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**Validity and reliability of seismocardiography for the estimation of cardiorespiratory fitness**

Mikkel T. Hansen, MSc, Rue Rømer, MSc, Amalie Højgaard, BM, Karina Husted, PhD, Kasper Sørensen, PhD, Samuel E. Schmidt, PhD, AP, Flemming Dela, MD, Jørn W. Helge, PhD

From the *Xlab, Center for Healthy Aging, Department of Biomedical Sciences, Faculty of Health and Medical Sciences, University of Copenhagen, Copenhagen, Denmark, †Department of Health Science and Technology, Aalborg University, Aalborg, Denmark, ‡VentriJect ApS, Hellerup, Denmark, and ††Department of Geriatrics, Bispebjerg University Hospital, Copenhagen, Denmark.

**BACKGROUND** Low cardiorespiratory fitness (ie, peak oxygen consumption [VO2peak]) is associated with cardiovascular disease and all-cause mortality and is recognized as an important clinical tool in the assessment of patients. Cardiopulmonary exercise test (CPET) is the gold standard procedure for determination of VO2peak but has methodological challenges as it is time-consuming and requires specialized equipment and trained professionals. Seismofit is a chest-mounted device for estimating VO2peak at rest using seismocardiography.

**OBJECTIVE** The purpose of this study was to investigate the validity and reliability of Seismofit VO2peak estimation in a healthy population.

**METHODS** On 3 separate days, 20 participants (10 women) underwent estimations of VO2peak with Seismofit (×2) and Polar Fitness Test (PFT) in randomized order and performed a graded CPET on a cycle ergometer with continuous pulmonary gas exchange measurements.

**RESULTS** Seismofit VO2peak showed a significant bias of −3.1 ± 2.4 mL·min⁻¹·kg⁻¹ (mean ± 95% confidence interval) and 95% limits of agreement (LoA) of ±10.8 mL·min⁻¹·kg⁻¹ compared to CPET. The mean absolute percentage error (MAPE) was 12.0%. Seismofit VO2peak had a coefficient of variation of 4.5% ± 1.3% and an intraclass correlation coefficient of 0.95 between test days and a bias of 0.0 ± 0.4 mL·min⁻¹·kg⁻¹ with 95% LoA of ±1.6 mL·min⁻¹·kg⁻¹ in test–retest. In addition, Seismofit showed a 2.4 mL·min⁻¹·kg⁻¹ smaller difference in 95% LoA than PFT compared to CPET.

**CONCLUSION** The Seismofit is highly reliable in its estimation of VO2peak. However, based on the measurement error and MAPE >10%, the Seismofit VO2peak estimation model needs further improvement to be considered for use in clinical settings.

**KEYWORDS** Seismocardiography; VO2max estimation; Nonexercise VO2peak equation; Cardiorespiratory fitness test; Method agreement

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**Introduction**

Cardiorespiratory fitness is a powerful independent predictor of cardiovascular disease (CVD) and all-cause mortality.1–4 Measurement of peak oxygen consumption (VO2peak) during a graded cardiopulmonary exercise test (CPET) is considered the gold standard method for the determination of cardiorespiratory fitness.1,5 Routine assessment of VO2peak in the clinical setting is recommended by the American Heart Association (AHA)1 because it significantly improves CVD risk classification compared to traditional CVD risk models.6,7 Furthermore, even a small increment in VO2peak is found to be associated with reduced mortality risk8,9 and reduced risk of future CVD readmission in cardiac patients.10 The AHA recommendation has not yet been successfully adopted, as it might not be possible or feasible to perform exercise testing during most patient encounters.11 Nonexercise estimation of VO2peak has been proposed as a pragmatic alternative to CPET.1,11–14 Due to recent advantages in heart rate monitoring technology that allow estimation of VO2peak to be performed in the resting condition, Polar Electro Oy (Kempele, Finland) created the Polar Fitness Test (PFT), which uses age, body weight, height, and self-reported weekly training hours together with resting heart rate and heart rate variability to estimate...
VO₂peak. However, the validity of the PFT is still considered inadequate for application in clinical health care and in sports.15–17 Seismocardiography (SCG) is a technique for noninvasive evaluation of cardiac activity through the measurement of precordial vibrations using an accelerometer.18–20 The complexity of SCG signals has previously been a challenge; however, the new advantages of low-cost lightweight sensors, signal processing, feature extraction, and machine learning methods have made the SCG methodology relevant for clinical application.20 It is widely accepted that maximal cardiac output (ie, maximal heart rate and stroke volume) is the primary factor limiting VO₂peak in the healthy population,21 and this is highly dependent on diastolic function.22 A faster relaxation and increase in diastolic filling would increase cardiac output and thus VO₂peak (ie, the Frank-Starling law). Fiducial points in the resting SCG signal have previously been shown to correlate with characteristic events in the cardiac cycle and provide information on ventricular performance.24 In addition, a high correlation between the diastolic SCG peak-to-peak value (fiducial point C_d to D_d) and the diastolic relaxation parameter e' measured by echocardiography in the resting condition has recently been established.25 Functionally, a faster relaxation would lead to a more rapid drop in left ventricular pressure, thereby creating a greater pressure difference between the left ventricle and ascending aorta, which would result in a larger amplitude of the C_d to D_d fiducial point.26 A VO₂peak estimation model using both diastolic and systolic SCG information at rest has been proposed26 and validated against CPET.27,28 This led to the development of a new wireless sensor device containing an accelerometer with a compatible smartphone app and a cloud-based solution for automated SCG signal processing (Seismofit system).29 The Seismofit is an interesting novel solution and potentially is a clinically applicable alternative to the standard CPET. However, thorough assessment of the validity and reliability of the Seismofit estimation of VO₂peak compared with the CPET is needed to evaluate the applicability of the method. This study aimed to examine the validity and reliability of the Seismofit VO₂peak estimation compared with CPET in a healthy population sample. It was hypothesized that the Seismofit would prove valid and reliable for estimation of VO₂peak, with a mean absolute percentage error (MAPE) ≤10% between methods and a within-method coefficient of variation (CoV) ≤5%.

