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Abstract

The purpose of this study was to investigate the correlation between the seismocardiogram and cardiorespiratory fitness. Cardiorespiratory fitness can be estimated as VO_2max using non-exercise algorithms, but the results can be inaccurate. Healthy subjects were recruited for this study. Seismocardiogram and electrocardiogram were recorded at rest. VO_2max was measured during a maximal effort cycle ergometer test. Amplitudes and timing intervals were extracted from the seismocardiogram and used in combination with demographic data in a non-exercise prediction model for VO_2max. 26 subjects were included, 17 females. Mean age: 38.3 ± 9.1 years. The amplitude following the aortic valve closure derived from the seismocardiogram had a significant correlation of 0.80 ($p < 0.001$) to VO_2max. This feature combined with age, sex and BMI in the prediction model, yields a correlation to VO_2max of 0.90 ($p < 0.001$, 95 % CI: 0.83–0.94) and a standard error of the estimate of 3.21 $mL \cdot kg^{-1} \cdot min^{-1}$. The seismocardiogram carries information about the cardiorespiratory fitness. When comparing to other non-exercise models the proposed model performs better, even after cross validation. The model is limited when tracking changes in VO_2max. The method could be used in the clinic for a more accurate estimation of VO_2max compared to current non-exercise methods.

Key Words:

Cardiovascular Fitness, Maximal Oxygen Consumption, prediction of aerobic capacity

Introduction

The importance of cardiorespiratory fitness (CFR) is underlined by the Scientific Statement from the American Heart Association (AHA), in 2016, which concludes that low CRF is related to a high risk of cardiovascular disease. Further, low CRF is associated with all-cause mortality [1].

The recommendations from the AHA Scientific Statement includes, that during their annual healthcare examination, all adults should have CRF estimated and ideally measured using a cardiopulmonary exercise test (CPX) [1]. For patients with chronic disease, CRF should be measured regularly with a peak or symptom-limited CPX [1].

One way of expressing CRF is by maximal oxygen consumption (VO_2max) [2]. VO_2max is most accurately obtained by measuring the O_2 content in samples of expiration gas during a maximal-effort treadmill or cycle ergometer test [3]. Directly measuring VO_2max during such a test is the most objective approach for assessment of CRF. Maximal effort test on cycle ergometer or treadmill is accurate for determining the VO_2max level, but it involves performing incremental exercise to exhaustion. The test can be uncomfortable and impractical, especially for elderly and people with, for instance, obesity or orthopedic conditions [4, 5]. Furthermore, it requires special and expensive equipment and specially trained personnel to perform the test. Alternatively, VO_2max can be estimated with submaximal work tests or even with non-exercise algorithms [1, 6]. The Ekblom Bak Cycle Ergometer Test is an example of a sub-maximal exercise test, which, besides age and sex also relies on measurement of changes in heart rate and work load [5]. The revised Ekblom Bak ergometer test demonstrates a sum of squared error (SEE) of 0.30 $L \cdot min^{-1}$ with an adjusted R^2 of 0.90 in an external cross validation group of 115 subjects (60 males) [5]. The use of non-exercise algorithms is attractive in some cases due to the aforementioned limitations with the exercise test, but the disadvantage is lower accuracy, especially when using the algorithms for groups that are different from those used to develop the models [7, 8]. The importance of accurate estimation of CRF is underlined by the considerable improvement in survival (10–25 %) with only a small change in CRF of 1 metabolic equivalent (MET), corresponding to approximately 3.5 mL · kg^{-1} · min^{-1}[1], a change that is achievable by most people.

One way to improve the accuracy of non-exercise regression models may be to add resting intrinsic cardiac performance measures into the equation. For example, based on left ventricular (LV) isovolumetric contraction time (IVCT), LV isovolumetric relaxation time (IVRT) and the LV ejection time (LVET), the Tei Index can be derived as the sum of IVCT and IVRT divided by LVET [9]. Cardiac timing intervals themselves as well as index of function is known to change as a result of aerobic fitness [9, 10]. In 2010 Andersen and colleagues demonstrated that both running and football training change the functional and structural composition of the heart within 16 weeks [10]. Andersen et al. examined the systolic as well as the diastolic parts of the heart cycle. They conclude that left ventricular contractility and diastolic function improved as a result of training [10].

