# Wearable-based Assessment of Heart Rate Response to Physical Stressors in Patients After Open-Heart Surgery With Frailty

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***Abstract*— Due to frailty, cardiac rehabilitation in older patients after open-heart surgery must be carefully tailored, thus calling for informative and convenient tools to assess the effectiveness of exercise training programs. The study investigates whether heart rate (HR) response to daily physical stressors can provide useful information when parameters are estimated using a wearable device. The study included 100 patients after open-heart surgery with frailty who were assigned to intervention and control groups. Both groups attended inpatient cardiac rehabilitation however only the patients of the intervention group performed exercises at home according to the tailored exercise training program. While performing maximal veloergometry test and submaximal tests, i.e., walking, stair-climbing, and stand up and go, HR response parameters were derived from a wearable-based electrocardiogram. All submaximal tests showed moderate to high correlation ($r$ = 0.59–0.72) with veloergometry for HR recovery and HR reserve parameters. While the effect of inpatient rehabilitation was only reflected by HR response to veloergometry, parameter trends over the entire exercise training program were also well followed during stair-climbing and walking. Based on study findings, HR response to walking should be considered for assessing the effectiveness of home-based exercise training programs in patients with frailty.**

***Index Terms*— Remote monitoring, heart rate recovery, heart rate reserve, frailty status, exercise training, aging.**

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## I. Introduction

Frailty syndrome is characterized by decline in physiological reserve and vulnerability to internal (e.g., disease, surgery) and external (e.g., activities of daily living) stressors [1], [2]. Frailty is becoming one of the most important challenges of the aging population [3], manifesting in 17% of community-dwelling adults over 60 years old [4]. The syndrome is associated with increased risk of adverse outcomes such as impaired mobility, disability, falls, and death [5]. Fortunately, evidence grows that improvement in frailty can be achieved by the timely prescription of an appropriate exercise training program [6].

Older adults with frailty referred to open-heart surgery are prone to postoperative complications and often need longer recovery [7]. Considering the dramatically increasing number of older frail patients who enter cardiac rehabilitation programs, it becomes a serious issue deserving research attention [8]. In particular, this patient population suffers from reduced muscle mass, lack of endurance, and decreased physiological functions which complicate cardiac rehabilitation and preclude the utilization of regular exercise training programs [9]. To achieve rehabilitation goals without harming the patient, the type, intensity, and duration of physical activity sessions, together with exercise recommendations at home, have to be carefully tailored to the individual patient [10]. Therefore, there is a need for informative and convenient tools to assess the effectiveness of exercise training programs, especially if programs are supposed to be continued outside the clinical setting.

Despite the abundance of various indexes and questionnaires covering physical, physiological, cognitive, and social components, no standardized tool for frailty assessment has yet been universally accepted [11]. Given that clinical tools are unsuitable for use outside the clinical environment, there has been a great interest in studying new markers, often obtained using wearable devices [12], that would enable earlier identification of frailty. A decline in physical abilities is the first component to manifest thus former research focused on physical markers of which slowness of gait is among the most informative in identifying frailty [12], [13]. However, there is growing evidence suggesting cardiovascular function-describing markers as better reflecting physiological reserve [14].

Since the cardiovascular function is regulated by the autonomic nervous system, cardiac autonomic imbalance may contribute to frailty worsening [14]–[17], which in turn may decrease the capacity to maintain homeostasis when exposed to physical stressors [14]. The autonomic nervous system controls the rate at which the sinoatrial node produces electrical impulses thus abnormal heart rate (HR) characteristics, such as increased resting HR, decreased HR complexity and variability, slower and weaker HR response to physical activity, and attenuated HR recovery after exercise, often relate to the autonomic imbalance [14], [18].

In a recent study, HR response to walking, which is obviously the most common physical stressor among older adults, was investigated and linked to frailty status [19]. Slower and weaker HR response to walking was found among frail older adults compared to non-frail, suggesting the potential of HR-characterizing markers to improve frailty assessment. However, the study focused only on normal and rapid walking therefore the effect of other physical stressors on HR response remains to be explored. In addition, data were available only 5 s before and 10 s after the walking activity precluding from the reliable characterization of baseline HR. For this reason, the authors expressed great interest in addressing baseline HR complexity and full HR recovery parameters in future studies [19].

A rapidly growing population of patients with frailty referred for surgery calls for convenient tools that would enable a better understanding of the efficiency of exercise-based rehabilitation [9]. Accordingly, this study explores HR response to various physical stressors throughout the exercise training program aiming at the development of wearable-based technology for home-based assessment. By involving maximal (veloergometry) and various submaximal (6-minute walk, stair-climbing, and timed up and go) tests, the present study substantially complements the findings in [19] where HR response was only assessed in walking. The applications of the present approach to HR response assessment include routine evaluation of the effectiveness of exercise training programs and patient monitoring outside the clinical setting aiming at timely detection of impairment in frailty status.

## II. Materials and Methods

### A. Study population

The patients who had undergone open-heart surgery and were referred to Kulautuva Rehabilitation Hospital (Lithuanian University of Health Sciences Hospital Kaunas clinics, Kulautuva, Lithuania) were invited to participate in the study. Upon arrival at the rehabilitation hospital (17.0 ± 7.4 days post-surgery), 337 patients were examined for eligibility, of which 100 (38 females) fulfilled the criteria for inclusion: age ≥65 years, the Edmonton frail scale score ≥4 at the beginning of the study, 6-minute walk distance ≥150 meters. Exclusion criteria were implanted cardiac devices, diseases of the musculoskeletal system or other organs complicating exercise training, exercise-limiting orthopedic and neurological conditions, severe chronic heart failure (New York Heart Association Class IV), hemoglobin <9 g/dL, wound healing disturbance, and cognitive or/and linguistic deficits.