Methods

Study outline and objectives

Three identical test days separated by at least 48 hours and within 14 days were conducted to assess the validity and reliability of the Seismofit VO₂peak estimation. On each test day, VO₂peak was estimated twice with Seismofit (Seismofit 1 and 2) and once with PFT before being measured directly with the gold standard CPET using indirect calorimetry. CPET was used as a reference method to assess the agreement of Seismofit and PFT and to compare the reliability against the different estimation methods. The repeated Seismofit measurement within each test day was used to assess repeatability. The present study only compares estimated and measured VO₂peak values performed in a clinical setting and is not addressing the algorithms behind the estimation models. Testing was conducted between June 2020 and November 2020. The study conformed to the Helsinki Declaration and was approved by the Science Ethical Committee of the Greater Region of Copenhagen, Denmark (H-19081375). The study was registered as ClinicalTrials.gov Identifier NCT05356871.

Study population

Twenty healthy participants were recruited (10 women, 10 men). A priori recruitment strategy including 4 trained and 4 untrained between the ages of 18 to 39 years, and 6 trained and 6 untrained between the ages of 40 to 75 years with equal distribution between sexes was completed. A detailed description of the recruitment strategy is provided in the Supplementary Materials (Supplemental Table 1). Inclusion criteria were healthy adults between the ages of 18 and 75 years. Exclusion criteria were a history of previous or current CVD, pregnancy, and/or conditions that prevent maximal exercise testing. Before volunteering and signing a written consent form, the participants received oral and written information about the study and its possible risks.

Experimental design

Measurements of anthropometrics and blood pressure together with collection of a resting blood sample were obtained on each test day, and body composition was determined on the first test day (Table 1). A detailed description of the measurements, experimental procedures, and equipment used is given in the Supplemental Material.

Estimation of VO₂peak in resting condition

The Seismofit system was used for recording of the SCG signal and estimation of VO₂peak at supine rest.29 The Seismofit system consists of a small medical device containing a

### KEY FINDINGS

- The reliability of the Seismofit peak oxygen consumption (VO₂peak) estimation was high both within and between test days.
- The Seismofit underestimated VO₂peak compared to the gold standard measurement and the mean absolute percentage error was above the predefined level of 10% for clinical relevance.
- The reliability indicates that the Seismofit is dependable in recording and processing the seismocardiography signal. Thus, it is expected that Seismofit VO₂peak estimation will improve when more data are available for training the algorithm.
3-axis digital output accelerometer, a smartphone app, and a cloud solution for signal processing. The SCG recording was performed with the Seismofit device mounted on the sternum with double adhesive tape 2 cm proximal to the xiphoid process (Supplemental Figure 1). Before estimation, the age, height, weight, and sex of the participant were entered into the app. VO2peak estimation lasted approximately 5 minutes, which included SCG recording, data transfer to the app, and signal processing. Subsequently, the result of the VO2peak estimation was shown in the app. The newest version, at the time of the study, of the VO2peak estimation model was used (SCG Version 4.3), which has previously been described.27 The VO2peak estimation model is reproduced in Equation (1):

\[
\text{VO2 peak estimation} = (-15.108) + (-0.122 \cdot S2 \text{ FrequencySpec}) + (0.371 \cdot S2 \text{ Morphology}) + (0.001 \cdot RR) + (0.294 \cdot S1 \text{ FrequencySpec}) + (0.701 \cdot \text{FIENDS study prediction model}) + (143.4 \cdot \text{amp_Dd}) + (-159.45 \cdot \text{amp_Ks}) + (-0.042 \cdot SYSRV_STD) + (-87.583 \cdot \text{amp_Ls}) + (42.993 \cdot \text{amp_Fs})
\]

\[ (1) \]

