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# Cardiopulmonary and hemodynamic responses to *Baduanjin* exercise and cycle ergometer exercise among chronic heart failure patients: a comparison

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**Objective:** *Baduanjin* is a traditional Chinese exercise and serves as an alternative to conventional cardiac rehabilitation in China. In this study, we compare the cardiopulmonary and hemodynamic responses of *Baduanjin* to those of cycle ergometer exercise in chronic heart failure patients.

**Methods:** For this cross-sectional study design, following baseline data collection, participants underwent a series of tests including impedance cardiography (ICG) and a maximal cardiopulmonary exercise test (CPET) to determine peak exercise capacity. Participants then engaged in 9-min of *Baduanjin* exercise. The average oxygen consumption (EqualVO$_2$) during *Baduanjin* was calculated. Participants then engaged 9 min of constant-load cycling at 60 rpm at an intensity which elicited the EqualVO$_2$. Cardiopulmonary and hemodynamic data were measured continuously during both Baduanjin and cycling exercise.

**Results:** A total of 30 participants were included. Although *Baduanjin* and cycling exercise showed similar VO$_2$ levels (8.2 ± 1.3 vs. 8.4 ± 1.4, $p$ = 0.339, respectively), there was a bimodal distribution during *Baduanjin* exercise compared to a unimodal distribution during cycling exercise. Compared to conventional cycling, *Baduanjin* demonstrated lower respiratory burden which is associated with greater ventilatory efficiency as evidenced by lower respiratory rate values ($p$ = 0.003), minute ventilation ($p$ < 0.001), end-tidal carbon dioxide pressure ($p$ < 0.001), and minute ventilation to carbon dioxide production ratio ($p$ < 0.001). In terms of hemodynamic response, *Baduanjin* is demonstrated significantly lower cardiac output ($p$ = 0.017) and elevated arterial-venous oxygen difference ($p$ = 0.036).

**Conclusion:** Our study offers novel insight into the cardiopulmonary and hemodynamic differences between *Baduanjin* and cycling when performed

at consistent intensity levels. *Baduanjin* demonstrates an intermittent intensity pattern and increased peripheral oxygen utilization, which is attributed to more pronounced muscle activation. Furthermore, *Baduanjin* has been linked to a reduction in both cardiac and respiratory burdens.

# 1 Introduction

Comprehensive exercise-based cardiac rehabilitation (CR) is a Class 1A recommend therapy for patients with chronic heart failure (HF) (Pelliccia et al., 2020; McDonagh et al., 2023; Ponikowski et al., 2016). Patients with HF who engage in exercise based CR demonstrate improved quality of life, reduced hospitalization, and lower mortality rates (Molloy et al., 2024-03; Bozkurt et al., 2021). However, these CR programs are underutilized, with participation rates ranging from 10% to 30% worldwide (Beatty et al., 2023; Ozemek and Squires, 2021; Balady et al., 2011; Grace et al., 2008-10; Sanderson et al., 2003). In China, primary barriers to participation in CR have been identified and include resource scarcity and limited healthcare funding (Zhang et al., 2023; Zhang et al.). Therefore, solutions to improving CR uptake HF patients must be tailored to these barriers. In addition to overcoming the above noted barriers, resource-adapted CR programs must be sensitive to the cultural context in which they are embedded.

Commonly accepted as beneficial to one's health, traditional Chinese exercise is a form of exercise embedded within communities throughout different regions of mainland China for nearly sixteen centuries (Wang et al., 2016; Health Qigong Management Center, 2003). Thus, this equipment-free exercise may be ideal for hospitals with limited resources (Sun, 2015), as well as patients, because it can be practiced at home, reducing barriers such as weather, transportation, and cost (Deka et al., 2017; Conraads et al., 2012). *Baduanjin*, translated as "eight silken movements", is one form of traditional Chinese exercise which has been practiced for over 1,000 years. It is characterized by slow movements (physical training) synchronized with meditation (mindfulness-based training) and regulated breathing (respiratory training) to achieve a harmonious flow of energy (*qi*) in the body (Zou et al., 2017). *Baduanjin* is easy to learn, with minimal physical or cognitive demands, as it only entails eight simple movements based on traditional Chinese medicine theory. Moreover, it is an adaptable form of exercise that can be practiced in any location, at any time, without any special equipment, and requires minimal time investment (Chen et al., 2022). Hence, it is easily incorporated into daily routines and could easily be integrated into a comprehensive CR program.

Moderate intensity continuous aerobic exercise is the most widely researched type of exercise in CR and has been shown to be efficient, safe, and well-tolerated by patients with HF (Molloy et al., 2024-03). Historically, *Baduanjin* has been considered light-intensity exercise, regardless of the individual's physical fitness. In contrast, our group has recently demonstrated that *Baduanjin* exercise falls within the moderate intensity aerobic

exercise classification, based on the percent of measured oxygen consumption ($VO_2$), particularly for deconditioned patients such as those with HF (Chen et al., 2020). However, to date there is a lack of evidence comparing *Baduanjin* with conventional moderate intensity aerobic exercise such as cycle ergometer exercise, among CHF patients. This highlights a key knowledge gap for referring physicians. Therefore, the purpose of this study was to 1) compare the cardiopulmonary responses between *Baduanjin* and cycle ergometer exercise; and 2) compare the hemodynamic responses between *Baduanjin* and cycle ergometer exercise, in patients with CHF.

# 2 Methods

## 2.1 Participants

We utilized a cross-sectional design to recruit patients from the chronic disease management cohort at the Heart Failure Center at Guangdong Provincial Hospital of Chinese Medicine, between June 2023 and January 2024. Eligible participants included stable heart failure patients aged 18–85 years, classified as New York Heart Association (NYHA) class II or III, who had practiced *Baduanjin* for at least 3 months. The exclusion criteria for the trial included conditions that contraindicate exercise testing. Inclusion and exclusion criteria details are listed in Supplementary S1.