Cardiac timing intervals and dimensions can be obtained from the echocardiogram and correlation between VO_2max and echocardiogram has been shown [10]. However, echocardiography is time consuming and operator dependent. Because of this we propose the seismocardiogram (SCG) is as modality for estimation of cardiac function. The SCG is a recording of the cardiac vibrations on the chest wall caused by the beating heart [11, 12]. The accelerations produced when the heart contracts and relaxes are recorded with an accelerometer usually positioned on the xiphoid process [13]. The first description of the SCG was by Mounsey in 1956 and the technique has since been investigated in different settings, al- though SCG is not used by clinicians today [11, 13]. The fiducial points in the SCG signal are correlated to events such as heart valve opening and closings in the cardiac cycle [14]. Time intervals have previously been correlated with those obtained by echocardiography in both healthy subjects and heart failure patients [12, 15–17]. Thus, based on the SCG signal cardiac timing intervals can be derived [16, 17].

SCG have previously been used in studies involving exercise testing. In 1992 Salerno et al. and Wilson et al. used SCG in combination with electrocardiography (ECG), demographic data and angina status in a linear model for detection of coronary artery disease [18, 19]. In this study, addition of SCG significantly improved the sensitivity of the model when compared to using only exercise (ECG), demographic data and angina status [19]. Libonati and coworkers found that increased exercise capacity, defined as time to exhaustion on a treadmill test, correlated with a lower Tei Index, derived from the SCG [9, 20].

Previous studies have also examined how SCG can be used in exercise testing for patients with heart failure [21, 22]. Inan and colleagues used features from the SCG in a graph similarity score and was able to successfully differentiate between decompensated and compensated heart failure patients [22] while Shandi and colleagues documents that simultaneous SCG and ECG recording can detect changes in the pre-ejection period (PEP) and thus assess cardio- pulmonary exercise testing variables for heart failure patients [21].

We hypothesize, that timing and amplitude parameters, derived from the SCG are correlated with the mechanical contraction and relaxation of the heart, and that these parameters correlate to VO_2max.

Therefor we investigate the correlation between VO_2max and the timing and amplitudes of SCG fiducial points [14]. Besides investigating these parameters by them self, we also include the parameters in a linear model together with demographic data for estimation of VO_2max.

Materials and Methods

The overall purpose of the study was to investigate if there is a correlation between VO_2max and SCG and determine if VO_2max can be estimated using a model including the SCG. VO_2max was measured using a Vyntus® CPX metabolic cart (Jaeger, Carefusion, Hoechberg, Germany) and a maximum effort protocol on a stationary bicycle ergometer (Ergomedic Peak Bike 894, Monark, Vansbro Sweden).

Subjects

Female subjects (n = 17) were recruited from a local fitness center in the city of Aalborg, Denmark. The female subjects had signed up for an eight-week training course in the center and were asked to participate as volunteers in the study. Male subjects (n = 9) were recruited in the Cardiotechnology Reasearch Group Department of Aalborg University. The male subjects did not participate in a training program.

Inclusion criteria for participating was: Healthy male or female in the age 18–80 years. Exclusion criteria were pregnancy, drug ad- diction defined as the use of cannabis, opioids or other drugs, previous neurologic, musculoskeletal or mental illnesses and lack of ability to cooperate. Further exclusion criteria were known cardio- vascular disease including subjects receiving cardiovascular related medications such as medication for hypertension and hyperlipidemia and inability to complete the eight-week training course.

Ethical considerations

The study protocol was approved by the local scientific ethics committee of Northern Jutland. Subjects signed a written informed consent form before participating in the study. All methods were performed in accordance with relevant guidelines and regulations [23].

Study design

The longitudinal study was designed to investigate the changes of the contractility of the heart (assessed by SCG) following training for an eight-week period. During the eight weeks the female sub- jects participated in two training sessions per week for an hour duration per session. The training was a combination of cardiorespiratory training and weight-lifting training. In addition, the female subjects also received advice for dietary change.

The subjects underwent the recording session described below. For the females, the recording session was identical before and after the 8 weeks training. The male subjects only participated in the pre-training recording session.

Demographic data (age, weight, height and sex) were recorded.

Three-lead ECG was recorded with four electrodes, placed on the left and right shoulders and on the left and right iliac crests. An ultra-sensitive accelerometer (Silicon Designs 1521-002) was placed on the xiphoid process with double adhesive tape for recording of the cardiac vibrations (the SCG signal). The accelerometer has a resolution of ± 2 g, low noise at 7 μg / √Hz and frequency response

0–300 Hz (minimum, 3dB). The accelerometer was placed in a 3D-printed ABS plastic housing measuring 19 mm in width, 21 mm in length and 11 mm in height and weighed 5 grams including the electronic components. Another 1521-002 accelerometer was placed in intercostal space 4 (IC4) near the left border of the sternum. ECG and accelerometer placement is visualized in Fig 1.