Table 1 Measured and estimated values from three separate test days

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Within-subject SD</th>
<th>Within-subject CoV%</th>
<th>ICC</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs.)</td>
<td>47 ± 7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>176 ± 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>73.7 ± 5.1</td>
<td>73.7 ± 5.1</td>
<td>73.8 ± 5.4</td>
<td>0.5</td>
<td>0.6 ± 0.1</td>
<td>1.00</td>
<td>0.837</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>26.1 ± 3.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Systolic BP (mmHg)</td>
<td>132 ± 9</td>
<td>128 ± 7</td>
<td>128 ± 8</td>
<td>5</td>
<td>3 ± 1</td>
<td>0.91</td>
<td>0.063</td>
</tr>
<tr>
<td>Diastolic BP (mmHg)</td>
<td>80 ± 5</td>
<td>77 ± 5*</td>
<td>76 ± 4*</td>
<td>4</td>
<td>5 ± 1</td>
<td>0.85</td>
<td>0.009</td>
</tr>
<tr>
<td>HRrest (beats·min⁻¹)</td>
<td>55 ± 4</td>
<td>54 ± 4</td>
<td>54 ± 4</td>
<td>3</td>
<td>5 ± 2</td>
<td>0.85</td>
<td>0.280</td>
</tr>
<tr>
<td>Haematocrit (%)</td>
<td>9.2 ± 0.4a</td>
<td>8.9 ± 0.4a*</td>
<td>8.9 ± 0.4b*</td>
<td>0.2</td>
<td>2.3 ± 0.7</td>
<td>0.94</td>
<td>0.031</td>
</tr>
<tr>
<td>Haematocrit (%)</td>
<td>45.5 ± 2.0a</td>
<td>44.0 ± 2.0b*</td>
<td>44.2 ± 2.1b*</td>
<td>1.0</td>
<td>2.2 ± 0.6</td>
<td>0.95</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Non-exercise V̇O2peak estimation

Seismoft 1 (ml·min⁻¹·kg⁻¹) | 36.6 ± 3.4 | 36.6 ± 3.1 | 36.6 ± 3.4 | 1.7 | 4.5 ± 1.3 | 0.95 | 0.907   |
Seismoft 2 (ml·min⁻¹·kg⁻¹) | 36.6 ± 3.3 | 36.7 ± 3.1 | 36.5 ± 3.5 | 1.5 | 3.8 ± 1.2 | 0.96 | 0.872   |
Polar Fitness Test (ml·min⁻¹·kg⁻¹) | 43.5 ± 4.8 | 44.9 ± 4.8 | 43.9 ± 4.6 | 1.8 | 3.0 ± 1.4 | 0.97 | 0.168   |

Cardiopulmonary exercise test

VO2peak (ml·min⁻¹·kg⁻¹) | 39.6 ± 2.7 | 39.7 ± 3.1 | 39.2 ± 3.2a | 1.5 | 3.4 ± 0.8 | 0.95 | 0.907   |
V̇O2peak (ml·min⁻¹) | 2916 ± 293 | 2930 ± 315 | 2837 ± 289 | 116 | 3 ± 1 | 0.97 | 0.808   |
V̇O2peak (L·min⁻¹) | 124 ± 14 | 127 ± 15 | 124 ± 14 | 8 | 5 ± 2 | 0.94 | 0.246   |
HRpeak (beats·min⁻¹) | 173 ± 7 | 172 ± 6 | 172 ± 7 | 3 | 2 ± 0 | 0.96 | 0.150   |
Watt peak (W) | 251 ± 28 | 252 ± 30 | 242 ± 29a | 8 | 2 ± 1 | 0.99 | 0.896   |