## 2.2 Data collection

### 2.2.1 Procedures, equipment, and requirements

Our study was conducted in the CR department at the Heart Failure Center at Guangdong Provincial Hospital of Chinese Medicine. The main process of this study included three steps (Figure 1). First, after collecting the baseline information (i.e., medical history, physical examination, anthropometric measurements, and echocardiograph data), we conducted a maximal cardiopulmonary exercise test to determine individual maximal exercise capacity (e.g., $VO_2$ peak). Second, we conducted a real-time monitoring test of cardiopulmonary and hemodynamic metrics during *Baduanjin* exercise. Third, we conducted a real-time monitoring test of the same cardiopulmonary and hemodynamic metrics during cycle ergometer exercise. Details of data collection were listed in Supplementary S2. All of the hemodynamic data collected and constructed by PhysioFlow are listed below with their clinical meanings listed in Table 1.
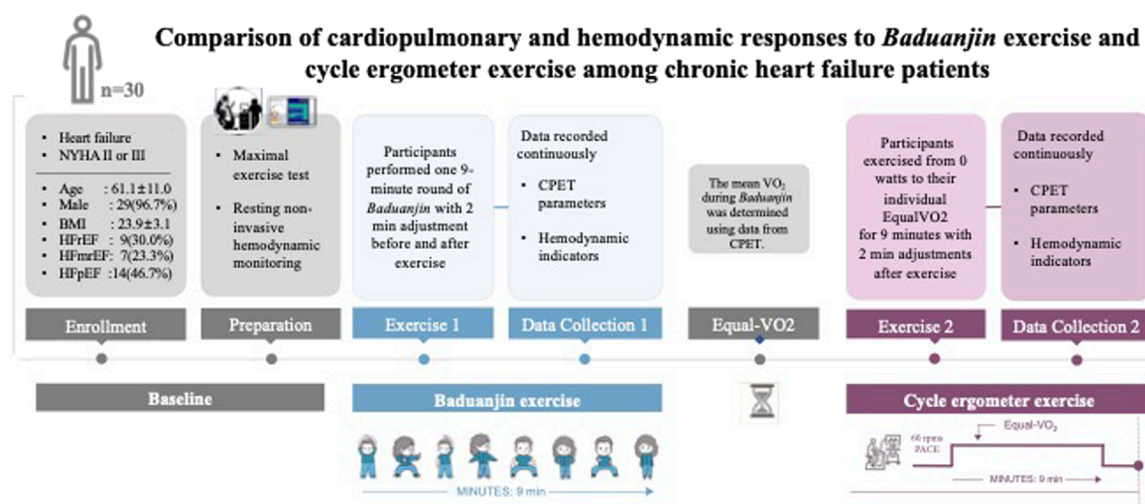
**FIGURE 1**
Study procedures Legends: NYHA, New York Heart Association; BMI, body mass index; HFrEF, heart failure with reduced ejection fraction; HFmrEF, heart failure with middle ranged ejection fraction; HFpEF, heart failure with perceived ejection fraction; VO₂, volume of Oxygen; EqualVO2, the average oxygen consumption; CPET, cardiopulmonary exercise testing.

## 2.3 Statistical analysis

We adopted statistical analyses similar to those described in our previous work (Chen et al., 2020). Data from the maximal exercise test as well as the average cardiorespiratory and hemodynamic parameters obtained during *Baduanjin* exercise and cycle ergometer exercise were summarized as mean and standard deviation (SD). The mean $VO_2$ and HR collected during *Baduanjin* exercise and cycle ergometer exercise were compared to individual maximum exercise capacity measured during the cardiopulmonary exercise test and reported as a percentage (expressed as $\%VO_{2max}$ and $\%HR_{max}$). In order to categorize the exercise intensity, we referred to a position statement on exercise intensity terminology (Norton et al., 2010). Moreover, in order to explore the cardiopulmonary response patterns throughout the session, all cardiopulmonary parameters were summarized at 10-s intervals as mean ± SD, and plotted over time. All statistical procedures were performed with SPSS (version 18.0, Chicago, IL, USA).

## 3 Results

### 3.1 Participant characteristics

The participants (n = 30, 29 male and 1 female, ages 61.1 ± 11.0 years) had a clinical history of heart failure for a median of 3.5 years and were classified as either New York Heart Association (NYHA) II (n = 19, 63.3%) or NYHA III (n = 11, 36.7%). The mean left ventricular ejection fraction (LVEF) was 49.4% ± 13.4%, and they were either with reduced LVEF (HFrEF, n = 9, 30.0%), middle ranged LVEF (HFmrEF, n = 7, 23.3%), or preserved LVEF n (HFpEF, n = 14, 46.7%). In addition, 96.7% of the participants (n = 29) had been taking β-blockers. Spirometry showed that 66.7% (n = 20) of participants had normal lung function; and 26.7% (n = 8), 3.3% (n = 1), and 3.3% (n = 1) showed restrictive, obstructive, and mixed pulmonary ventilatory dysfunction, respectively. Details on demographic and anthropometry characteristics, medical history, heart failure status, and comorbidities are presented in Table 2.

### 3.2 Results of maximum exercise tests and resting hemodynamic status

As shown in Table 3, the results of the maximum exercise test revealed that the average RER of the 30 participants was 1.1 ± 0.1. All participants stopped testing due to leg muscle fatigue. VT was detected in all cases. Participants had an impaired exercise capacity with a mean $VO_{2max}$ of 18.4 ± 4.2 mL/kg/min and demonstrated an elevated $V_E/VCO_2$ slope (30.8 ± 5.8).

The results of hemodynamic assessment indicated that this sample exhibited normal resting SV at 76.6 ± 14.4 mL, CO at 5.2 ± 1.1 L/min, $C_{(a-v)}O_2$ at 5.18 ± 2.2 mL/dL, and SVR with a median of 2,202.0 dyn·s/cm⁵. Additional details regarding hemodynamic indices are presented in Table 3.

### 3.3 Comparison of the average cardiopulmonary and hemodynamic responses between *Baduanjin* exercise and cycle ergometer exercise

For the average cardiopulmonary responses (Table 4), the intensity of the two exercises are similar. During exercise, the average $VO_2$ during *Baduanjin* was 44.6% of $VO_{2max}$ compared to 45.7% of $VO_{2max}$ during cycling with no statistically significant difference between the two groups (8.2 ± 1.3 vs. 8.4 ± 1.4, $p$ = 0.339, respectively; Table 4). For ventilatory and metabolic measures,

TABLE 1 Cardiopulmonary and hemodynamic parameters collected in this study.

| A. Hemodynamic parameters | | | |
|---|---|---|---|
| | Parameters | Abbreviations | Clinical meaning |
| Left Ventricular Ejection Function | Stroke Volume | SV (mL) | The amount of blood pumped out by the heart with each contraction |
| | Cardiac Output | CO (L/min) | The amount of blood the heart pumps per minute, CO = SV*HR |
| Myocardial Contraction | Contractility Index | CI | An index to evaluate heart contraction function |
| Preload | Early Diastolic Filling Rate | EDFR (%) | The rate of left ventricular filling in the early diastolic phase |
| Afterload | Systemic Vascular Resistance | SVR (dyn·s/cm$^5$) | The systemic peripheral vessels' resistance to cardiac pumping |
| Peripheral oxygen utilization | Arterial-venous oxygen difference | $C_{(a-v)}O_2$ (mL/dL) | The difference in oxygen content between arterial and venous blood, reflecting the balance between oxygen delivery and consumption at the tissue level |
| B. Cardiopulmonary parameters | | | |
| Exercise Tolerance | Load | Load (W) | The load imposed on the body during exercise |
| | Maximum Oxygen Consumption | $VO_{2max}$ (mL/kg/min) | The amount of oxygen consumed per minute during maximum intensity exercise |
| | Anaerobic Threshold | AT | The critical point at which anaerobic metabolism exceeds aerobic metabolism during exercise |
| | Respiratory Exchange Ratio | RER | The ratio of carbon dioxide production to oxygen consumption during respiration |
| | Metabolic Equivalents | METs | The multiple of metabolic rate during exercise compared to the rate at rest, indicating the relative energy metabolism level |
| Circulatory Function | Heart Rate | HR (bpm) | The number of heart beats per minute |
| | Maximum Heart Rate | $HR_{max}$ (bpm) | The highest heart rate that can be achieved during maximum exercise intensity |
| | Oxygen Pulse | $O_{2pulse}$ (ml/beat) | The amount of oxygen consumed by the body per heartbeat, calculated from $VO_2$/HR |
| | Systolic Blood Pressure | SBP (mmHg) | Blood pressure value during heart contraction |
| | Diastolic Blood Pressure | DBP (mmHg) | Blood pressure value during heart relaxation |
| | 1-min Heart Rate Recovery | $HRR_1$ (bpm) | An index of parasympathetic activity |
| Ventilation Function | Minute Ventilation | $V_E$ (L/min) | The amount of gas exhaled per minute |
| | Respiratory Rate | RR (bpm) | The number of breaths per minute |
| Gas Exchange | End-Tidal Carbon Dioxide Pressure | $P_{ET}CO_2$ (mmHg) | The carbon dioxide pressure in the terminal airways during exhalation |
| | Ventilation/Carbon Dioxide Production | $V_E$/$VCO_2$ | The ratio of ventilation per carbon dioxide production |
| | Ventilation/Carbon Dioxide Production Slope | $V_E$/$VCO_2$ slope | The rate of increase in ventilation per unit increase in carbon dioxide production |