The patients were randomly assigned to the intervention and control groups on the first day of admittance. The groups were well-matched except that fewer women were in the control group (Table I). Patients of both groups participated in exercise training during inpatient cardiac rehabilitation but only the intervention group was asked to exercise at home according to the tailored training program (see Sec. II-B).

TABLE I: Demographic and clinical characteristics of the patients in the intervention and control groups.

| | Intervention | Control |
|---|---|---|
| Women | 24 | 14 |
| Men | 25 | 37 |
| Age, years | 73.3 ± 4.8 | 73.4 ± 5.3 |
| Height, m | 1.66 ± 0.1 | 1.69 ± 0.1 |
| Weight, kg | 74.7 ± 12.9 | 78.7 ± 13.2 |
| Body mass index, kg/m$^2$ | 27.1 ± 4.7 | 27.6 ± 4.1 |
| Post-surgery, days | 16.6 ± 7.4 | 17.6 ± 7.5 |
| **Surgery** | | |
| Coronary artery bypass graft | 22 | 34 |
| Isolated valve | 11 | 5 |
| Combined | 16 | 12 |
| **Medications** | | |
| Angiotensin-converting enzyme | 37 | 40 |
| Beta adrenoblockers | 49 | 50 |
| Calcium channel blockers | 2 | 1 |
| **Heart failure class** | | |
| NYHA I | 2 | 3 |
| NYHA II | 39 | 35 |
| NYHA III | 8 | 13 |
| **Comorbidities** | | |
| Atrial fibrillation | 15 | 17 |
| Diabetes mellitus | 7 | 7 |
| Obstructive pulmonary disease | 0 | 3 |
| Depression | 1 | 2 |
| Multisceletal system diseases | 1 | 3 |
| Oncological diseases | 4 | 8 |
| **Physical capacity** | | |
| Veloergometry duration, s | 161.8 ± 97.8 | 154.4 ± 95.2 |
| 6-minute walking distance, m | 293 ± 85.9 | 282 ± 78.0 |
| Timed up and go duration, s | 8.8 ± 2.3 | 8.6 ± 1.9 |
| **Edmonton frail scale score** | 6.1 ± 1.5 | 6.1 ± 1.7 |

Certain values are given as mean ± standard deviation.
Only medications that may affect HR response and baseline HR are listed.
NYHA stands for New York Heart Association classification of heart failure.

The degree of frailty was assessed using the Edmonton frail scale (EFS) [20], which includes nine domains of frailty, i.e., functional performance, general health status, functional independence, cognition, medication usage, nutrition, social support, mood, and continence. The EFS score was determined by healthcare specialists at the beginning of inpatient cardiac rehabilitation, after completing rehabilitation (average duration 16.3±2.9 days), and after completing home-based exercise training (average duration 102.6±23.9 days). Scores for EFS ranged from 4 to 10 with higher scores indicating a more severe frailty status.

The study entitled Unobtrusive Technologies for Monitoring of Autonomic Nervous System Function in Elderly Frail Patients (FrailHeart) is registered in ClinicalTrials.gov (No. NCT04636970) [21], and is approved by the Ethics Committee of Kaunas region (protocol no. BE-2-99; September 23, 2020).

### B. Exercise training

All study participants attended inpatient cardiac rehabilitation. The intensity and duration of the exercise training program were tailored considering the patient's functional and clinical status. The exercise training program for inpatient cardiac rehabilitation consisted of endurance training, resistance training, balance training, respiratory muscle training, and aerobic gymnastics.

Patients of the intervention group had to attend three additional physiotherapy sessions at the end of inpatient cardiac rehabilitation to familiarize themselves with the home-based program, which consisted of four exercise types and was intended to last for 12 weeks. Home-based exercise training included aerobic endurance training (e.g., walking, stair-climbing, and cycling), sensomotoric training (e.g., coordination, balance, and postural control), resistance training (exercises involving leg muscles), and flexibility training (e.g., leg, arm, and neck stretching).

Patients were contacted twice a month and inquired about adherence to home-based training. A more detailed description of inpatient and home-based exercise training programs can be found in [13], [22].

### C. Data acquisition

Electrocardiogram and triaxial acceleration signals, sampled at 130 Hz and 200 Hz, were acquired using a textile strap with a wearable sensor (Polar H10; Polar Electro OY, Kempele, Finland), placed under the chest. RR intervals with a resolution of 1 ms were provided separately. The signals and RR intervals were transferred to a smartphone with a mobile app in real-time via Bluetooth. To ensure a stable Bluetooth connection, the smartphone was placed in the holder wrapped around the upper arm of the patient. The smartphone was only taken out when a healthcare specialist logged the beginning of each test. Some data were lost or excluded due to various issues, see Discussion. A detailed description of available data for each test is given in Fig. 1. A part of the signal database is accessible from Physionet [23].

### D. Exercise testing

Submaximal clinical tests, namely, 6-minute walking, stair-climbing, and timed up and go, were chosen as representatives of common physical stressors in activities of daily living. Meanwhile, veloergometry was chosen as a maximal test for reference. Due to substantial effects on the patient's condition, veloergometry was performed on a different day than submaximal tests. Before and after each test, a patient had to rest in a sitting position for at least three minutes. The tests were performed at the beginning of inpatient rehabilitation, after inpatient rehabilitation, and after home-based exercise training.

Veloergometry is a clinical standard for exercise testing used to evaluate cardiovascular function under conditions of increasing physical workload. Veloergometry was performed on a cycle ergometer Viasprint 150P (Ergoline GmbH, Germany) using a ramp protocol starting at 25 watts and then increasing by 12.5 watts per minute until subjective exhaustion or occurrence of termination criteria (dyspnoea, chest pain, leg fatigue, systolic blood pressure $>$220 mmHg, decrease in baseline a systolic blood pressure $>$20 mmHg).