Data are presented as mean ± 95% CI. n=20.
a n=18.
b n=17 V̇O2, oxygen consumption; V̇E, minute ventilation; HR, heart rate; Seismoft, V̇O2peak estimation model using seismocardiography version 4.3; Polar Fitness Test, V̇O2peak estimation using the Polar Fitness Test. SD; standard deviation. CoV; coefficient of variation. ICC; interclass correlation coefficient. The Watt peak is calculated using the last completed Watt stage + (Seconds / 60 seconds * watt increments in the representative protocol). The p-value represent the fixed effect; test day from a mixed-effect model fitted using Restricted Maximum Likelihood (REML) for assessment of systematically differences. *denotes significant different from day 1 (p<0.05).
Determination of \( \dot{V}O_2\text{peak} \) with CPET

Graded CPET until voluntary exhaustion was performed on a cycle ergometer to verify whether the SeismoFit \( \dot{V}O_2\text{peak} \) estimation could accurately determine \( \dot{V}O_2\text{peak} \) in healthy adults. The warm-up and initial test workload of the CPET protocol differed between sexes and training status and increased by 20 and 25 W every minute for women and men, respectively (Supplemental Table 2). The different protocols were applied to achieve a test duration of 8 to 12 minutes. Pulmonary gas exchange was continuously obtained breath by breath during the CPET (Quark CPET, Cosmed, Rome, Italy) and sampled into 10-second intervals by an automatic online system (PFT Suite, Cosmed). Heart rate was continuously measured with a chest-strapped sensor (H10, Polar, Finland). Directly after test termination, the participants rated the perceived exhaustion on the Borg 6–20 scale. \( \dot{V}O_2\text{peak} \) was calculated as the highest value measured over consecutive 30 seconds. The primary criterion for achieving \( \dot{V}O_2\text{peak} \) was a plateau in \( \dot{V}O_2 \), defined as \(<2.1 \text{ mL.min}^{-1}.\text{kg}^{-1}\) increment in \( \dot{V}O_2 \) with increasing workload. The secondary criteria were respiratory exchange ratio \( >1.10 \), maximal heart rate within 5 bpm of the highest measured value on the 3 test days, and \( \geq 18 \) on the Borg 6–20 scale. \( \dot{V}O_2\text{peak} \) was accepted if the primary criterion or 2 of 3 of the secondary criteria were met. CPET data from the third test of 2 participants were excluded due to a calibration error. Data and the premises for exclusion are given in Supplemental Figure 2. A detailed description of the equipment calibration and evaluation of the \( \dot{V}O_2\text{peak} \) plateau is presented in the Supplemental Material.

Statistical analysis

All data were treated as normally distributed. Data are given as mean ± 95% confidence interval (CI). Agreement and prediction error of SeismoFit 1 and PFT compared with CPET was determined by the following statistical analyses: Bland-Altman plot with 95% limits of agreement (BA-plot), standard error of estimate (SEE), MAPE, and CoV. Pearson correlation coefficient \( r \) was used to evaluate the relation between SeismoFit 1 and CPET, and between PFT and CPET.

Bland-Altman plots show the difference between the intra-method means plotted on the y-axis and the CPET mean plotted on the x-axis when CPET is the reference method. Otherwise, the average of the 2 intra-method means is plotted on the x-axis. SEE was calculated using \( \text{SEE} = \sqrt{\frac{\sum (Y - Y')^2}{n-2}} \), with \( Y \) representing CPET \( \dot{V}O_2\text{peak} \) and \( Y' \) representing SeismoFit or...
Results

CPET

After the exclusion of 2 recordings with measurement errors, excellent ICC and no statistically significant difference in measures of pre-exercise body weight or peak values of VO$_2$, minute ventilation, heart rate, and workload were observed between test days for CPET (Table 1). A difference was observed for pre-exercise hematocrit and hemoglobin (Table 1). CPET displayed a low within-subject SD and CoV (Table 1). Individual values from the CPET are shown in Supplemental Figure 3.

Validity of VO$_2$peak estimations

Seismofit 1 estimated VO$_2$peak was, on average, 7% lower compared to CPET VO$_2$peak (Figure 2). The agreement between methods showed a relatively large negative bias together with substantial 95% limits of agreement (LoA) (Figure 3C). A fair SEE (Figure 3A) together with a moderate CoV and MAPE above the predefined clinical limit for relevance were found between Seismofit 1 and CPET (Table 2). A high Pearson $r$ was found between methods (Table 2).

In comparison, PFT estimated VO$_2$peak was 11% higher than CPET VO$_2$peak (Figure 2). The agreement between PFT and CPET showed a relatively large positive bias together with large 95% LoA (Figure 3D). A poor SEE (Figure 3B), a moderate CoV, and a MAPE well above the predefined clinical limit for relevance were found between PFT and CPET (Table 2). A high Pearson $r$ was found between PFT and CPET.