TABLE 2 Participants' characteristics (n = 30).

| Parameters | Mean ± SD or number (%) (n = 30) |
|---|---|
| **Demographic and anthropometrical characteristics** | |
| Male | 29 (96.7%) |
| Age, years | 61.1 ± 11.0 |
| BMI | 23.9 ± 3.1 |
| Smoker | 10 (33.3%) |
| Drinker | 5 (16.7%) |
| **Heart failure characteristics** | |
| Heart failure history, years | 3.5 (2.0, 6.0) ▲ |
| NYHA classification | |
| - NYHA II | 19 (63.3%) |
| - NYHA III | 11 (36.7%) |
| LVEF classification | |
| -HFrEF | 9 (30.0%) |
| -HFmrEF | 7 (23.3%) |
| -HFpEF | 14 (46.7%) |
| HR, bpm* | 67.7 ± 10.8 |
| SBP, mmHg* | 108.8 ± 14.1 |
| DBP, mmHg* | 66.8 ± 9.8 |
| NT-proBNP, pg/mL | 394.0 (189.5,855.1) ▲ |
| LVEF, % | 49.4 ± 13.4 |
| PASP, mmHg | 25.2 ± 5.9 |
| β-blocker users | 29 (96.7%) |
| **Comorbidities** | |
| Coronary heart disease | 21 (70.0%) |
| Previous MI | 12 (40.0%) |
| Atrial fibrillation | 6 (20.0%) |
| Hypertension | 14 (46.7%) |
| Type 2 diabetes | 14 (46.7%) |
| Chronic kidney disease | 7 (23.3%) |
| Peripheral vascular disease | 14 (46.7%) |
| **Lung function** | |
| FVC(%) | 84.2 ± 11.7 |

TABLE 2 (*Continued*) Participants' characteristics.

| Parameters | Mean ± SD or number (%) (n = 30) |
|---|---|
| FEV$_1$ (%) | 84.9 ± 10.5 |
| FEV$_1$/FVC(%) | 105.2 ± 7.4 |
| MVV(%) | 96.6 ± 17.5 |

▲*Median* ($P_{25}$, $P_{75}$).
*Collected by the research nurse using an electronic sphygmomanometer as the baseline information.
Abbreviations: bpm, beats per minute; BMI, body mass index; DBP, diastolic blood pressure; EF, ejection fraction; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; HFrEF, heart failure with reduced ejection fraction; HFmrEF, heart failure with middle ranged ejection fraction; HFpEF, heart failure with perceived ejection fraction; HR, heart rate; LVEF, left ventricular ejection fraction; MI, myocardial infarction; MVV, maximum voluntary ventilation; NYHA, new york heart association; NT-proBNP, N-terminal B-type natriuretic peptide; PASP, pulmonary artery systolic pressure; SBP, systolic blood pressure; SD, standard deviation.

*Baduanjin* demonstrated significantly lower RR, $V_E$, $P_{ET}CO_2$, and $V_E/VCO_2$ (all $P < 0.001$), compared to the cycling exercise (Table 4).

For the average hemodynamic responses (Table 4), the average HR during *Baduanjin* exercise was significantly higher when compared to cycling (Table 4). Similarly, the peak heart rate during *Baduanjin* was significantly higher than during cycle exercise (93.9 bpm *versus* 86.0 bpm, $P < 0.001$, Table 4). Furthermore, our data indicate that SBP was significantly lower during *Baduanjin* compared to cycling while DBP was not different between the two activities (Table 4). In addition, the average SV and CO during *Baduanjin* exercise (SV: 64.5 ± 11.3 mL, CO: 5.2 ± 0.8 L/min) were both significantly lower than cycle exercise (SV: 70.9 ± 10.4 mL, $P = 0.001$; CO: 5.6 ± 0.9 L/min, $P = 0.017$). Moreover, significantly higher $C_{(a-v)}O_2$ ($P = 0.036$) and SVR ($P = 0.036$) were found during *Baduanjin* exercise than during cycle exercise.

## 3.4 Comparison of the real-time cardiopulmonary and hemodynamic responses between *Baduanjin* exercise and cycle ergometer exercise

The VO$_2$ responses are shown in Figures 2a,b. The VO$_2$ response curve of the cycle exercise is smooth with no obvious peaks. After the cycle ergometer exercise reached moderate intensity in the second minute, it leveled off and remained at moderate intensity. However, the fluctuations in VO$_2$ during the *Baduanjin* exercise are greater than those during the cycle exercise. The VO$_2$ responses exhibited a bimodal distribution during *Baduanjin*. The VO$_2$ increased during the first 3 min when a hemi-squat posture was involved (second posture), followed by a small drop in VO$_2$ after the transition to third posture. The intensity reached the second peak at the seventh minute during an additional two hemi-squat postures (fifth and seventh). It then dropped to the baseline during the resting phase. Overall, the absolute VO$_2$ response remained under the VT (Figure 2a) and the %VO$_{2max}$ response remained within the moderate-intensity range (Figure 2b).

The HR responses are shown in Figures 2c,d. Similar to the VO2 response, the HR response was smooth during cycle exercise and exhibited a bimodal distribution with smaller magnitudes during *Baduanjin* (Figures 2c,d). Overall, the absolute HR response remained under the equivalent HR for the VT (Figure 2c) and the %HRmax response remained within the moderate-intensity range (Figure 2d).

Figure 3 shows the participants' ventilatory responses, including respiratory rate (Figure 3a), $V_E$ (Figure 3b), $P_{ET}CO_2$ (Figure 3c), and $V_E/VCO_2$ (Figure 3d), during *Baduanjin* and cycling exercise. All three response lines from *Baduanjin* were lower than those from cycling.

Figure 4 illustrates the real-time hemodynamic responses during *Baduanjin* and cycle exercise. Overall, during cycling, hemodynamics initially increased from a low value and then stabilized, while *Baduanjin*'s SV and CO response lines showed fluctuations with time and movement changes. Compared to cycle exercise, the SV and CO response were both lower during *Baduanjin* (Figures 4a,b), while the $C_{(a-v)}O_2$ and SVR response was higher during *Baduanjin* (Figures 4c,d).

