treadmill set to zero slopes. Subsequently, participants performed a maximal cardiopulmonary exercise test under standard environmental conditions. The treadmill speed increased every minute (soccer) or every 5 minutes(triathletes) until exhaustion. Following the exercise, participants immediately entered a recovery protocol, during which maximal heart rate (MHR) was recorded. Participants then engaged in passive recovery for three minutes on the treadmill, during which heart rate was recorded each minute (at the first minute, the second minute and the third minute). Heart rate recovery (HRR) was calculated as the decrease from MHR to HR measured each minute during recovery. Respiratory gas measurements were continuously recorded throughout the treadmill exercise using a breath-by-breath gas analyzer. Each minute the average oxygen consumption (VO2), carbon dioxide production (VCO2), and minute ventilation (VE) were constantly recorded. The same investigator conducted all tests.

Figure 1. Flow diagram of Recruitment Participants and Test Procedure.



4.2 Participants

Participants in this study comprised seventy-six well-trained soccer players (n=76) and six well-trained triathletes (n=6) from the highest division of the Czech Republic. Nineteen soccer players and all triathletes were 18 years old or younger, while the remaining soccer players were over 18 years old. Participants were categorized into three groups based on age and sport: Group Youth soccer players (16 ± 1yrs) n=19 (Group Y); Group Adult soccer players (24 ± 3yrs) n=57 (Group A) and Group Triathletes (17 ± 1yrs) n=6 (Group T). All participants volunteered to participate in the study and obtained an informed consent form. Before the recruitment, the test procedures were explained to the participants and screening for health risks. All the participants had a valid medical report before the experiment, and they were requested to complete a written statement of informed consent and an additional questionnaire about family heart disease history and medication habits to determine whether safe for them to be included in the experiment. It was validated that participants gave maximal effort during test procedures and all questions were answered truthfully. None of them had a cardiovascular disease medical history or were suffering from any musculoskeletal disorders (muscle soreness, pain, injuries). The participants were asked to avoid intake of any food within the last 2 hours and avoid intake of caffeine for 6 hours. Besides, vigorous physical activity should be avoided for 24 hours before the experiment to ensure cardiovascular measurements are approximately as normal status.

4.3 Inclusion criteria

Participants qualified for enrollment in this study must meet the following inclusion criteria:

1. Well-trained athletes: Individuals with regular endurance training and competition at a highly competitive level.
2. Age range: Individuals are between 16 to 28 years old at the time of enrollment.
3. Willingness and capability: Individuals are required to exhibit both the willingness and the capacity to commit to and complete the study protocol under its prescribed guidelines and methodologies.

4.4 Exclusion criteria

Participants who had been excluded from enrollment in this study meet any of the following exclusion criteria:

1. Smoking or drug use: Individuals who smoke cigarettes or use any other drugs will be ineligible for participation.
2. Medical history: Participants who have associated medical complications such as obesity, metabolic disorders, cardiovascular disease, and musculoskeletal disorders.
3. Pre-existing condition: Prospective participants who are aware of pre-existing medical conditions such as diabetes, hypertension, or any other conditions that may significantly impact the study outcomes will be excluded from enrollment.

4.5 Ethics approval

All participants were informed of the testing procedures and provided written informed consent to participate in the study. The study received approval from the Ethical Committee of the Faculty of Physical Education and Sport, Charles University, under approval number 107/2021. The preparation of ethical documents and measurement protocols adhered strictly to the ethical principles outlined in the Declaration of Helsinki and the established ethical standards governing research in sport and exercise science (Harriss et al., 2017).

4.6 Procedures

Screening: Upon arrival at the sports laboratory, before participation in this study, participants signed an informed consent exemption and completed the additional questionnaire. The participants were informed about the extent of the study's content and also signed a university research participation release form before its commencement. Each participant was requested to measure Blood Pressure before the experiment.

Measurements of body composition: Participants were asked to remove all electronic devices such as electronic watches and other metal accessories. Height was recorded using a stadiometer (Medihum, Slovakia). Body composition and multi-frequency bioimpedance segmental analysis were conducted using the following devices: Tanita MC-780MA (Tanita, Japan) (Figure 2).

Figure 2. Tanita MC-780MA (Tanita, Japan)

Figure 3. Polar H10 (Polar Electro OY, Finland)

Warm-up Preparation: Each participant was requested to perform a warm-up protocol with a 15-minute low-intensity exercise using resistance bands and finish with 5-minute stretching.