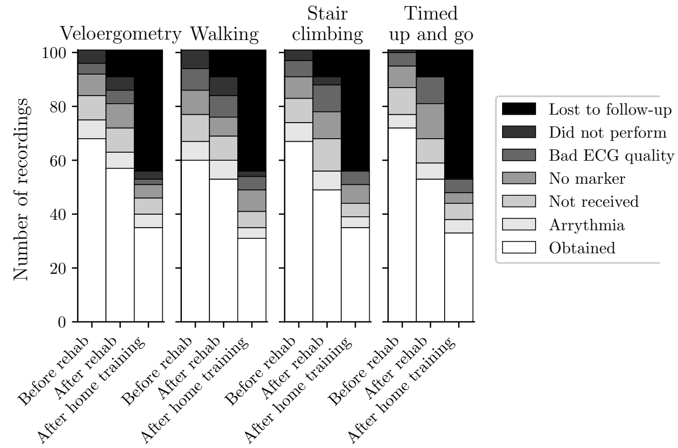


Fig. 1: Data availability for each test. Here "lost to follow up" refers to patients who left the rehabilitation clinic earlier or did not return after home-based exercise training, "did not perform" refers to tests that were not performed by the patients due to pain and other reasons, "bad ECG quality" refers to an unrecognizable electrocardiogram, "no marker" refers to the absence of a marker indicating the onset of a test, "not received" refers to the signals that were not received due to technical or user-related issues, "arrhythmia" refers to atrial fibrillation, and "obtained" refers to acquired good quality signals.

A 6-minute walk test is a well-established, safe, and inexpensive approach to assess functional performance. The test was found to be beneficial in assessing treatment efficiency across a variety of cardiopulmonary conditions [24]. The test does not demand maximal physical effort hence it is accessible to most except severely impaired older adults [25]. During the 6-minute walk test, the distance walked on a flat surface under the encouragement of a supervising staff member is judged based on the individual-specific reference distance.

Stair-climbing was chosen assuming that terrain-dependent peculiarities may require additional physical effort compared to ordinary walking [26]. Stair-climbing has not yet been standardized for use in clinical practice thus the common approach is to instruct patients to climb the maximum number of stairs at a convenient pace [27]. Taking into account that frail patients after open-heart surgery are especially vulnerable, they were asked to climb only a set of 12 stairs at a convenient pace without assistance from a healthcare specialist and were allowed to terminate the test whenever they felt exhaustion, leg fatigue, or chest pain.

A timed up and go test was chosen assuming that body position change may alter HR response [28]. During the test, the patient is asked to change the body position from sitting to standing, walk 3 meters forward, turn around, and walk back to the chair to sit down.

### E. Heart rate characterization

*1) Preprocessing:* Before HR characterization, RR series were processed to ensure that only normal-to-normal intervals were included for analysis. Atypical RR intervals that include missed, extra, and ectopic beats were corrected by analyzing successive RR interval differences using the algorithm described in [29]. Extra beats were corrected by removing the corresponding beats, whereas new beats were added in place of missed beats so that the long RR interval was divided into two halves. Ectopic beats were corrected by interpolating the corresponding RR intervals. Additionally, all corrected RR series were manually inspected by analyzing a synchronously recorded electrocardiogram.

Estimation of HR response parameters requires detection of peak HR and HR recovery onset. Peak HR rate is the maximal HR during the entire HR response phase. Detection of the recovery onset immediately after the cessation of physical activity is explained in detail in our previous work [30]. Briefly, a search for the recovery onset is performed by fitting a line to the HR series in a sliding window of 1 min. Then, the time interval with the steepest falling slope is chosen as a suspected recovery phase. The HR series 25 s before and 25 s after the beginning of the steepest falling curve is taken for fitting a polynomial curve where the maximal value determines the onset of the recovery phase.

Baseline HR parameters were estimated from a resting phase of three minute duration before the exercise test. To ensure that parameters are not altered by movements, the rest phase with less intense activity, as measured by the triaxial accelerometer, is chosen as the most representative.

*2) Exclusion of HR series:* HR series unacceptable for parameter estimation, i.e., showing no HR response to physical activity or exhibiting high HR variation during a recovery phase, were excluded from the analysis. No response to an exercise test was considered when HR did not rise at least 5 bpm above the average baseline HR. HR variations either caused by physiological factors or unexpected activity (e.g., turning or leaning) were considered unacceptable when exponential fitting to the recovery phase, determined via the coefficient of determination $R^2$, was below the fixed threshold of 0.5 [30]. Examples of typical and unacceptable HR series for each type of exercise test are given in Fig. 2.

*3) Characterization of heart rate response:* With the onset of exercise, HR starts to increase due to parasympathetic withdrawal and sympathetic activation, whereas decays towards its pre-exercise level after the cessation of physical activity due to parasympathetic reactivation and sympathetic withdrawal. To comprehensively characterize HR response, the parameters covering the accelerating phase, decelerating phase, and entire HR response were chosen for investigation.

The accelerating phase of HR response is characterized by the time interval $T_\mathrm{a}$ during which HR accelerates until it reaches the peak HR ($HR_\mathrm{p}$) starting at the onset of a particular exercise test [19]. Time to peak HR was found to be prolonged in frail older adults compared to non-frail during walking [19].