## 4 Discussion

This is the first study to compare chronic heart failure patients' cardiopulmonary and hemodynamic responses to *Baduanjin* exercise to their responses to constant-load moderate intensity cycle exercise. The intensity of both exercise modalities was calibrated according to VO$_2$, resulting in comparable average VO$_2$ for each modality. In terms of the cardiopulmonary response, *Baduanjin* exercise is characterized by a bimodal distribution of VO$_2$ responses as well as a lower respiratory burden, which is associated with greater ventilatory efficiency compared to conventional cycling. In terms of hemodynamic response, *Baduanjin* is demonstrated significantly lower cardiac output and elevated arterial-venous oxygen difference. These cardiopulmonary and hemodynamic responses to *Baduanjin* may be attributed to a higher degree of muscle engagement compared to cycle ergometer exercise.

The strength of this study lies in its comparison of the cardiopulmonary and hemodynamic differences between *Baduanjin* exercise and cycle exercise during matched intensity levels. Our study suggests that *Baduanjin* is a moderate-intensity aerobic exercise suitable for CHF patients, similar to our prior findings (Chen et al., 2020). However, there is a lack of research on real-time physiological responses comparing these two exercise modalities. When studying the cardiopulmonary and hemodynamic responses to different exercises, maintaining a consistent intensity level is crucial (Taylor et al., 2021). In a previous study, exercise intensity was matched based on heart rate response (Gary et al., 2019), while in this study, mean VO$_2$ during *Baduanjin* exercise was used for match intensity. As such, there was no significant difference in average VO$_2$

TABLE 3 Ventilation and gas exchange data during maximal exercise and resting hemodynamic data.

| Parameters | Values (Mean ± SD) |
|---|---|
| Load (W)_MAX | 91.7 ± 30.4 |
| **A. Ventilation and Gas Exchange during maximal exercise** | |
| Maximum RER | 1.1 ± 0.1 |
| Maximum $VO_2$ (mL/kg/min) | 18.4 ± 4.2 |
| Maximum METS | 5.2 ± 1.2 |
| Maximum RR (bpm) | 33.4 ± 5.0 |
| Maximum $V_E$ (L/min) | 48.1 ± 10.4 |
| Maximum $P_{ET}CO_2$ (mmHg) | 37.4 ± 5.6 |
| VE/VCO$_2$ slope$^\triangle$ | 30.8 ± 5.8 |
| **B. Hemodynamics during rest** | |
| Resting HR (bpm)* | 70.2 ± 8.2 |
| Resting SV (mL) | 76.6 ± 14.4 |
| Resting CO (L/min) | 5.2 ± 1.1 |
| Resting CI | 152.8 ± 54.6 |
| Resting $O_2$ pulse (mL/beat) | 4.3 ± 1 |
| Resting EDFR (%) | 63.6 (49.4, 71.4)▲ |
| Resting SBP (mmHg)* | 117.3 ± 22 |
| Resting DBP (mmHg)* | 73.3 ± 17.8 |
| Resting SVR (dyn·s/cm$^5$) | 2202.0 (1948.0, 2376.0)▲ |
| Resting $C_{(a-v)}O_2$ (mL/dL) | 5.18 ± 2.2 |

▲Median ($P_{25}$, $P_{75}$).
$^\triangle$from rest to maximum.
*Collected during the "Maximal exercise test".
Abbreviations: bpm, beats per minute; CI, contractility index; CO, cardiac output; $C_{(a-v)}O_2$, arterial-venous oxygen difference; DBP, diastolic blood pressure; EDFR, early diastolic filling rate; HR, heart rate; MAX, maximal intensity; METs, metabolic equivalents; $O_2$ pulse, oxygen pulse (oxygen consumption to heart rate ratio); $P_{ET}CO_2$, end-tidal carbon dioxide partial pressure; RR, respiratory rate; RER, respiratory exchange ratio; SBP, systolic blood pressure; SD, standard deviation; SV, stroke volume; SVR, systemic vascular resistance; $V_E$, minute ventilation; $V_E$/VCO$_2$ slope, ventilation efficiency for carbon dioxide elimination; $VO_2$, oxygen consumption.

between the two modes of exercise. This suggests that $VO_2$ as a parameter is a good tool for balancing determining exercise intensity as complexities may arise when using HR due to the HR-modulating effect of pharmacotherapies commonly prescribed for CHF patients, such as β-blockers.

While average $VO_2$ levels were comparable between the two modes of exercise, distinct differences emerged in the intensity response curves. Cycle exercise plateaued in intensity due to a consistent power output, whereas *Baduanjin* exhibited an intermittent pattern with notable fluctuations, leading to a bimodal response curve. The bimodal $VO_2$ response observed during

*Baduanjin* exercise is a reflection of the unique characteristics of this traditional Chinese practice, likely attributed to its structured sequence of movements with varying intensities. The presence of two $VO_2$ peaks corresponds to movements involving semi-squat postures, indicating that *Baduanjin* offers a distinctive form of moderate-intensity intermittent training. Moderate-intensity intermittent physical activity has been shown to be associated with improved executive function in older adults (MacDonald et al., 2024). Furthermore, a systematic review demonstrated that following training, moderate-intensity intermittent training results in greater reductions in fat mass, as well as improved performance on functional tests for elderly women, compared to moderate-intensity continuous training (Coswig et al., 2020/02). Therefore, *Baduanjin* exercise may be particularly suitable for heart failure patients with impaired executive function or functional performance, as well as for those aiming to achieve fat loss.

*Baduanjin* exercise imposes a lower respiratory burden by enhancing ventilatory efficiency compared to conventional cycle exercise. Similarly, a meta-analysis has also demonstrated that *Baduanjin* improves ventilatory efficiency (Zou et al., 2017). Patients with CHF typically exhibit an exaggerated ventilatory response for a given metabolic demand during exercise (Dubé et al., 2016-09). Our study's findings indicate that during *Baduanjin* exercise, the respiratory rate is lower than that observed during cycle exercise at the same intensity, suggesting a more stable exercise-induced respiratory response during *Baduanjin*. This can be particularly advantageous for individuals with heart failure working to improve exercise endurance. In addition, our study show that both $V_E$ and $V_E$/VCO$_2$ were lower during *Baduanjin* exercise, compared to cycle exercise. $V_E$ quantifies the total volume of gas inhaled or exhaled per minute and is influenced by respiratory rate and tidal volume. The $V_E$/VCO$_2$ ratio indicates the proportion of ventilation relative to carbon dioxide production. The observed decrease in $V_E$ and $V_E$/VCO$_2$ during *Baduanjin* exercise suggests that less ventilation is needed for the same amount of carbon dioxide production. This indicates a higher efficiency for gas exchange per breath compared to cycle exercise. *Baduanjin* exercise involves movements that elongate respiratory muscles, enhance thoracic compliance and mobility, reduce respiratory center stimulation, and reduce exertional dyspnea (Xie et al., 2022). Additionally, it incorporates respiratory muscle and breathing training to increase respiratory muscle strength and endurance, decrease mechanical loads such as chest wall stiffness, and facilitate deeper, slower breathing for improved gas exchange efficiency.