The second accelerometer was used as a proxy for heart sound, used for segmentation of individual heart beats. Resting ECG and SCG were recorded for 5 minutes with the subjects in supine position using an iWorx IX-228/s (IWORX, Dover, New Hampshire) acquisition unit sampling at 5000 Hz, connected to a PC. LabScribe recording software was used (version 3. Dover, New Hampshire). Before each recording session the flow, gas and ambient sensor of the Vyntus CPX was calibrated, according to manufacturer recommendations. The system continuously measures minute ventilation using a mass flow meter together with measurement of fractions of expired CO2 and O2.

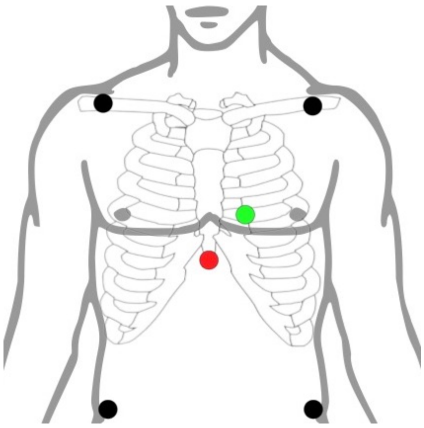

Fig. 1 Illustration of electrode placement for electrocardiogram (black circles), accelerometer on xiphoid process for seismocardio- grapic recording (red circle) and accelerometer for heart sound recording in intercostal space 4 (green circle).

The subject moved from the examination bed to a cycle ergometer (Ergomedic Peak Bike 894, Monark, Vansbre, Sweden). The height of the seat was adjusted to each subject, ensuring near full extension of the legs. Subjects were asked to warm up for four minutes before the VO_2max protocol started. The warmup period consisted of 2 minutes pedaling with 80 W load followed by 2 minutes with 104 W load. During warm up, the mask used with the Vyntus CPX metabolic cart to measure VO_2max was fitted around the subject's mouth and nose ensuring an air-tight seal. When the subject was accustomed to the mask, the flow and gas sensor of the Vyntus CPX system was attached to the mask. Following the four minutes warm up, the subjects were allowed to relax for 2 minutes before the VO_2max protocol started.

The VO_2max protocol for the females consisted of 1-minute intervals starting at 104 W load, with increase in load of 24 W between intervals. Subjects were asked to keep a consistent cadence at 80 revolutions per minute (RPM) to keep the load consistent. RPM was shown on a display on the bike and the subject was verbally informed if RPM dropped or rose to help the subject keep a consistent cadence.

The same protocol was used for the males, with the exception that after 2 minutes the load was increased to 160 W. After the third minute the load was increased with 40 W between intervals.

The protocol continued until the subject was unable to maintain the 80 RPM due to exhaustion. For both males and females respiratory exchange rate (RER) > 1.15 was used as indication that maximal effort was reached.

Signal Processing

ECG and SCG were recorded with the iWorx system and were ex- ported and processed in MATLAB (2018a. The MathWorks, Inc.). Using the algorithm described by Jensen et al. [24]. the signals were divided into single heart beats in order to calculate the median beats. This approach uses the ECG as reference and segments the signal into beats based on the R-peak of the ECG. As the alignment to the ECG R-peak can result in a smoothed second heart sound (S2) with inaccurate fiducial points around S2, due to variation in the systolic to diastolic time interval, the individual beats were aligned to the S2 as follows: The acceleration signal recorded from IC4 was forward-backward filtered with a Butterworth bandpass filter of 1st order with cutoff frequencies of 50 and 500 Hz to obtain a proxy for heart sound. Using this filtered signal, the individual beats were aligned to the location of the peak envelope of the S2-sound as de- scribed in [14].

Data from the Vyntus CPX were exported as mean values in intervals of ten seconds. The highest VO2 value before exhaustion was used as a subject's VO_2max.

Feature selection in seismocardiographic signal

A standard set of SCG fiducial points was defined in previous work [14]. In the present work the amplitudes of selected fiducial points were identified from the SCG and correlated with the VO_2max, to determine which fiducial point had the highest correlation with VO_2max. Some fiducial points in the SCG correlate with certain cardiac events, such as valves opening and closing [14]. Six fiducial points where selected for investigation in this study, see Fig 2.