Measurements of cardiovascular variables: Heart rate (HR) was recorded by Polar H10 heart rate monitor (Polar Electro OY, Finland) (Figure 3) to establish baseline values before exercise, during exercise, and during the recovery phase. HR was measured immediately before the cardiovascular test and every 30 seconds during exercise. HRmax was recorded by the average of last-minute HR before the subject was exhausted. HRR was measured from the first minute of recovery to every 60 seconds of each subsequent minute for a total of 3 minutes of recovery (HRR 1min, HRR 2min, HRR 3min) during each test.

Measurements of respiratory gas: Each participant was provided with a suitable mask or Hans-Rudolph mouthpiece for measuring respiratory gas using a breath-by-breath gas analyser (Metalyzer 3B, Cortex Biophysic, Germany) (Figure 5). VO2 uptake, carbon dioxide production (VCO2) and expired minute volume (VE) were measured while participants ran on a treadmill (h/p/cosmos Quasar, Cosmos, Germany) (Figure 4) at a 5 % incline, with velocities increasing 1 km/h each minute from 11 km/h until exhaustion. Calibration was done before the test with a known gas mixture of 15% O2 and 5% CO2. VO2max was observed at the peak value during the whole exercise. The gas analyser software calculates the respiratory exchange ratio (R=VCO2/VO2), the oxygen ventilatory equivalent (VE/VO2) and the carbon dioxide ventilator equivalent (VE/VCO2). Prior to each measurement, ambient air auto-calibration and volume calibration were conducted following the manufacturer's guidelines. Volume calibration was carried out using a 3L syringe.

Exercise protocol: There are two protocols for testing different athletes.
For the soccer players, before the main test, participants underwent a 3-minute warm-up exercise on a treadmill set to 0% incline and a speed of 11 km/h. Following the warm-up, the treadmill was adjusted to a 5% incline for the duration of the test. The initial velocity of 11 km/h was incremented by 1 km/h each minute until participants met the termination criteria.
For the triathletes, before the main test, participants underwent a 3-minute warm-up exercise on a treadmill set to 0% incline and a speed of 8 km/h. After the warm-up, the treadmill was adjusted to a 1% incline for the duration of the test. The initial velocity of 8 km/h was incremented by 2 km/h each 5 min until participants met the termination criteria.

Figure 4. Treadmill (h/p/cosmos Quasar, Cosmos, Germany)

Figure 5. Gas analyser (Metalyzer 3B, Cortex Biophysics, Germany)

The end criteria were according to the maximal perceived exertion of the participant and traditional standard: (1) A plateau in oxygen consumption despite an increase in workload; (2) An elevated respiratory exchange ratio (RER) equal to or greater than 1.0; (3) Exceeding 90% of the predicted MHR based on age (220 - age); (4) Investigator or supervisor consider the subject was at high risk of falls or other conditions that may be harmful to safety. Verbal support was given to guarantee maximal exertion. After the test, the participant stood on the treadmill to have 3 minutes of recovery protocol. The HRR was recorded by the investigator each minute for a total of 3 minutes.

4.7 Data collection

The VT2 was determined by 2 methods of gas analysis: VE and R, V-slope. The turning points were utilized to determine the threshold of the VE/VCO2, VE/VO2 and VE. VT2 is characterized by a second rapid rise in VE accompanied by an increase in VE/CO2 and VE/VO2. In the meanwhile, the respiratory exchange ratio (R=VCO2/VO2) should be over 1.0 during VT2 determination, as higher exercise intensity leads to increased VCO2 exhalation compared to the steady state (Datta et al., 2015).

Moreover, during incremental exercise testing, VO2 does not decrease due to the buffering of lactate produced by anaerobic metabolism, while VCO2 rises. VT2 is often expressed as the VO2 at the onset of this process. The V-slope method is commonly utilized for the indirect measurement of VT2, where the slope of VCO2 against VO2 (VCO2−VO2 slope) displays a sudden increase.

All VT2 determinations were performed independently by two experienced exercise investigators with visual inspections of graphs. If the result has over a 5% difference, a third experienced exercise researcher would independently analyse the data. The adjudicated VT2 value was then compared to the initial determinations and averaged using the values that were closer to the adjudicated value.

The %VO2maxVT2 was calculated after VT2 and VO2max determination using formulas implemented in Excel.