The decelerating phase of HR response is characterized by post-exercise HR recovery which reflects the capacity to respond and adapt to maximal or submaximal physical activity [31]. Normally, HR recovers exponentially with a fast decrease during the first minute after physical activity, followed by a slow gradual decay until reaching the baseline HR. The fast recovery phase is characterized by the short-term time constant ($T_{30}$), which is found by fitting the line of 30 s duration to the logarithm of HR, where $T_{30}$ is the negative inverse of the slope of the resulting line. To improve reproducibility, $T_{30}$ is estimated within the first min after the recovery onset in a sliding window of 30 s and the lowest value is selected [32]. Meanwhile, the slow recovery phase is characterized by a decay of HR at 120 seconds ($HRR_{120}$) after the recovery onset. A slower HR recovery may indicate cardiac autonomic dysfunction and was found to be associated with a broad range of cardiovascular diseases and increased risk of mortality [31].

The entire HR response is characterized by HR reserve which is a measure of chronotropic competence independent of age, resting HR, and physical fitness [33]. HR reserve is found by,

$$RES = \frac{HR_\mathrm{p} - HR_\mathrm{r}}{HR_\mathrm{a} - HR_\mathrm{r}} \times 100, \quad (1)$$

where $HR_\mathrm{r}$ is a resting HR derived from the resting period before the exercise test, and $HR_\mathrm{a}$ is the attainable HR calculated as 220 – age in years.

Low $RES$ may indicate an impaired chronotropic response, whereas it is roughly 100% in healthy people during peak exercise.

*4) Characterization of baseline heart rate:* Elevated resting HR, reduced HR complexity and reduced HR variability indicate autonomic imbalance manifesting as increased sympathetic and/or decreased parasympathetic tone [18].

Resting HR ($HR_\mathrm{r}$) is calculated as an average HR over the entire resting phase prior to the exercise test. Elevated resting HR is an established independent risk factor for all-cause and cardiovascular mortality [34], and was also found to be higher among frail older adults compared to non-frail [28].

HR complexity during rest prior to exercise is assessed using sample entropy (SampEn) [16], [35]. Given the HR pattern length $m$ and the similarity threshold $\eta$ showing the tolerance for accepting similar patterns, the sample entropy estimates the logarithmic probability of similar $m$-length patterns to remain similar for $m+1$ [35]. Sample entropy is close to 0 for regular HR whereas takes larger values for unpredictable HR. In this study, $\eta$ was set to 0.15, and $m$ was set to 2 as in [16]. Reduced HR complexity may indicate autonomic dysfunction in people with frailty.

To assess ultra-short-term HR variability [36], the standard deviation of all normal-to-normal RR intervals (SDNN) during rest before the exercise test is computed. Reduced SDNN may indicate decreased parasympathetic activity in frail adults [16].

Characterization of HR response and baseline HR is illustrated in Fig. 3.

## F. Statistical analysis

Some veloergometry, walking, stair-climbing, and timed up and go tests were unavailable, resulting in an unequal number of patients with completed tests for a particular analysis.

The agreement between HR response to veloergometry and submaximal tests is expressed as the mean difference and 95% confidence interval. Associations between HR response to veloergometry and each submaximal test are represented by scatter plots. The relationship is assessed using linear regression and given as Pearson correlation coefficient.

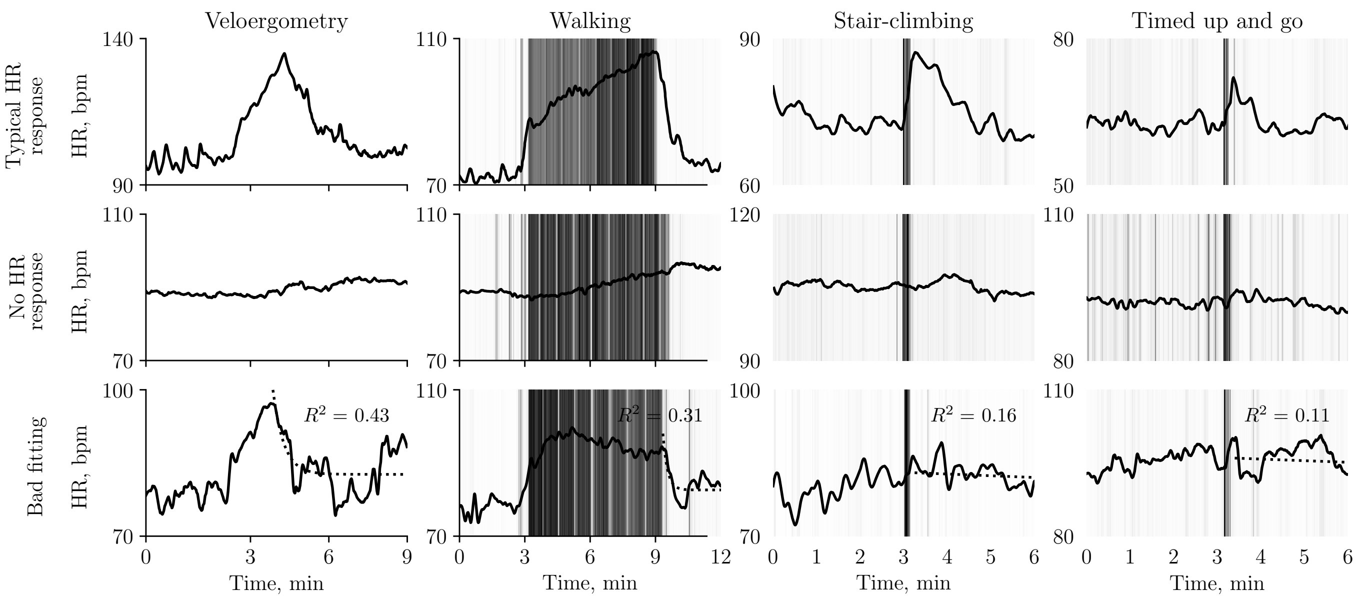


Fig. 2: Exemplary illustrations of typical and unacceptable HR series for parameter estimation during veloergometry and submaximal tests. Grey bars indicate physical activity intensity estimated as a mean absolute deviation of the triaxial acceleration signal. Physical activity intensity can not be estimated during veloergometry due to sitting on the cycle ergometer.