The Es point is correlated with the mitral valve closure (MC). Following Es is first a downwards deflection (F_s), followed by a large upwards deflection (G_s). This upwards deflection is associated with the aortic valve opening (AO), hence the annotation of the two points AO_{min} and AO_{max}.

In the diastolic complex (starting around 320 ms after the ECG R-peak in Fig. 2) the fiducial point B_d is associated with the aortic valve closure (AC). The following two fiducial points (C_d and D_d [14]) are here labeled AC_{min} and AC_{max}. Amplitudes are measured in acceleration (g).

Based on those peaks, the following subset of amplitudes were derived:

- $AO_{pp} = AO_{max} - AO_{min}$
- $AC_{pp} = AC_{max} - AC_{min}$

Using the same fiducial points, the following cardiac timing intervals were computed: left ventricular isovolumetric contraction time (IVCT) from E_s to AO_{max}, left ventricular ejection time (LVET) from AO_{max} to B_d and mechanical Systolic Time from E_s to B_d.

These three cardiac timing intervals were all normalized with respect to the RR interval recorded with the ECG.

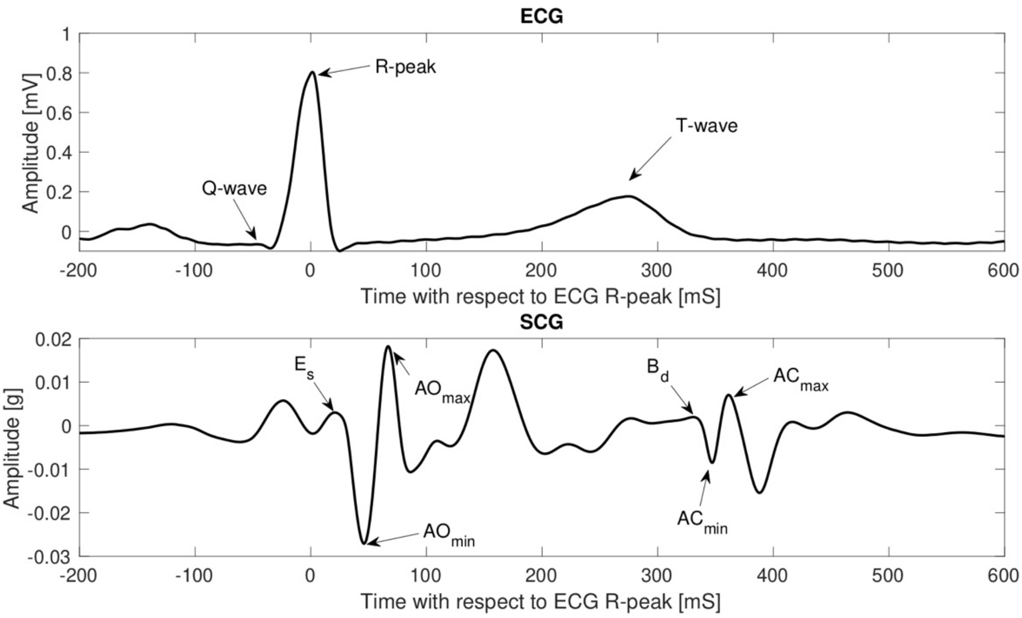

Fig. 2 Representative filtered signals from a subject. Signals are means of simultaneously recorded ECG and SCG recordings. Arrows on the SCG signal indicate the fiducial points used in this article:

E_s: Mitral Valve Closure. AO_{min} and AO_{max}: Aortic Valve Opening minimum and maximum point. B_d: Aortic Valve Closure beginning. AC_{min} and AC_{max}: Aortic Valve Closure minimum and maximum point.

Model deisng

With demographic data (Table 1) and features from the SCG and ECG (Table 2 for the list of features), a model for estimation of VO_2max was constructed. The model was fitted to the data with a built-in function of MATLAB (stepwiselm), which uses forwards and backwards stepwise regression. At each step an independent variable is included (step up) or removed (step down) from the model, based on the statistical significance of the change in the sum of squared errors. For addition of a variable to the model the criterion was $p < 0.05$, for removal $p > 0.10$ was used. This process is repeated until no more parameters can be added or removed. The function is constricted to only include an intercept term and linear terms for the independent variables.