4.8 Statistical analysis

All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS) (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as Mean ± Standard Deviation. One-way analysis of variance (ANOVA) was utilized to evaluate differences between groups for each independent variable, followed by Bonferroni's post-hoc analysis to further discern differences between each pair of groups.

The correlation between the heart rate recovery index (HRR 1min, HRR 2min, HRR 3min) and variables of aerobic fitness (VT2, %VO2maxVT2, VO2max) was analyzed using Pearson's correlation coefficient (r). The magnitudes of correlation were interpreted based on the following thresholds: 0 to 0.30 (weak), 0.31 to 0.49 (moderate), 0.50 to 0.79(strong) and 0.80 to 1.00(very strong).

The level of statistical significance was set at $p < 0.05$.

5. RESULTS

5.1 Participants

A comprehensive overview of participant characteristics (n=82) is provided in Table 1 detailing fundamental biological attributes. All participants successfully completed the maximal cardiopulmonary exercise test according to the pre-established physiological criteria outlined in the methodology section. The participants comprise well-trained athletes with an average age of 21 ± 4 years, with a corresponding mean height of

181.6 ± 7.1 cm. The mean body mass index (BMI) was computed at 22.9 ± 1.5 kg/m^2. Remarkably, all participants attained a VO2max of 57.8 ± 4.2 ml/kg/min and a maximum HR of 195 ± 7 bpm.

Table 1. Descriptive data of the participants (n = 82). (mean ± SD)

Parameter	Value
Age (years)	21±4
Height (cm)	181.6±7.1
Weight (kg)	75.8±7.4
BMI (kg/m^2)	22.9±1.5
VO2max (ml kg^{-1} min^{-1})	57.8±4.2
HRR 1min (bpm)	29±10
HRR 2min (bpm)	53±12
HRR 3min (bpm)	64±12

5.2 Differences in physiological parameters

A comparative analysis of different variables between groups is described in Table 2. All data obey a normal distribution, exhibit uniform variance and are mutually independent. Noteworthy disparities are noticed across several metrics, as analyzed by ANOVA of the associated p-values, and subsequently compared using Bonferroni's post-hoc analysis.

Table 2. One-way ANOVA analysis and Bonferroni's post-hoc analysis of physiological parameters among groups. (Group A- Adult Soccer players, Group Y- Group Youth Soccer players; Group T- Group Triathletes) (mean ± SD)

	Group Y (n=19)	Group A (n=57)	Group T (n=6)	F	P value	Difference
Age (years)	16±1	24±3$^{††\#\#}$	17±1	92.375	<0.000**	A-Y/A-T
Height (cm)	182.0±6.8	181.9±7.4	178.2±4.0	0.755	0.473	-
Weight (kg)	73.8±6.1	77.2±7.4††	68.9±6.6	4.699	0.012*	A-T
HRR 1min (bpm)	32±11$^{\#}$	27±9	39±12††	5.793	0.004**	A-Y/A-T
HRR 2min (bpm)	57±12	51±11	59±13	2.343	0.103	-
HRR 3min (bpm)	67±13	63±11	69±13	1.415	0.249	-
%VO2maxVT2 (%)	89±3$^{\$\$}$	89±4††	85±2	4.881	0.010*	A-T/ Y-T
VO2(VT2) (ml kg^{-1} min^{-1})	53.2±3.5$^{\#}$	50.5±4.3	52.3±3.8	3.149	0.048*	A-Y
VO2max (ml kg^{-1} min^{-1})	59.5±2.9$^{\#}$	56.9±4.1	61.9±4.4††	6.608	0.002**	A-Y/A-T

**P<0.01, *P<0.05

Bonferroni's post-hoc analysis results as below:

†† Group A vs Group T, P <0.01 † Group A vs Group T, P <0.05

Group A vs Group Y, P <0.01 # Group A vs Group Y, P <0.05

$$ Group Y vs Group T, P <0.01 $ Group Y vs Group T, P <0.0

5.3 Body composition analysis

In body composition measurement, as shown in Table 2, age and weight showed significant differences among all three groups, but no differences were observed in height (P= 0.473). Compared to the other groups, Group A was older (24 ± 3 years). However, Group A (77.2 ± 7.3 kg) demonstrated a similar weight to Group Y (73.8 ± 6.1 kg) but had a significant difference to Group T (68.9 ± 6.6 kg). Weight comparisons between Group Y and Group T revealed no discernible difference.