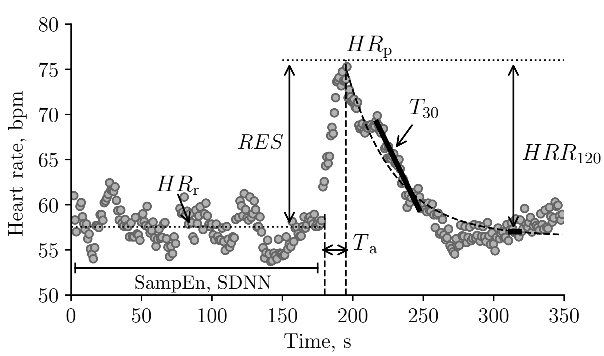


Fig. 3: Characterization of baseline HR and HR response. Note that $RES$ also involves normalization by [(200 – age) – $HR_r$]. The onset and the cessation of physical activity are at 180 s and 195 s, respectively.

To assess the relationship between HR parameters and frailty status, HR response and baseline HR parameter values are subdivided into quartiles. Corresponding EFS values of each quartile are given as mean and standard deviation. The Shapiro-Wilk test was used to assess data normality and because of non-normal distribution, the nonparametric Kruskal-Wallis H-test was used to calculate the $p$-value for the differences between EFS values of the corresponding quartiles.

To investigate the effect of inpatient cardiac rehabilitation on HR response parameters, only patients with available tests both before and after inpatient rehabilitation were included in the analysis. In the case of a normal distribution, the Student t-test for paired data was applied to calculate the $p$-value. Otherwise, the Wilcoxon signed-rank test was used.

The effect of the entire exercise training program, covering inpatient cardiac rehabilitation and home-based training, is expressed as mean and standard deviation. HR response parameters were estimated after home-based training and before inpatient rehabilitation whenever data were available. When data were unavailable, data recorded after inpatient rehabilitation was used instead. In the case of a normal distribution, the Student t-test for paired data was used to calculate the $p$-value for the change of parameters within the intervention and control groups. Otherwise, the Wilcoxon signed-rank test was applied. Meanwhile, the differences in the change of parameter values before and after the entire exercise training program between the intervention and control groups were assessed using the Student t-test for unpaired data in the case of a normal distribution. Otherwise, the Mann–Whitney U test was applied.

## III. Results

### A. Distribution of unacceptable HR series

Table II sheds light on the distribution of unacceptable HR series for different exercise tests in frail/vulnerable and non-frail patients. Bad fitting of the exponential curve to the recovery phase prevailed in veloergometry and walking, whereas insufficient HR response was the most common cause of HR series exclusion for stair-climbing and timed up and go. No notable difference is observed between frail/vulnerable and non-frail patients, except for timed up and go, which resulted in a twice as large number of excluded tests due to insufficient HR response in frail/vulnerable compared to non-frail.

### B. Agreement between submaximal testing and veloergometry

Compared to veloergometry, the lowest parameter estimation errors are obtained during walking, which are considerably lower than those during other submaximal tests, see Table III.

TABLE II: Percentage of unacceptable HR series for different exercise tests in frail/vulnerable (EFS $\geq$ 4) and non-frail (EFS $<$ 4) patients.

| | Frail/Vulnerable | Non-frail | Total |
|---|---|---|---|
| Veloergometry | | | |
| No HR response | 2.0% | 0.0% | 1.6% |
| Bad fitting | 5.2% | 5.4% | 5.2% |
| Walking | | | |
| No HR response | 0.7% | 0.0% | 0.6% |
| Bad fitting | 9.6% | 11.1% | 9.9% |
| Stair-climbing | | | |
| No HR response | 11.9% | 14.3% | 12.4% |
| Bad fitting | 3.4% | 3.6% | 3.4% |
| Timed up and go | | | |
| No HR response | 19.0% | 10.7% | 17.5% |
| Bad fitting | 11.3% | 12.1% | 11.4% |

Percentages are given for pooled data from before inpatient rehabilitation, after inpatient rehabilitation, and after home-based training.

TABLE III: Agreement between HR response to veloergometry and each submaximal exercise test.

| Submaximal | $T_a$, s | $HRR_{120}$, bpm | $T_{30}$, slope | $RES$, % |
|---|---|---|---|---|
| Walking | -66.5 [-97.6, -35.3] | 1.6 [0.12, 3.1] | 0.04 [0.01, 0.07] | 2.2 [-0.4, 4.8] |
| Stair-climbing | 203 [180.7, 225.3] | 7.25 [6.0, 8.5] | -0.07 [-0.09, -0.04] | 15.9 [13.5, 18.2] |
| Timed up and go | 212.9 [185.1, 240.8] | 10.9 [9.1, 12.7] | -0.06 [-0.09, -0.03] | 18.4 [15.4, 21.4] |

The agreement is expressed as mean difference and 95% confidence interval. Results are given for pooled data from before inpatient rehabilitation, after inpatient rehabilitation, and after home-based training.

### C. Relationship between submaximal testing and veloergometry

Fig. 4 shows an association between HR response parameters estimated during veloergometry and each submaximal exercise test. All submaximal tests show moderate to high correlation for HR recovery parameters $T_{30}$ and $HRR_{120}$, and for HR reserve. On the other hand, none of the submaximal tests induced similar HR acceleration patterns as during veloergometry resulting in uncorrelated $T_a$ values.