In addition, a linear regression model based on the demographic data only (age, sex and BMI) was created to determine the improvement of the model when parameter(s) from the SCG were added.

The linear models were developed using all the data from both before and after the 8-week training course and includes all data from both the females and males. Following the initial design, the model was validated using both k-fold and leave-one-subject-out (LOO) cross validation to ensure that the model was not overfitted to the data. The k-fold cross validation was performed with 20 iterations and 10-fold validation, calculating a mean correlation for the 20 iterations.

Four known non-exercise models from the literature [7, 25–28] were used with the data obtained from this present study to estimate VO_2max. These models only include demographic variables, allowing for VO_2max estimation with the data obtain in this study. This was done in order to compare the non-exercise models developed in this study with other models. This also allowed for calculation of the correlation and standard error between estimated and measured VO_2max for these models.

Statistical analysis

For the model developed in this study and the four models used for comparison, the following statistics were calculated:

- Pearson's correlation coefficient: R
- Standard error of the estimate: $SEE = \sqrt{\sum(Y - Y')^2/n - 2}$
- Percentage error of the SEE: $\%SEE = SEE/(\sum Y'/n) \cdot 100$

With Y and Y' defining the measured and estimated VO_2max values respectively.

A paired t-test was used to test for significance of the differences in the data obtained before and after the eight-week training period. A Bland-Altman plot was constructed for the final model to visually inspect trends in the estimated compared to the measured VO_2max.

Results

A total of 32 subjects were recruited for the study, 23 of which were females. 17 of the female subjects participated in both the pre and post training recording session, thus 6 subjects participated in only one of the sessions and were not included in the data-analysis. Ten male subjects were recruited to participate in the pre-training session. One male subject was excluded due to diagnosed cardiac hypertrophy.

Table 1. Demographic and seismocardiographic data (mean ± SD).

Features	Female pre-training (n = 17)	Female post-training (n = 17)	Males (n = 9)
Age [years]	36.7 ± 5.4	36.9 ± 5.5	41.2 ± 13.7
Height [cm]	167.9 ± 5.0	167.9 ± 5.0	184.9 ± 4.1 **
Mass [kg]	78.0 ± 16.1	74.2 ± 16.3 *	83.9 ± 12.7
VO_2max [$mL \cdot kg^{-1} \cdot min^{-1}$]	28.7 ± 4.5	31.2 ± 6.5 *	40.1 ± 8.4 **
AO_{pp} [mg]	26.6 ± 17.6	26.3 ± 14.3	36.4 ± 29.3
AC_{pp} [mg]	16.2 ± 6.9	19.8 ± 9.0	28.3 ± 17.8 **
IVCT [ms]	48.4 ± 13.0	48.4 ± 13.9	38.5 ± 4.8 **
LVET [ms]	294.5 ± 21.7	299.2 ± 16.0	287.4 ± 21.7
Mechanical Systolic Time [ms]	342.9 ± 19.2	347.6 ± 13.8	325.9 ± 22.8
RR-interval [ms]	915.1 ± 168.2	1064.7 ± 138.7 *	907.9 ± 94.7

* = significant ($p < 0.05$) difference between pre and post-training

** = significant ($p < 0.05$) difference between female and male pre-training

Demographic data for the subjects is presented in Table 1. For the females, both pre and post training date are presented. The VO_2max value was significantly higher ($p = 0.0024$) for the females after the training period as compared with the initial recording session. VO_2max values for the males were significantly higher as com- pared with the females pre-training recording. There was a significant difference in weight for the female group between pre and post training.

Table II – Pearson's Correlation Coefficient and p-values between demographic and seismocardiographic variables and VO_2max.

Variable	r	p-value
Age	-0.18	0.23
Sex	0.56	< 0.001
Height	0.51	< 0.001
Mass	-0.38	< 0.01
BMI	-0.61	< 0.001
Mean AO peak to peak amplitude (AO_{pp})	0.47	< 0.001
Mean AC Peak to peak amplitude (AC_{pp})	0.80	< 0.001
Mean IVCT	-0.40	< 0.01
Mean LVET	-0.26	0.079
Mean Mechanical Systolic Time	-0.53	< 0.001
Mean RR-Interval (Resting Heart Rate)	0.01	0.94

AO = aortic opening, AC = aortic closure, IVCT = isovolumetric contraction time, LVET = left ventricle ejection time.

The correlations between the demographic parameters: weight, height, BMI, age, sex and the measured VO_2max values are listed in Table 2 which also includes correlation between the features extracted from both the SCG and ECG and VO_2max.