5.4 Heart rate recovery analysis

In Table 2, comparing all three groups, HRR 1min also observed a significant difference ($P<0.01$) between groups whereas HRR 2min ($P= 0.103$) and HRR 3min ($P= 0.249$) found no difference. Group A in HRR 1min (27 ± 9 bpm) has a significantly lower value than Group Y (32 ± 11 bpm) and Group T (39 ±12 bpm). However, no difference was found in HRR 1min between Group Y and Group T.

5.5 Aerobic fitness variables analysis

In Table 2, All the indicators of aerobic fitness (%VO2maxVT2, VO2(VT2) and VO2max) were found significantly different ($P<0.05$) between all groups, respectively. Group T in %VO2maxVT2 (85 ± 2 %) has a significantly lower value than Group A (89 ± 4 %) and Group Y (89 ± 3 %). However, %VO2maxVT2 was found no difference between Group A and Group T.

Group Y in VO2(VT2) (53.2 ± 3.5 ml kg^{-1} $min^{-1)}$ has a significantly higher value than Group A (50.5 ± 4.3 ml kg^{-1} min^{-1}) but both groups found no difference with Group T (52.3 ± 3.8 ml kg^{-1} min^{-1}). Group A in VO2max (56.9 ± 4.1 ml kg^{-1} min^{-1}) has a significantly lower value than Group Y (59.5 ± 2.9 ml kg^{-1} min^{-1}) and Group T (61.9 ± 4.4 ml kg^{-1} min^{-1}). However, VO2max was found no difference between Group Y and Group T.

5.6 Correlation with aerobic fitness

Pearson's correlation analysis in Table 3 was conducted within distinct groups and clarified significant associations between various aerobic fitness variables and post-exercise heart rate recovery.

Observing the percentage of VO2max at the second ventilatory threshold in Table 3, group Y encompassing younger soccer players, a strong correlation was observed between the %VO2maxVT2 and HRR 3min ($r=-0.508$, $p= 0.027$). Similarly, Group T displayed significant very strong correlations between the %VO2maxVT2 and HRR 3min ($r=-0.845$, $p= 0.034$). However, there is no correlation in both All subjects ($r=-0.214$, $p= 0.053$) and group A ($r=0.064$, $p=0.636$).

Table 3. Pearson's correlation analysis of physiological parameters among groups. (Group A- Adult Soccer players, Group Y- Group Youth Soccer players; Group T- Group Triathletes)

Group	Value	HRR 1min	HRR 2min	HRR 3min
Group Y (n=19)	%VO2maxVT2	-0.282(0.243)	-0.427(0.069)	-0.508(0.027*)
Group A (n=57)		-0.215(0.108)	-0.093(0.491)	-0.064(0.636)
Group T (n=6)		-0.625(0.184)	-0.700(0.121)	-0.845(0.034*)
All subjects (n=82)		-0.292(0.008**)	-0.208(0.061)	-0.214(0.053)
Group Y (n=19)	VO2(VT2)	-0.448(0.055)	-0.517(0.023*)	-0.552(0.014*)
Group A (n=57)		-0.056(0.678)	-0.005(0.972)	-0.066(0.624)
Group T (n=6)		0.013(0.980)	0.182(0.730)	0.059(0.911)
All subjects (n=82)		-0.043(0.704)	-0.026(0.814)	-0.104(0.353)
Group Y (n=19)	VO2max	-0.388(0.100)	-0.377(0.112)	-0.369(0.120)
Group A (n=57)		0.057(0.675)	0.05(0.712)	-0.038(0.778)
Group T (n=6)		0.251(0.632)	0.446(0.376)	0.372(0.468)
All subjects (n=82)		0.122(0.275)	0.093(0.407)	0.008(0.942)