*Baduanjin* exercise imposes a lower cardiac demand with increased peripheral oxygen utilization, compared to cycling. Our results demonstrate a significantly lower CO response during *Baduanjin* compared with cycling. This reduction in CO, which represents the volume of blood the heart pumps per minute, suggests that *Baduanjin* imposes less cardiac demand than cycling. Moreover, applying the Fick principle, the $C_{(a-v)}O_2$ was significantly higher during *Baduanjin* exercise when compared to the cycling. The $C_{(a-v)}O_2$, which quantifies the oxygen concentration disparity between arterial and venous blood post-circulation through active muscle, indicates the efficiency with which peripheral organs, tissues, and cells extract oxygen from the mitochondria. Thus, patients engaged in *Baduanjin* exercise may experience improved

TABLE 4 Comparison of cardiopulmonary and hemodynamic responses to *Baduanjin* exercise or cycle exercise.

| Parameters | *Baduanjin* (Mean ± SD) | Cycling (Mean ± SD) | *P*-value |
|---|---|---|---|
| Load (W) | — | 21.9 ± 8.4 | - |
| **A. Ventilation and Gas Exchange** | | | |
| $VO_2$ (mL/kg/min) | 8.2 ± 1.3 | 8.4 ± 1.4 | 0.339 |
| METs | 2.3 ± 0.4 | 2.4 ± 0.4 | 0.299 |
| RR (bpm) | 21.1 ± 4.6 | 23.2 ± 3.3 | 0.003* |
| $V_E$ (L/min) | 18.8 ± 4.5 | 21.3 ± 3.9 | <0.001* |
| $P_{ET}CO_2$ (mmHg) | 31.6 ± 3.2 | 34.0 ± 3.4 | <0.001* |
| $V_E/VCO_2$ | 39.5 ± 5.4 | 42.0 ± 5.4 | <0.001* |
| **B. Hemodynamics** | | | |
| HR (bpm) | 81.8 ± 9.7 | 79.9 ± 10.2 | 0.005* |
| $HR_{max}$ (bpm) | 93.9 ± 12.0 | 86.0 ± 11.9 | <0.001* |
| $HRR_1$ (bpm) | 5.0 (2.0, 8.0)▲ | 5.0 (3.0, 8.0)▲ | 0.343 |
| SV (mL) | 64.5 ± 11.3 | 70.9 ± 10.4 | 0.001* |
| CO (L/min) | 5.2 ± 0.8 | 5.6 ± 0.9 | 0.017* |
| CI | 145.9 ± 57.8 | 176.9 ± 63.4 | <0.001* |
| $O_2$ pulse (ml/beat) | 6.8 ± 1.5 | 7.2 ± 1.4 | 0.001* |
| EDFR (%) | 60.1 (56.4, 68.2)▲ | 59.5 (53.1, 69.6)▲ | 0.586 |
| SBP (mmHg) | 109.1 ± 16.4 | 113.1 ± 15.7 | 0.021* |
| DBP (mmHg) | 65.9 ± 8.1 | 65.9 ± 10.1 | 0.544 |
| SVR (dyn·s/cm$^5$) | 1,451.4 (1,198.7, 1663.7)▲ | 1,140.1 (1,040.9, 1220.9)▲ | <0.001* |
| $C_{(a-v)}O_2$ (mL/dL) | 11.2 ± 3.5 | 10.4 ± 2.6 | 0.036* |

▲*Median* ($P_{25}$,$P_{75}$).
Abbreviations: bpm, beats per minute; $C_{(a-v)}O_2$, arterial-venous oxygen difference; CI, contractility index; CO, cardiac output; DBP, diastolic blood pressure; EDFR, early-diastolic filling rate; HR, heart rate; $HR_{max}$, maximum heart rate during exercise; $HRR_1$, 1-min heart rate recovery; METs, metabolic equivalents; $O_2$ pulse, oxygen pulse (oxygen consumption to heart rate ratio); $P_{ET}CO_2$, end-tidal carbon dioxide partial pressure; RR, respiratory rate; SBP, systolic blood pressure; SD, standard deviation; SV, stroke volume; SVR, systemic vascular resistance; $V_E$, minute ventilation; $V_E/VCO_2$ slope, ventilation efficiency for carbon dioxide elimination; $VO_2$, oxygen consumption.

peripheral oxygen extraction, potentially due to the engagement of multiple muscle groups characteristic of this form of exercise.

*Baduanjin* has been recognized for its comprehensive muscle training program which targets both the upper and lower extremities. In contrast to cycle exercise, which involves simple movements with less muscle mass engagement, *Baduanjin* incorporates a diverse range of movements that engage muscles throughout the body. For instance, postures such as the horse-riding stance in Postures 2, 5, and 7 can be likened to targeted quadriceps training, effectively strengthening the thigh muscles. Additionally, dynamic movements involving the forearms and fists in Postures 1, 2, 3, and 7 provide comprehensive upper extremity training, enhancing strength and coordination in the arms and hands. Furthermore, *Baduanjin* emphasizes high-impact and weight-bearing exercises, as illustrated in Posture 8 where practitioners push upward from their toes and land forcefully on their feet. Thus, this holistic approach to physical conditioning extends beyond the focus on lower body muscle endurance typically associated with cycle exercise. However, our current data do not allow us to distinguish perfusion changes specifically in the upper or lower extremities. The higher SVR observed during *Baduanjin* compared to that during cycle ergometer exercise may suggest greater muscular engagement, further evidenced by high $C_{(a-v)}O_2$. Previous research demonstrated that a single bout of resistance training elevates systemic peripheral resistance (Wakeham et al., 2025a; Wakeham et al., 2025b; Dawson et al., 1985; Miles et al., 1987). Therefore, the engagement of multiple muscle groups in *Baduanjin* contributes to its therapeutic benefits,
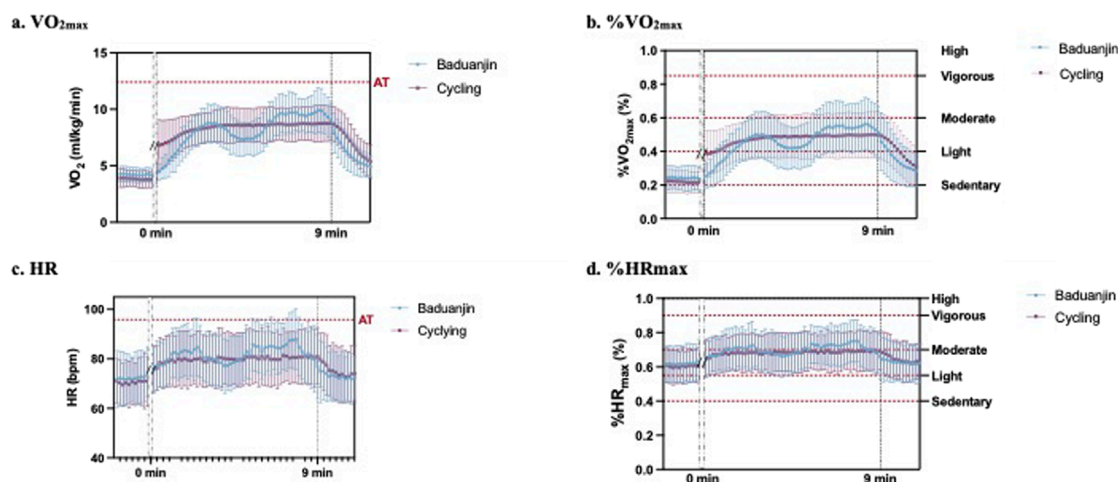
**FIGURE 2**
Comparison of the real-time cardiopulmonary responses of **(a)** VO$_2$max, **(b)** %VO$_2$max, **(c)** HR, and **(d)** %HRmax between Baduanjin exercise and cycle ergometer exercise.
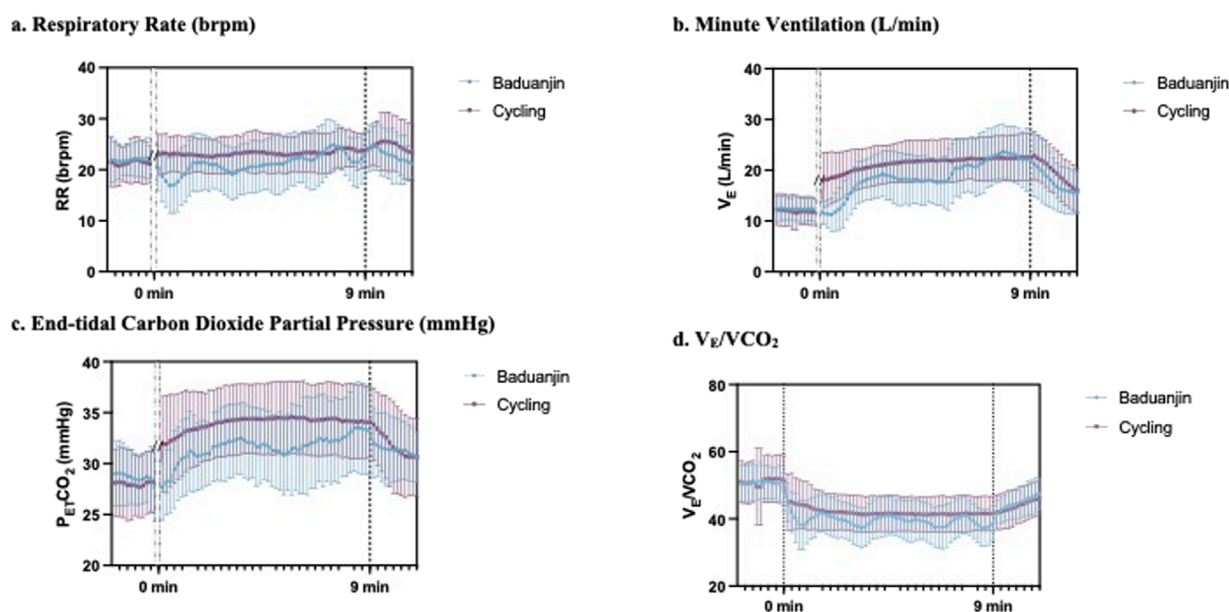