Table III – Statistics for the two models developed in this study and the four non-exercise models for comparison. For model 1 and 2 statistics from the leave one subject out cross validations are presented in parentheses.

Reference	R	R^2	SEE [$mL \cdot kg^{-1} \cdot min^{-1}$]	SEE percentage [%]
Model 1	0.83 (0.79)	0.69 (0.62)	4.03 (4.45)	10.6 (11.7)
Model 2	0.90 (0.87)	0.81 (0.75)	3.18 (3.62)	7.53 (8.55)
Jones et al.	0.82	0.67	5.08	16.1

FairBarn et al.	0.83	0.68	8.15	25.8
Cooper and Storer.	0.83	0.69	10.6	33.3
Davis et al.	0.81	0.66	6.23	19.7

$\%SEE = SEE/\left(\sum Y'/n\right) \cdot 100$

VO_2max estimation model results

Of the five features from the SCG, the AC_{pp} has the highest correlation to VO_2max of 0.80 (95 % CI: 0.67–0.88). The final linear model also includes this parameter, as the only feature from the SCG, see model 2.

$$VO_2\text{max} = 62.1 - 0.749 \cdot BMI + 9.94 \cdot SEX - 0.332 \cdot AGE \qquad (1)$$

$$VO_2\text{max} = 44.1 - 0.465 \cdot BMI + 6.79 \cdot SEX - 0.187 \cdot AGE + 0.292 \cdot AC_{pp} \qquad (2)$$

The correlation was 0.83 (95 % CI: 0.72–0.90, k-fold cross validation: 0.79, LOO cross validation: 0.79) and 0.90 (95 % CI: 0.83–0.94, k-fold cross validation: 0.87, LOO cross validation: 0.87) for model 1 and 2, respectively. Both models were significant with $p < 0.001$. Model 2 was used for estimation of VO_2max in Fig. 3. Table 3 lists the performance characteristics of the two models from this study together with the four models from prior studies.

The measured and estimated VO_2max with model 2 are visualized for both the pre and post training course sessions in Fig. 3 with the Bland Altman plot (mean difference: $2.04 \cdot 10^{-14}$ mL $\cdot$ kg^{-1} $\cdot$ min^{-1} standard deviation: ± 6.2 mL $\cdot$ kg^{-1} $\cdot$ min^{-1}.

There is one outlier in the dataset with a difference between measured and estimated VO_2max of more than 10 mL · kg^{-1} · min^{-1}, Fig. 3. Removing this subject results in a correlation between measured and estimated VO_2max with model 2 of 0.92 (95 % CI: 0.87–0.95), k-fold cross validation: 0.90 and LOO cross validation: 0.90. The SEE and %SEE for the LOO cross validation was reduced to 3.07 mL · kg^{-1} · min^{-1} and 8.16 %, respectively.