**P<0.01, *P<0.05

%VO2maxVT2: Percentage of VO2max at VT2

VO2VT2: Volume of oxygen consumption at the second Ventilatory Threshold

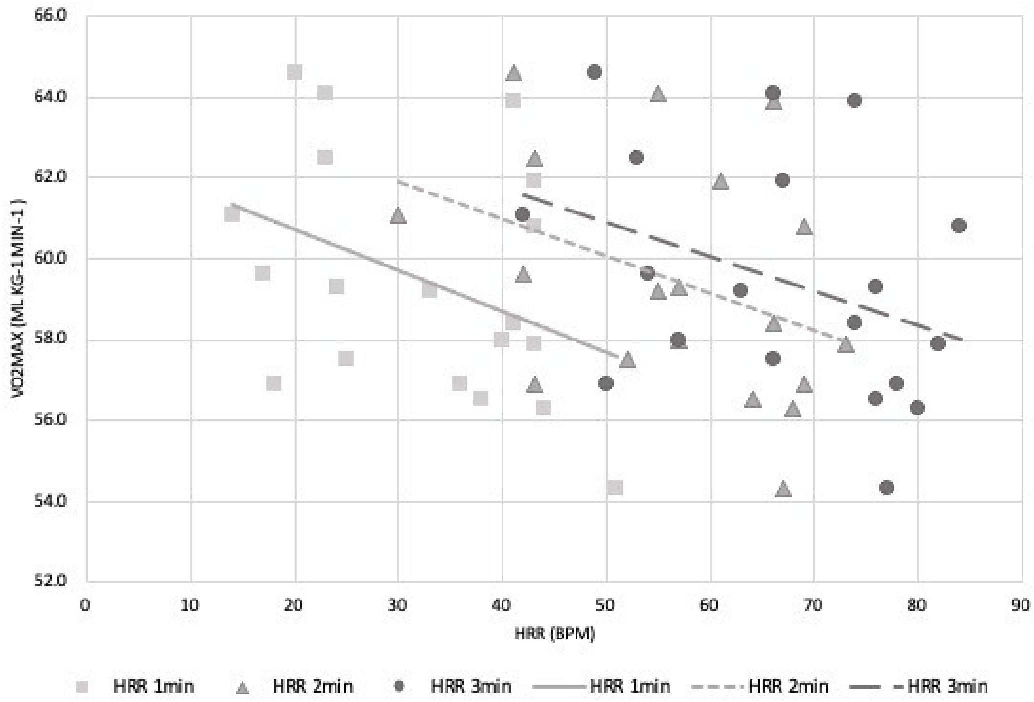
VO2max: The highest volume of oxygen consumption in intense exercise

Noticeably, in group T, the correlation between %VO2maxVT2 and HRR 1min (r=-0.625, p= 0.184), as well as HRR 2min (r=-0.7, p= 0.121), are strong but not statistically significant. At the same time, in all subjects, the correlation between %VO2maxVT2 and HRR 1min is weak but statistically significant (r=-0.292, p= 0.008).

Examining oxygen uptake at the second ventilatory threshold (VO2(VT2)) in Table 3, Group Y found a significantly strong correlation with HRR 2min (r=-0.517, p=0.023) and HRR 3min (r=-0.552, p=0.014). Conversely, no significant correlations were observed within Group A and Group T.

Analysis of maximal oxygen uptake (VO2max) in Table 3 revealed moderate correlations in Group Y between VO2max and HRR at all three-time intervals, respectively (r=-0.388, p=0.100; r=-0.377, p=0.112; r=-0.369, p=0.120), but the correlations were not statistically significant. Observing Figure 6, there is a considerable variance in individual HRR and there is a shift in the trend line from HRR 1min to HRR 3min. After all, the relationship between HRR in all groups and VO2max were insignificant.

Figure 6. Correlation between VO2max and HRR in Group Youth soccer players.



HRR 1min: Heart rate decreases in 1 minute.

HRR 2min: Heart rate decreases in 2 minutes.

HRR 3min: Heart rate decreases in 3 minutes.

VO2max: The highest volume of oxygen consumption in intense exercise

Table 4 presents correlations between age and HRR variables alongside aerobic fitness variables. Participants were divided into two age groups: those aged 18 or younger (Group $\leq$ 18) and those older than 18 (Group > 18). The correlation coefficients are provided along with their corresponding p-values in parentheses.

For participants aged 18 or younger, there is a moderate correlation between age and HRR 1min ($r=-0.38$, $p = 0.061$) and HRR 2min ($r=-0.412$, $p = 0.041$). Notably, the correlation for HRR 2min meets the statistical significance ($p < 0.05$), whereas the correlation for HRR 1min does not.

However, there are no significant correlations between age and any of the HRR or aerobic fitness variables for participants older than 18.

Table 4. Correlations between age and HRR variables and aerobic fitness variables.