**FIGURE 3**
Comparison of the real-time pulmonary responses of **(a)** respiratory rate, **(b)** minute ventilation, **(c)** end-tidal carbon dioxide partial pressure, and **(d)** V$_E$/VCO$_2$ between Baduanjin exercise and cycle ergometer exercise.

particularly in expanding practitioners' functional capacity and overall muscle strength (Esposito et al., 2011).

## 4.1 Study limitations

As with any study, this study has potential limitations. Firstly, the sample size was small and we were unable to perform a sample size calculation, as we did not find adequate data for our research question and study design *a priori*. Although the number of participants was low, the within-subject repeats narrowed

the estimates' confidence intervals. Secondly, the interpretability and generalizability of the results are limited by the analyzed population's clinical characteristics; our study population included mainly NYHA II CHF patients, and only one female. Therefore, our findings are specific to the population studied. Thirdly, our research employed a non-invasive technique known as ICG, which offers benefits for patients. However, ICG also has limitations regarding specific hemodynamic measurements (such as volume and contractility) that need to be estimated or recalculated. Fourthly, it is crucial to recognize that *Baduanjin* exercise encompasses elements of strength training and balance training in addition
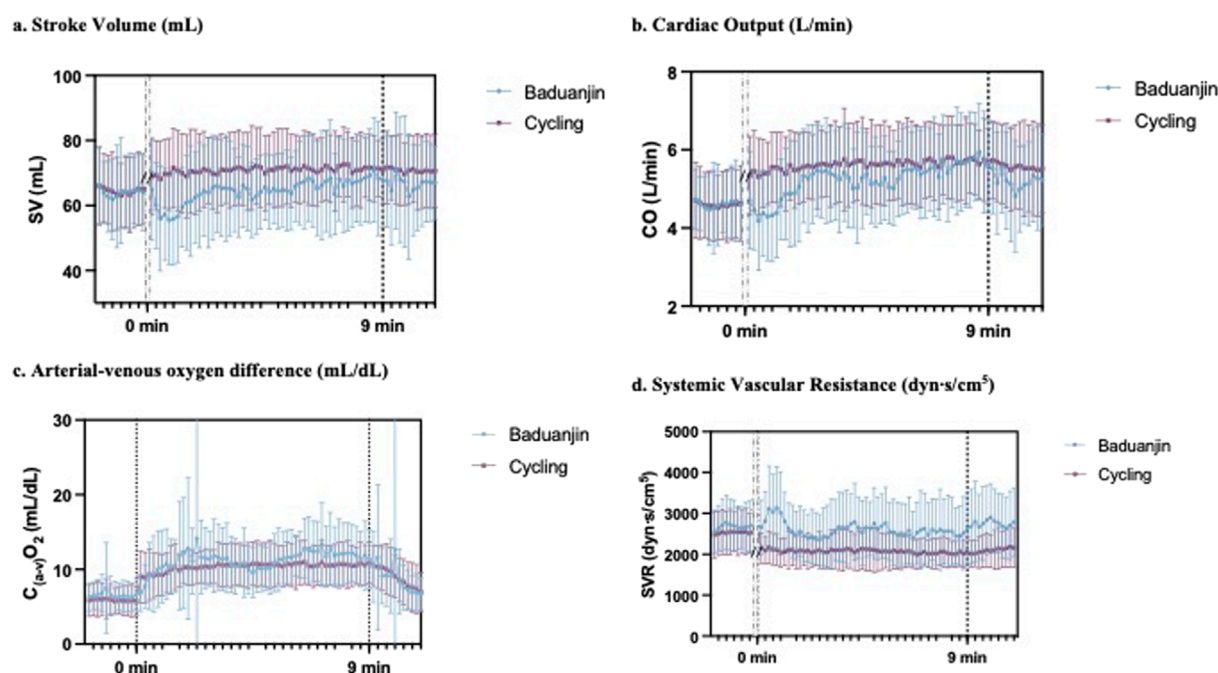
**FIGURE 4**
Comparison of the real-time hemodynamic responses of **(a)** stroke volume, **(b)** cardiac output, **(c)** arterial-venous oxygen difference, and **(d)** systemic vascular resistance between Baduanjin exercise and cycle ergometer exercise.

to endurance exercise training. This multifaceted nature sets *Baduanjin* apart from endurance cycling, which primarily focuses on cardiovascular endurance. As such, the unique combination of strength, balance, and endurance components in *Baduanjin* requires careful consideration when interpreting the results and comparing it to other forms of exercise. Fifth, this study was specifically designed to observe the gas and hemodynamic changes during the two types of exercise. We did not measure the changes in peak $VO_2$ or $VO_2$ at the first ventilatory threshold following the two types of exercise in this study. However, these parameters are crucial for reflecting improvements in endurance capacity (Christou et al., 2024). Comparing these two parameters would be valuable for further elucidating the differences between the two exercises.