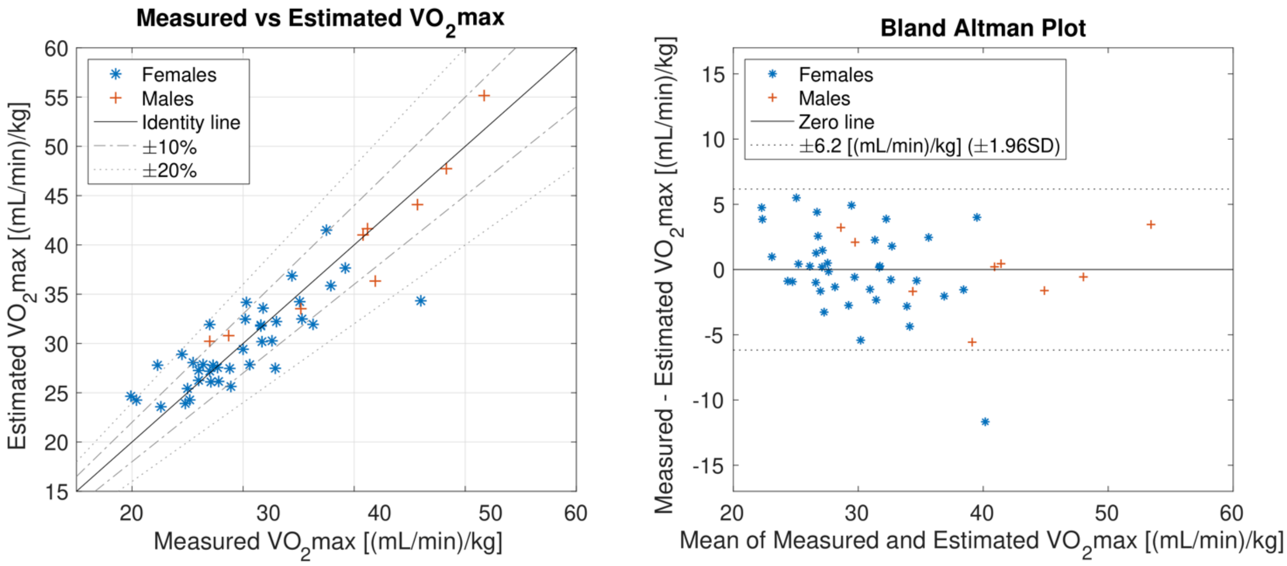

Fig. 3 Left: Measured and estimated VO_2max with the use of model 2. Right: Bland Altman plot of measured and estimated VO_2max with model 2. For the females, measurements from both pre and post training course are included.

Estimation of changes in VO_2max

The measured and estimated (with model 2) changes in VO_2max for the females during the eight-week training course are visualized in Fig. 4. The correlation between the measured and estimated changes in VO_2max is –0.05 ($p = 0.86$) and 0.22 ($p = 0.39$) with model 1 and 2 respectively. Mean estimated change of VO_2max is 0.96 mL · kg^{-1} · min^{-1} and 1.65 mL · kg^{-1} · min^{-1} by model 1 and model 2 respectively, compared to the mean measured change of 2.55 mL · kg^{-1} · min^{-1}.

Model 1 estimated a correct positive change in VO_2max for 11 (64.7 %) subjects compared to 10 (58.8 %) for model 2. Model 1 estimated false negative change in VO_2max for 2 (11.8 %) subjects compared to 3 (17.6 %) for model 2. Both model 1 and model 2 estimated false positive change for 3 subjects (17.6 %). Both model 1 and model 2 estimated a positive change for one subject (5.9 %), when there was no change in measured VO_2max.

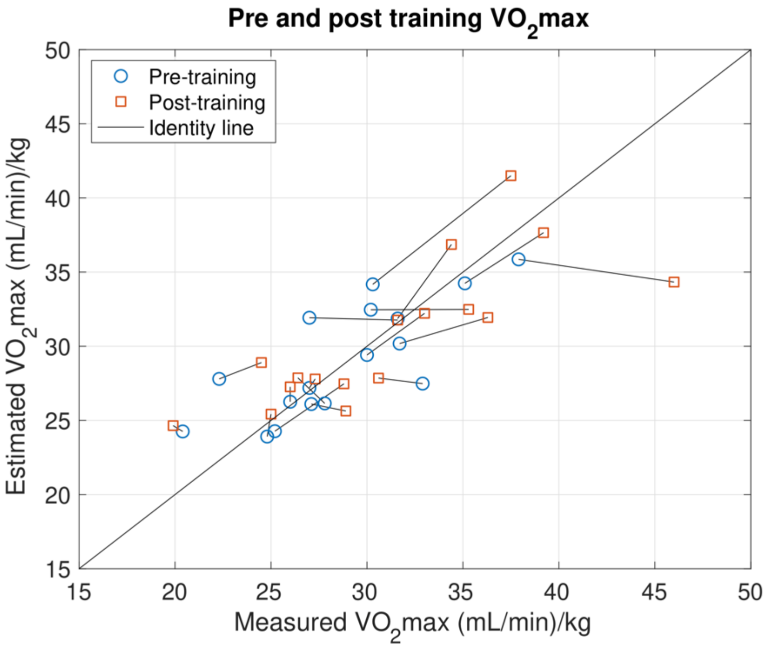

Fig. 4 Measured and estimated VO_2max pre and post training. Only data from the female subjects is used in the figure. Pre and post data for individual subjects are connected with a line.

Discussion

In this paper we present a novel, accurate, easy to use, non-exercise method for estimation of VO_2max using the SCG. We found that some features derived from the SCG signal are highly correlated to VO_2max. The part of the SCG signal representing the aortic valve closure is, in itself, associated with VO2max with a correlation of 0.80 (95 % CI: 0.67–0.88). A regression model based on the SCG feature with the inclusion of sex, age and BMI increases the correlation with VO_2max to 0.90 (95 % CI: 0.83–0.94) with a SEE of 3.2 mL · kg^{-1} · min^{-1}. This model improves the estimation of VO_2max compared to commonly used models that only includes parameters such as age, sex and BMI, as demonstrated, see Table 3. The method could be used in a clinical setting to accurately and easily determine a patient's VO_2max, without needing to perform a cycling or running test.