### D. Relationship of HR parameters with frailty status

Fig. 5 shows associations between HR response to veloergometry and baseline HR parameters, subdivided into quartiles, and frailty status. The results indicate an obvious association between worsening of HR response parameters and deteriorating frailty status, as indicated by increasing EFS score. Baseline HR parameters, namely resting HR, SampEn, and SDNN exhibit the same trend until the highest quartile.

### E. Effect of inpatient cardiac rehabilitation

To explore the effect of inpatient rehabilitation on HR response and baseline HR, the parameters were computed before and after rehabilitation for veloergometry and submaximal tests. Veloergometry, walking, stair-climbing, and timed up and go tests before and after inpatient rehabilitation were available in 41, 29, 26, and 18 patients, respectively. HR response parameters noticeably changed only for veloergometry. That is, $T_a$ increased from 175±84 s to 242±78 s ($p < 0.05$), $T_{30}$ decreased from -0.21±0.12 to -0.29±0.14 ($p < 0.05$), $HRR_{120}$ increased from 10.6±6.2 bpm to 13.9±7.3 bpm ($p < 0.05$), and $RES$ increased from 23.3±11.3% to 29.2±14.6% ($p = 0.05$).

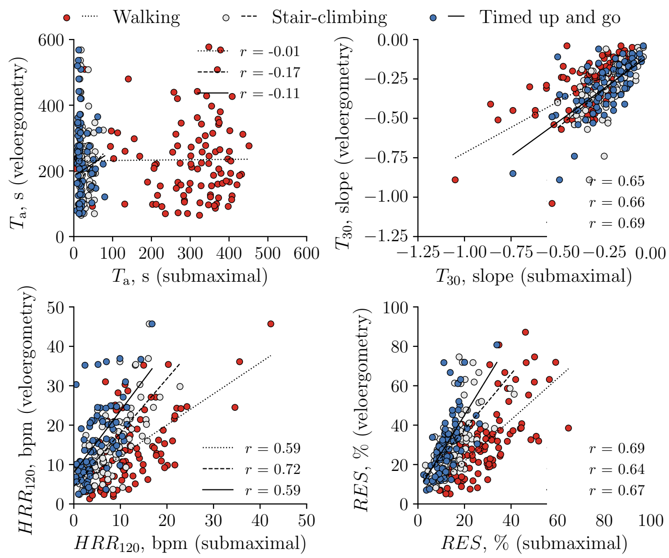


Fig. 4: Association between HR response parameters during veloergometry and submaximal exercise tests. Correlations are given for pooled data from before inpatient rehabilitation, after inpatient rehabilitation, and after home-based training.

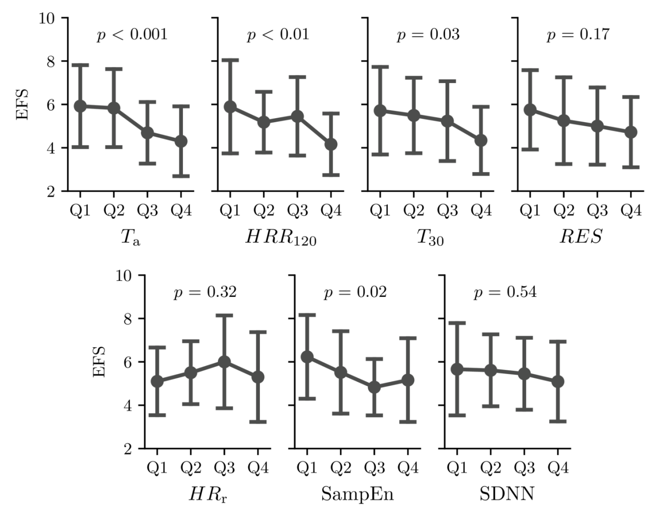


Fig. 5: Frailty status in quartiles of HR response to veloergometry and baseline HR parameters. Results are given as mean±standard deviation for pooled data from before inpatient rehabilitation, after inpatient rehabilitation, and after home-based training. $p$-value refers to the difference in the EFS scores across corresponding HR parameter quartiles.

No significant change was reflected by walking, stair-climbing, and timed up and go.

### F. Effect of the entire exercise training program

Fig. 6 shows the effect of the entire exercise training program on HR response parameters in intervention and control groups. Veloergometry, walking, stair-climbing, and timed up and go tests which covered the entire exercise training, were available in 30, 25, 22, and 15 patients, respectively. All HR response parameters improved significantly during veloergometry ($p < 0.05$), except $T_{\mathrm{a}}$ for the control group.

When comparing submaximal tests with veloergometry, the parameter trends were best followed during walking, whereas stair-climbing and timed up and go seem to be less suitable to capture parameter change.

No difference is reflected by the change in HR parameter values before and after the entire exercise training program between the intervention and control groups, except for $T_{\mathrm{a}}$ during stair-climbing. The absence of difference corresponds well with similar EFS scores after completing the entire training program in the intervention (4.13±1.45) and control (4.78±1.66) groups.

## IV. Discussion

To the best of our knowledge, this is the first study that provides insights on HR response to various physical stressors in patients with frailty after open-heart surgery. The main study finding is that HR response, as indicated by parameters estimated during veloergometry, improved in most patients after surgery. The improvement was the most obvious in the intervention group to whom home-based exercise training was assigned. This suggests home-based training as a proper intervention to improve physiological reserve. When considering the applicability of submaximal tests, walking and stair-climbing are the most suitable to induce HR response sufficient enough to follow parameter trends observed using veloergometry. Furthermore, the present approach may also be beneficial for monitoring the effectiveness of preoperative training [37].