## 5 Conclusion

Our study offers novel insight into the cardiopulmonary and hemodynamic differences between *Baduanjin* and cycle ergometer exercise when performed at consistent intensity levels. Unlike the steady intensity of cycle exercise, *Baduanjin* exhibits an intermittent intensity pattern which is the result of more prominent muscle activation during various postures. Additionally, *Baduanjin* is associated with superior improvement in oxygen respiratory efficiency and increased peripheral oxygen utilization, which is crucial to CHF patients' health. Furthermore, *Baduanjin* reduces cardiac and respiratory burden, providing a more comfortable exercise experience. From the clinical perspective, the practice's ease-of-use and flexibility regarding time commitment and space requirements make it an attractive option for cardiac rehabilitation programs. Given these advantages, *Baduanjin* would be particularly

effective for inclusion in cardiac rehabilitation programs for CHF patients in China, where it is widely practiced and culturally familiar.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The research protocol was approved by the Ethics Committee at Guangdong Provincial Hospital of Chinese Medicine under ethical approval number YF2023-119-01. Prior to participation, each subject received an oral explanation of the study and provided written and verbal informed consent.

## Author contributions

XC: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Writing – original draft, Writing – review and editing. XH: Data curation, Formal Analysis, Writing – original draft, Writing – review and editing. TO: Writing – review and editing. YQ: Data curation, Writing – review and editing. HZ: Writing – review and editing. ZW: Writing – review and editing. HC: Funding acquisition, Writing – review and editing. WL: Funding acquisition, Writing – review and editing. WJ: Conceptualization, Methodology, Project administration, Writing – review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2025.1620785/full#supplementary-material

## References

Balady, G. J., Ades, P. A., Bittner, V. A., Franklin, B. A., Gordon, N. F., Thomas, R. J., et al. (2011). Referral, enrollment, and delivery of cardiac rehabilitation/secondary prevention programs at clinical centers and beyond: a presidential advisory from the American Heart Association. *Circulation* 124 (25), 2951–2960. doi:10.1161/CIR.0b013e31823b21e2

Beatty, A. L., Beckie, T. M., Dodson, J., Goldstein, C. M., Hughes, J. W., Kraus, W. E., et al. (2023). A New era in cardiac rehabilitation delivery: research gaps, questions, strategies, and Priorities. *Circulation* 147 (3), 254–266. doi:10.1161/circulationaha.122.061046

Bozkurt, B., Fonarow, G. C., Goldberg, L. R., Guglin, M., Josephson, R. A., Forman, D. E., et al. (2021). Cardiac rehabilitation for patients With Heart Failure: JACC Expert Panel. *J. Am. Coll. Cardiol.* 77 (11), 1454–1469. doi:10.1016/j.jacc.2021.01.030

Chen, X., Marrone, G., Olson, T. P., Lundborg, C. S., Zhu, H., Wen, Z., et al. (2020). Intensity level and cardiorespiratory responses to Baduanjin exercise in patients with chronic heart failure. *Esc. Heart Fail.* 7 (6), 3782–3791. doi:10.1002/ehf2.12959

Chen, X., Jiang, W., Salazar, M., Zhu, H., Wen, Z., Chen, X., et al. (2022). Traditional Baduanjin exercise through the eyes of patients with chronic heart failure: a qualitative content analysis study. *Front. Cardiovasc Med.* 9, 1049036. doi:10.3389/fcvm.2022.1049036

Christou, G. A., Christou, M. A., Davos, C. H., Markozannes, G., Christou, K. A., Mantzoukas, S., et al. (2024). Ergophysiological evaluation of heart failure patients with reduced ejection fraction undergoing exercise-based cardiac rehabilitation: a systematic review and meta-analysis. *Hell. J. Cardiol.* 77, 106–119. doi:10.1016/j.hjc.2024.01.004

Conraads, V. M., Deaton, C., Piotrowicz, E., Santaularia, N., Tierney, S., Piepoli, M. F., et al. (2012). Adherence of heart failure patients to exercise: barriers and possible solutions: a position statement of the study group on exercise training in heart failure of the heart failure association of the European Society of cardiology. *Eur. J. heart Fail.* 14 (5), 451–458. doi:10.1093/eurjhf/hfs048

Coswig, V. S., Barbalho, M., Raiol, R., Del Vecchio, F. B., Ramirez-Campillo, R., and Gentil, P. (2020). Effects of high vs moderate-intensity intermittent training on functionality, resting heart rate and blood pressure of elderly women. *J. Transl. Med.* 18 (1), 88. doi:10.1186/s12967-020-02261-8

Dawson, E. A., Green, D. J., Cable, N. T., and Thijssen, D. H. (1985). Effects of acute exercise on flow-mediated dilatation in healthy humans. *J. Appl. Physiol.* 115 (11), 1589–1598. doi:10.1152/japplphysiol.00450.2013

Deka, P., Pozehl, B., Williams, M. A., and Yates, B. (2017). Adherence to recommended exercise guidelines in patients with heart failure. *Heart Fail Rev.* 22 (1), 41–53. doi:10.1007/s10741-016-9584-1

Dubé, B.-P., Agostoni, P., and Laveneziana, P. (2016). Exertional dyspnoea in chronic heart failure: the role of the lung and respiratory mechanical factors. *Eur. Respir. Rev. Official J. Eur. Respir. Soc.* 25 (141), 317–332. doi:10.1183/16000617.0048-2016

Esposito, F., Reese, V., Shabetai, R., Wagner, P. D., and Richardson, R. S. (2011). Isolated quadriceps training increases maximal exercise capacity in chronic heart failure: the role of skeletal muscle convective and diffusive oxygen transport. *J. Am. Coll. Cardiol.* 58 (13), 1353–1362. doi:10.1016/j.jacc.2011.06.025

Gary, M. A., Henning, A. L., and McFarlin, B. K. (2019). Metabolic and cardiovascular responses on a novel, Whole body exercise Device compared to a cycle ergometer. *Int. J. Exerc. Sci.* 12 (2), 1206–1215. doi:10.70252/KICB9258

Grace, S. L., Gravely-Witte, S., Brual, J., Monette, G., Suskin, N., Higginson, L., et al. (2008). Contribution of patient and physician factors to cardiac rehabilitation enrollment: a prospective multilevel study. *Eur. J. Cardiovasc. Prev. Rehabilitation Official J. Eur. Soc. Cardiol. Work. Groups Epidemiol. and Prev. Cardiac Rehabilitation Exerc. Physiology* 15 (5), 548–556. doi:10.1097/HJR.0b013e328305df05

Health Qigong Management Center (2003). Health Qigong management center of general administration of Sport of China: health Qigong-Baduanjin.