	Age	
	Group ≤ 18(n=25)	**Group > 18(n=57)**
HRR 1min	-0.38(0.061)	-0.081(0.549)
HRR 2min	-0.412(0.041*)	-0.084(0.534)
HRR 3min	-0.322(0.117)	0.025(0.851)
%VO2maxVT2	0.019(0.929)	-0.017(0.901)
Vo2(VT2)	0.256(0.217)	-0.044(0.747)
Vo2max	0.289(0.162)	-0.037(0.782)

*P<0.05

%VO2maxVT2: Percentage of VO2max at VT2
VO2VT2: Volume of oxygen consumption at the second Ventilatory Threshold (VT2)
VO2max: The highest volume of oxygen consumption in intense exercise

6. DISCUSSION

The purpose of this study was to investigate the potential of HRR as an indicator of aerobic fitness in elite athletes, hypothesizing a significant correlation between HRR and aerobic fitness variables in elite athletes. Based on the results of this study, only a weak correlation was observed between HRR 1min and %VO2maxVT2 among all subjects. In groups aged 18 years old or younger, moderate correlations were observed between VO2VT2 and HRR 2min, as well as HRR 3min. However, no correlation was found between VO2max and HRR among all subjects.

6.1 Personal Factors

Lean muscle mass is one of the influencing factors in HRR (Buchheit et al,2011). Similarly, the results of this study found a significant difference in body mass between different groups. Group A has the highest age and weight comparing the other two groups while group A has a significantly lower HRR 1min than the other two groups. The slower HRR 1min in older subjects might be connected to their lower maximal HR because of the negative relationship between age and maximal HR based on the maximal HR predicted formula ([MHR=211 – (0.64*age)] (Nes et al.2013)). This result is consistent with Darr et al., (1988) reported that HRR is slower in older subjects because older subjects working at the same absolute workload are with greater relative intensity due to the effect of age on maximum HR. Nevertheless, from the point of muscle physiology, lower muscle glycolytic activity and increased oxidative capacity, coupled with quicker phosphocreatine resynthesis and better acid-base regulation, are proposed factors contributing to the faster HRR observed in younger individuals (Buchheit et al., 2010). However, there is an opposite result to Suzic Lazic et al. (2017) reported that a higher value of HRR 1min should be found in older athletes.

Additionally, dividing the subjects based on age, group A as well as group over 18 years found no correlation between age and HRR variables and aerobic fitness variables but there is a moderate correlation between HRR 2min and age in groups aged 18 years old or younger (Group T and Y) suggesting age may influence HRR in younger individuals but not in those older than 18 years old.

6.2 Heart rate recovery and aerobic fitness

Non-invasive techniques like HRR measurements can provide insights into cardiovascular health. (Arai et. al., 1989; Shetler et al., 2001, Zumbro, 2017). In this study, HRR value increased across all subjects as seen in Table 2, indicating decreasing heart rate every minute due to ANS activity. The rapid HRR within minutes post-exercise is attributed to parasympathetic reactivation and sympathetic withdrawal. (Arai et al., 1989, Goldberger et al., 2006, Bosquet et al., 2007). After exercise, the parasympathetic nerve function and the conduction function of the central nervous system were weakened, and the vagal nerve activity increased, thereby increasing the activity of the aortic receptors of subjects, as well as regulating the immediate change of heart function before and after exercise. Thus, the heart rate was reduced (Miles et al., 1984, Arai et al., 1989, Pichot et al., 2002).

The HRR 1min in this study was consistent with previous studies in HR decrease in first-minute recovery. The subject's HRR 1 min in this study was 29 ± 10(bpm) which compliant with Nishime et al. (2000) reported that ≥18 beats in the first-minute recovery is considered normal. Besides, the result of HRR 1min and 2min was similar to Suzic Lazic et al., (2017) reported 26 ± 13.8 (bpm) in the first minute recovery and 57.6±4.8(bpm) in the second minutes recovery, respectively. But a lower value of 64 ± 12 (bpm) in HRR 3min was found in this study compared to Suzic Lazic et al., (2017) reported 81.3 ± 11.3(bpm) in HRR 3min. In this study, there are no relationships were found between HRR and VO2VT2 as well as between HRR and VO2max in all subjects but only found a moderate correlation between VO2VT2 and both HRR 2min and HRR 3min in Group Y. The result of this study is inconsistent with Kulothungan et al., (2019) reported that higher aerobic capacity response to faster HRR and also varies from the report of Bandsode & Joshi, (2022) that a direct linear association between HRR and VO2max. However, the limited sample size in Group T may lead to the correlation between HRR 3min and VO2max statistically insignificant ($r=0.372$, $p=0.468$).