Walking, stair-climbing, and body position change were chosen as physical stressors assuming that these are feasible activities even in frail older adults. In the present study, 18% of patients examined for eligibility were unable to walk 150 m, and only 4% of eligible patients could not climb a flight of stairs. The numbers are similar to the percentages reported in [38], where 18% of older adults with frailty could not walk one bus-stop distance (about 50 m) and climb a flight of stairs. Another reason for choosing physical stressors is that they can be captured in daily activities using wearables. For instance, unintentional walk testing can be utilized to detect walking activity that resembles a clinical walk test [39], whereas stair-climbing can be detected in barometric pressure that depends on body elevation [30].

The chosen submaximal tests differ considerably according to induced physical exertion. That is, patients were asked to ascend 12 stairs during stair-climbing and walk 6 meters during the timed up and go test which was a feasible task in most patients. On the other hand, the ability to perform on 6-minute walk test largely depends on the patient's functional capacity. As a consequence, the 6-minute walk test resulted in a wide scale of distances, ranging from 150 to 736 meters. HR response to physical stressors of various intensities is understudied therefore it remains an interesting research direction to be explored [19]. For instance, a stronger association between frailty status and HR response during normal walking was found compared to rapid walking [19]. This finding may suggest an additional value of submaximal testing for frailty assessment. In addition, submaximal testing showed excellent reproducibility in terms of HR response at various physical exertions [40].

In this study, the effect of inpatient cardiac rehabilitation was reflected only by veloergometry. Physical inactivity due to unavoidable bed rest during early recovery from surgery is the most plausible explanation for insufficient HR response to submaximal tests [41], [42]. Physical inactivity is associated with autonomic imbalance [41], while cardiac atrophy can already be detected after only two weeks of bed rest [43]. The patients spent 17.0±7.4 days recovering from open-heart surgery with minimal or no physical activity and then were transferred to the rehabilitation hospital. Another important aspect is that patients received beta-blockers that alter HR response through the inhibition of the sympathetic branch of the autonomic nervous system [44]. Despite the inevitability of including patients who use HR-affecting medications, the number of medications was balanced in both groups. Furthermore, 14% of study participants had diabetes mellitus. Cardiac autonomic neuropathy is common in the diabetic population which, in turn, may lead to autonomic imbalance [45].

Post-exercise HR recovery is noteworthy for its established clinical value when assessing the autonomic nervous system [31] and predicting the risk of cardiovascular diseases and death [46]. For this reason, it was recommended to include the assessment of HR recovery in routine clinical practice as a fast and cheap alternative to spiroergometry [47]. In this study, two HR recovery parameters, characterizing fast and slow recovery phases, were investigated. The fast HR decrease occurs immediately after the end of physical activity and is due to an increase in parasympathetic activity, driven by the deactivation of the central cardiovascular control mechanism in the brain and the abolished feedback from muscle mechanoreceptors. Meanwhile, the subsequent slow HR decrease is due to coordinated parasympathetic-sympathetic interaction, mediated by the reduced feedback from muscle metaboreceptors and the adjustments in thermoregulation [48]. This study showed that both fast and slow HR recovery improved in most patients during veloergometry. The tendencies were also well reflected by walking and stair-climbing.

Differently from HR recovery, which has been extensively studied, the accelerating phase of HR response has received much less attention, despite both reflecting the balance of the autonomic nervous system [49]. Increased time to peak HR during walking was observed in frail older adults compared to non-frail [19]. However, the comparison with previous work is complicated since walking duration, which directly affects when the peak HR is achieved, differed among study participants due to the earlier termination of the 6-minute walk test. The changed