Link between SCG and cardiorespiratory fitness

The amplitude selected from the SCG as an independent variable in the model is located in the diastolic complex. Aortic valve closure (AC) is a very distinct feature of the SCG, making it easy to recognize. Patrick Mounsey who first described the SCG in detail pro- posed that the deflections could be caused by the heart moving towards its apex, as a consequence of the aortic valve closure [11].

Previous studies have shown that for elite athletes the ventricular relaxation is faster compared to normal healthy subjects [29, 30]. According to Gledhill and colleagues this could be assisted by the negative pressure created as the myocardium recoils from end systolic contraction [29]. The faster pressure drop in the LV causes a larger pressure difference between the LV and the ascending aorta, creating a larger amplitude in the SCG as the aortic valve closes. Libonati and colleagues did not find a significant difference in the timing of IVCT, derived from SCG, but documents that there was a non-significant trend towards shorter LV diastolic time intervals for the group who endured the test for more than 15 minutes [20].

The Frank-Starling law dictates that increased diastolic filling contributes to an increased stroke volume as well as cardiac output and consequently VO_2max. This underlines the importance of the diastolic part of the heart cycle that is also investigated in this pre- sent study [10, 29, 31, 32].

Monitoring of changes in VO2max using SCG

Model 2 proposed in this work does not estimate the change in VO_2max very well. The correlation of measured and estimated change in VO_2max is 0.22 and non-significant. The error between the estimated and measured change in VO_2max could be due to the relatively short period of time between the two recording sessions. The increase of measured VO_2max without a model response could be due to an increase in blood volume due to the exercise training [33]. Convertino and colleagues found the change in blood volume to occur within 8 days of consecutive exercise training with two hours of training each day. The increase in blood volume leads to a more efficient use of the Frank-Starling mechanism, a higher stroke volume, higher oxygen delivery and hence higher VO_2max [29, 32, 34]. It is likely that a similar change would be present in this group of subjects and that the myocardial adaptation and remodulation occurs later if training is maintained. Andersen and colleagues showed that within 16 weeks with either running or football training, the structure and function of the heart, measured by echocardiography, can change [10]. Thus, twice as long a training period compared to the present study.

It should also be noted that changes observed in measured VO_2max are quite small overall. The average change in VO_2max is 2.6 $mL \cdot kg^{-1} \cdot min^{-1}$ for the females. The reliability of the Vyntus CPX was previously demonstrated in a small study, showing the day-to-day difference in VO_2max 1.8 ± 2.2 % [35], which is almost 70 % of the measured change observed in this study.

Limitations

One limitation of this study is the low number of subjects. Inclusion of more subjects with a wider range of VO_2max values would allow us to further examine our hypothesis that the amplitude of the aortic event in the SCG signal is associated with respiratory fitness. The low number of subjects does in turn also limit the linear regression model, making it specific for the subject group. More data would contribute to making a more general model for estimation of VO_2max.

Another limitation is the inclusion of repeated measurements from only the females and not the male. A matched study population of sex, age and BMI would ensure that not one specific part of the population is favorized in the linear regression.

Perspective

The importance of CRF according to the AHA Scientific Statement and AHA's recommendations of annual CRF testing and regular testing of adults with a chronic disease indicates the relevance of the non-exercise VO_2max test. A further development and evaluation of the test is therefore desired, including studies with subjects at different fitness levels and with various body compositions in order to investigate how the SCG and the models change in response to different fitness / body composition parameters. The SCG feature AC_{pp} could possibly also be used in an exercise-based prediction model for VO_2max in future studies. In our study we found that inclusion of resting heart rate did not improve the prediction model. However, inclusion of recovery heart rate following exercise might improve the model [36, 37].

Conclusion

Features in the SCG signal are correlated with VO_2max. This paper proposes a novel method for estimation of VO_2max using one of these features. This non-exercise method is simple to use and could be used in a clinical setting for CRF estimation.

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Conflicts of Interest

KS, SES, JJS and PS are shareholders in VentriJect ApS. The company uses a method similar to the one described in this article in a commercial product. The study was not financially supported by VentriJect ApS.

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