Comparing Group Y and Group T, as seen in Table 2, they are the same age but performing different sports. The differences in training protocols and aims for training may explain variations in %VO2maxVT2 in Group Y with 89±3(%) higher than 85 ± 2 (%) in Group T. Soccer players may require a balance of aerobic and anaerobic abilities, affecting their training intensity distribution. Conversely, triathletes primarily focus on endurance performance, resulting in different %VO2maxVT2 values. The intensity of the soccer players identified 40% of the training sessions as under VT1, 34% between VT1 and VT2, and 27% over VT2 (Algrøy et al., 2011). However, triathletes daily train at 78% under VT1,4% between VT1 and VT2 and 18% over VT2 (Seiler, 2010) to perform a better endurance performance which also means that triathletes have less training at the intensity around VT2 than soccer athletes unless they train with the HIIT method to enhance their aerobic capacity (Stöggl & Björklund, 2017). A higher VT2 has been proven to be beneficial to maintaining a greater duration of higher-intensity exercise and reducing the risk of cardiovascular disease (CVD) (Martini et al., 2022). Conversely, the difference in training distribution may affect the difference in %VO2maxVT2 comparing between soccer players and triathletes.

Comparing Group A and Group Y, as seen in Table 2, they are performing the same sport but at different ages. Younger soccer players exhibited higher HRR 1min, VO2VT2 and VO2max than the older soccer players. The result of the difference in VO2max varies from the result by Lovell et al., (2015) reported soccer players who are more mature are likely to present greater aerobic performance. However, it consistent with Poole et al., (2017) reported that VO2max measurements may be not reliable when subjects in unmotivated may stop exercising before reaching VO2max while young subjects can perform until exhaustion.
Further research is required to give better insight into this situation. Different soccer teams have different training intensities and duration of exercise. There are several researchers said that low-intensity training (Lee et al., 2021) or HIIT training (Lamberts et al., 2009) may increase HRR. The variation in VO2max may be influenced by factors like motivation and training intensity distribution. However, further research is warranted to elucidate these findings.

6.3 Limitations

Several limitations to this pilot study need to be acknowledged. First of all, the sample size is too small for triathletes, which may affect statistical power. The small sample size affected the power of statistical significance even though the correlation was big enough. Secondly, since the intensity at warm-up was already above the aerobic threshold, the VT1 were not able to be observed both in soccer players and triathletes. Additionally, the subjects have unequal time to exhaust not only because of the difference in testing protocol between soccer players and triathletes but also their different tolerance abilities. With the exercise time running, the external load varied from each other which affected HRR (Chiu et al., 2024). Further research should consider these factors for a comprehensive understanding of HRR and aerobic fitness indicators in elite athletes. Addressing these limitations in future studies could enhance the reliability and validity of findings.

7. CONCLUSION

This study indicated the relationship between HRR and the indicators of aerobic fitness in elite athletes. HRR in this study followed the principle of physiology and observed a normal decrease in all participants. However, we didn't find a significant correlation in all subjects that could support HRR as an indicator of aerobic fitness, but we found HRR 3min has a high connection with VT2 in youth athletes. Based on individual sports training intensity distribution, elite athletes have different levels of anaerobic threshold, suggesting that the training intensity distribution should depend on individual sports purposes. Although trained under different exercise demands, they showed approximately the same recovery ability after exercise in this study. This study supported that HRR should only assess an individual recovery ability but not aerobic fitness. Understanding the relationship between HRR and aerobic fitness can provide valuable insights into athlete performance, training optimization, and cardiovascular health monitoring.

7.1 Significant of Finding

There are several important areas where this study made an original contribution to the field of aerobic training by offering practical and non-invasive methods for monitoring and evaluating training progress. Coaches and trainers can utilize individual HRR responses to track training effectiveness, with slower HRR potentially indicating the need for additional aerobic training or rest, while faster HRR may suggest a focus on technical training. Secondly, Understanding the relationship between HRR and aerobic fitness could allow for better prediction of athletic performance outcomes such as aerobic limit. Additionally, the finding could facilitate further study in related aerobic fitness mechanisms which may lead to a better understanding of the physiological adaptation in training and potential interventions to optimize athletic performance.

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