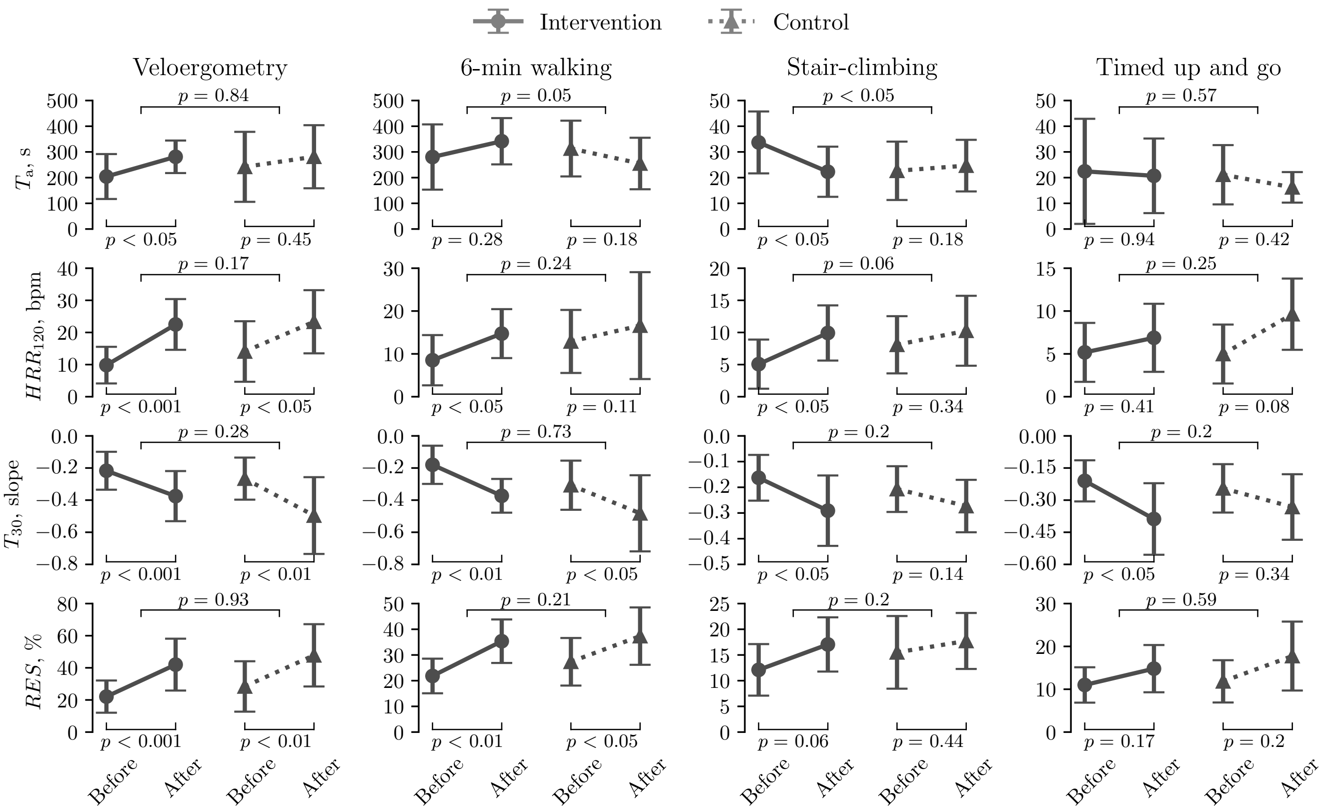


Fig. 6: Effect of the entire exercise training program on HR response parameters in intervention and control groups. $p$-value on the top of each subplot refers to the difference in the change of parameter values before and after the entire exercise training program between the intervention and control groups. $p$-values on the bottom of each subplot refer to the change in parameter values before and after the entire exercise training program within the intervention and control groups.

test duration due to improved physiological reserve explains why $T_a$ increased during veloergometry but decreased during stair-climbing in the intervention group after the entire exercise training program. That is, the patients were able to continue the veloergometry test 55% longer on average, and thus, reach peak HR later, at end of the training program. Conversely, stair-climbing lasted shorter since patients were able to climb the stairs faster. Accordingly, change in physiological reserve and ability to sustain physical exertion should be accounted for when considering HR acceleration as a measure for assessing the effectiveness of exercise training programs.

HR reserve is often used to assess chronotropic incompetence in patients with heart failure which was diagnosed in all participants of the present study. When estimated at peak exercise, HR reserve below 80% indicates impaired chronotropic response [50]. Despite that the threshold for patients on beta-blockers is reduced to 62% [51], none of the patients reached it at the beginning of the exercise training program. However, 27% of patients were able to exceed this threshold after completing the program. Even though submaximal testing does not allow to achieve peak HR, HR reserve reflected well the tendencies observed while performing veloergometry.

Baseline HR parameters, namely, resting HR, variability, and complexity may have prognostic value when assessing autonomic function in frail patients [14]. Nevertheless, baseline parameters were found to be less powerful when differentiating between frail and non-frail older adults compared to the difference between maximal and resting HR [14]. Similarly, our study showed that resting HR was the least associated with frailty status. Differently from [16], where HR complexity, as indicated by sample entropy, did not differ among frail, pre-frail, and non-frail, the complexity was associated with frailty status in our study. When assessing baseline HR, the effect of HR-altering medication should also be taken into account. A study on the effectiveness of cardiac rehabilitation showed that baseline HR parameters, such as variability, were less responsive in those who were taking beta-blockers [52]. Taking this into consideration, it can be assumed that HR response to exercise may be more beneficial for assessing autonomic function in patients on beta-blockers than baseline HR.

HR is typically obtained from an ECG acquired through electrodes therefore older frail adults may be less motivated to use the device for extended periods of time. While a chest strap does not cause notable discomfort when it is used for short periods, biooptical wrist-worn devices might be considered for monitoring in activities of daily living, obviously, at the expense of reduced estimation accuracy. Substantial errors were found when estimating HR variability parameters in elderly vascular patients using a reflective wrist photoplethysmogram device [53]. Similarly, in our previous study that included healthy participants, we reported an estimation error of $\leq$19.2% for $T_{30}$ and $\leq$20.7% for HR decay after 1 min [30]. Therefore, further studies are needed to explore whether it is feasible to estimate HR response using biooptical sensors.

### A. Limitations

A study limitation is that a considerable amount of data was unavailable due to different reasons. Wearable devices are inseparable from user-related, hardware, software, and network issues [54], therefore data loss should not be overlooked. In this study, the patients performed clinical tests over a few hours, thus the devices were turned on at the beginning of the first test and turned off at the end of the last test. We were able to identify several reasons that resulted in a termination of signal acquisition: Bluetooth interrupted when a patient walked away from the smartphone when a time stamp of the test was entered by a healthcare specialist; a patient unintentionally interacted with the device or smartphone; the device discharged before the session has ended; internet was unstable due to maintenance; signal transfer stopped due to the server updates; the device sometimes stopped sending signals to the smartphone during prolonged sessions. In addition to technical issues, one-third of patients did not show up for the final assessment after returning home.

## V. Conclusions

The present study shows that the parameters characterizing accelerating and decelerating phases of heart rate response to physical stressors are associated with frailty status. Submaximal tests, namely, walking, stair-climbing, and timed up and go, show moderate to high correlation with veloergometry for heart rate recovery and heart rate reserve parameters. Out of submaximal tests, the heart rate response parameter trends over the entire exercise training program were best followed during walking. Therefore, HR response to walking should be considered for assessing the effectiveness of home-based exercise training programs in frail patients after open-heart surgery. Despite the potential of submaximal testing for repeated monitoring, further research is needed to explore the feasibility to assess heart rate response to automatically detected physical stressors.

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