MacDonald, E., Morrison, E. G., Shivgulam, M. E., Pellerine, L. P., Kimmerly, D. S., Bray, N. W., et al. (2024). Moderate intensity intermittent lifestyle physical activity is associated with better executive function in older adults. *Front. Sports Act. Living* 6, 1393214. doi:10.3389/fspor.2024.1393214

McDonagh, T. A., Metra, M., Adamo, M., Gardner, R. S., Baumbach, A., Böhm, M., et al. (2023). 2023 Focused Update of the 2021 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure. *Eur. Heart J.* 44 (37), 3627–3639. doi:10.1093/eurheartj/ehad195

Miles, D. S., Owens, J. J., Golden, J. C., and Gotshall, R. W. (1987). Central and peripheral hemodynamics during maximal leg extension exercise. *Eur. J. Appl. Physiol. Occup. Physiol.* 56 (1), 12–17. doi:10.1007/bf00696369

Molloy, C., Long, L., Mordi, I. R., Bridges, C., Sagar, V. A., Davies, E. J., et al. (2024). Exercise-based cardiac rehabilitation for adults with heart failure. *Cochrane Database Syst. Rev.* 3 (3), CD003331. doi:10.1002/14651858.CD003331.pub6

Norton, K., Norton, L., and Sadgrove, D. (2010). Position statement on physical activity and exercise intensity terminology. *J. Sci. Med. sport* 13 (5), 496–502. doi:10.1016/j.jsams.2009.09.008

Ozemek, C., and Squires, R. W. (2021). Enrollment and Adherence to early Outpatient and Maintenance cardiac rehabilitation programs. *J. Cardiopulm. Rehabil. Prev.* 41 (6), 367–374. doi:10.1097/hcr.0000000000000645

Pelliccia, A., Sharma, S., Gati, S., Bäck, M., Börjesson, M., Caselli, S., et al. (2020). ESC Guidelines on sports cardiology and exercise in patients with cardiovascular disease. *Eur. Heart J.* 42 (1), 17–96. doi:10.1093/eurheartj/ehaa605

Ponikowski, P., Voors, A. A., Anker, S. D., Bueno, H., Cleland, J. G. F., Coats, A. J. S., et al. (2016). 2016 ESC Guidelines for the diagnosis and treatment of acute and chronic heart failure: the Task Force for the diagnosis and treatment of acute and chronic heart failure of the European Society of Cardiology (ESC). Developed with the special contribution of the Heart Failure Association (HFA) of the ESC. *Eur. J. heart Fail.* 18 (8), 891–975. doi:10.1002/ejhf.592

Sanderson, B. K., Phillips, M. M., Gerald, L., DiLillo, V., and Bittner, V. (2003). Factors associated with the failure of patients to complete cardiac rehabilitation for medical and nonmedical reasons. *J. Cardiopulm. Rehabilitation* 23 (4), 281–289. doi:10.1097/00008483-200307000-00005

Sun, X. G. (2015). Rehabilitation practice patterns for patients with heart failure: the Asian perspective. *Heart Fail. Clin.* 11 (1), 95–104. doi:10.1016/j.hfc.2014.09.001

Taylor, J. L., Bonikowske, A. R., and Olson, T. P. (2021). Optimizing Outcomes in cardiac rehabilitation: the Importance of exercise intensity. *Front. Cardiovasc. Med.* 8, 734278. doi:10.3389/fcvm.2021.734278

Wakeham, D. J., Pierce, G. L., and Heffernan, K. S. (2025a). Effect of acute resistance exercise and resistance exercise training on Central Pulsatile hemodynamics and Large artery stiffness: Part II. *Pulse (Basel)* 13 (1), 45–61. doi:10.1159/000543314

Wakeham, D. J., Pierce, G. L., and Heffernan, K. S. (2025b). Effect of acute resistance exercise and resistance exercise training on Central Pulsatile hemodynamics and Large artery stiffness: Part I. *Pulse (Basel)* 13 (1), 31–44. doi:10.1159/000543313

Wang, X. Q., Pi, Y. L., Chen, P. J., Liu, Y., Wang, R., Li, X., et al. (2016). Traditional Chinese exercise for cardiovascular diseases: systematic review and meta-analysis of Randomized Controlled trials. *J. Am. Heart Assoc.* 5 (3), e002562. doi:10.1161/jaha.115.002562

Xie, Q., Xiao, M., and Huang, J. (2022). The efficacy and physiological mechanisms of Baduanjin on dyspnea and exercise limitation in patients with COPD [in Chinese]. *Massage Rehabilitation Med.* 13 (22), 46–50. doi:10.19787/j.issn.1008-1879.2022.22.012

Zhang, Z., Pack, Q., Squires, R. W., Lopez-Jimenez, F., Yu, L., and Thomas, R. J. (2016). Availability and characteristics of cardiac rehabilitation programmes in China. *Heart Asia* 8 (2), 9–12. doi:10.1136/heartasia-2016-010758

Zhang, S., Ding, R., Chen, S., Meng, X., Jianchao, L., Wang, D. W., et al. (2023). Availability and trend of dissemination of cardiac rehabilitation in China: report from the multicenter national registration platform between 2012 and 2021. *Front. Cardiovasc Med.* 10, 1210068. doi:10.3389/fcvm.2023.1210068

Zou, L., SasaKi, J. E., Wang, H., Xiao, Z., Fang, Q., and Zhang, M. (2017). A systematic review and meta-analysis Baduanjin Qigong for health benefits: Randomized Controlled trials. *Evidence-based complementary Altern. Med. eCAM* 2017, 4548706. doi:10.1155/2017/4548706

# Glossary

| | |
|---|---|
| CHF | chronic heart failure |
| ICG | impedance cardiography |
| CPET | cardiopulmonary exercise testing |
| NYHA | New York Heart Association |
| EqualVO$_2$ | the average oxygen consumption |
| VO$_2$ | volume of oxygen |
| V$_E$ | minute ventilation |
| CO | cardiac output |
| EBCR | exercise-based cardiac rehabilitation |
| HF | heart failure |
| HR | heart rate |
| SV | stroke volume |
| CI | contractility index |
| EDFR | diastolic filling rate |
| SVR | systemic vascular resistance |
| VO$_2$max | maximum oxygen consumption |
| RER | respiratory exchange ratio |
| METs | metabolic equivalents |
| HRmax | maximum heart rate |
| O$_2$pulse | oxygen pulse |
| SBP | systolic blood pressure |
| DBP | diastolic blood pressure |
| HRR$_1$ | minute heart rate recovery |
| RR | respiratory rate |
| P$_{ET}$CO$_2$ | end-tidal carbon dioxide pressure |
| VE/VCO$_2$ | ventilation/carbon dioxide production |
| VE/VCO$_2$ slope | ventilation/carbon dioxide production slope |
| VT | ventilatory threshold |
| AT | anaerobic threshold |
| VCO$_2$ | volume of carbon dioxide |
| LVEF | left ventricular ejection fraction |
| SD | standard deviation |
| C(a-v)O$_2$ | elevated arterial-venous oxygen difference |
| BMI | body mass index |
| bpm | beats per minute |
| NT-proBNP | N-terminal B-type natriuretic peptide |
| PASP | pulmonary artery systolic pressure |
| MI | myocardial infarction |
| MAX | maximal intensity |
| O$_2$ pulse | oxygen pulse (oxygen consumption to heart rate ratio) |
| FEV$_1$ | forced expiratory volume in 1 s |
| FVC | forced vital capacity |

| | |
|---|---|
| MVV | maximum voluntary ventilation |