Reliability of VO$_2$peak estimations

Between test days, both Seismofit 1 and PFT demonstrated a low within-subject SD and CoV, together with an excellent ICC (Table 1).

Agreement analysis of the Seismofit test–retest revealed a nonsignificant bias of $-0.0 \pm 0.4$ mL·min$^{-1}$·kg$^{-1}$ ($P = .993$) with an acceptable 95% LoA (Figure 4B). A very high Pearson $r$ of 0.99 was found between Seismofit 1 and Seismofit 2 (Figure 4A).

Discussion

The present study provides novel insight into the validity and reliability of a nonexercise estimation of VO$_2$peak using SCG performed with a chest-mounted device—Seismofit—in a healthy population. The main finding was that even though Seismofit underestimated VO$_2$max significantly, Seismofit had a high correlation with the gold standard CPET and proved highly reliable in the estimation of VO$_2$peak both within test days and between test days. In addition, the Seismofit displayed an overall better agreement with CPET than PFT.

Validity of Seismofit VO$_2$peak estimation

When clinical variables are measured, some degree of error is always present. Therefore, when comparing methods, when neither method provides an unequivocally correct
measurement, the preference is to assess the degree of agreement between methods. Furthermore, evaluation of whether the methods agree sufficiently should be decided depending on the context in which the method will be used. To the best of our knowledge, there is no accepted measurement error (systematic and random) that indicates when the agreement of a VO2peak estimation is acceptable or not. However, it has previously been suggested that the contextual validity of estimating VO2peak requires a measurement error within the range of 3.5 mL·kg⁻¹·min⁻¹, if the purpose is to assess improvement in the subject’s health (ie, changes in VO2peak); otherwise, relevant clinical changes would be missed. This is based on the association between a small increase in VO2peak (1 METS or 3.5 mL·kg⁻¹·min⁻¹) and a lower risk of all-cause mortality and incidence of CVD. For VO2peak estimation models using either resting condition or exercise-based information, this still is not achieved as the estimation error at the individual level is too large.

The present results revealed a systematic error of -3.1 ± 2.4 mL·kg⁻¹·min⁻¹ with a substantial total random error span of 21.6 mL·kg⁻¹·min⁻¹. In addition, the MAPE was above the predefined level of <10% for clinical relevance. This advocates for future efforts to improve this methodology of estimating VO2peak, both at the population level and in terms of evaluating individual clinically relevant changes. This is a slight contrast to a previous study applying the same SCG algorithm version, in which the model proved valid in estimating VO2peak at a population level, based on the

Table 2  Accuracy between non-exercise VO2peak estimations and a gold standard cardiopulmonary exercise test (CPET)

<table>
<thead>
<tr>
<th></th>
<th>Pearson r</th>
<th>Bias ml·min⁻¹</th>
<th>SEE ml·min⁻¹</th>
<th>MAPE %</th>
<th>CoV %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeismoFit 1</td>
<td>0.70</td>
<td>-3.1 ± 2.4</td>
<td>6.6</td>
<td>12.0</td>
<td>9 ± 3</td>
</tr>
<tr>
<td>Polar Fitness Test</td>
<td>0.79</td>
<td>4.4 ± 8.3</td>
<td>14.8</td>
<td>10 ± 3</td>
<td></td>
</tr>
</tbody>
</table>

Data are presented as mean ± 95% CI, n=20. SeismoFit 1, VO2peak estimation model using seismocardiography version 4.3; Polar, VO2peak estimation using the Polar Fitness Test; SEE, standard error of estimate; MAPE, mean absolute percentage error. CoV; coefficient of variation. *significantly different from CPET (p<0.05).
systematic error (n = 97; bias −1.0 ± 1.2 mL·kg⁻¹·min⁻¹).\(^{28}\) Otherwise, the results were similar to the previous study (LoA −12.4 to 10.4 mL·kg⁻¹·min⁻¹; SEE 5.9 mL·kg⁻¹·min⁻¹; MAPE 12.3%; CoV 8% ± 1%; Pearson r 0.73).\(^{28}\) One reason for the discrepancy in systematic error might be related to the study population. The data used for developing the algorithm version 4.3 consisted primarily of subjects between the ages of 18 and 45 years. In addition, a proportional error estimate their activity level, and perhaps this is the reason for differences in LoA was smaller by 2.4 mL\(^2\) kg\(^{-2}\) min\(^{-1}\) whereas the fourth study found a bias of −0.5 ± 2.8 mL·kg⁻¹·min⁻¹ compared with CPET.\(^{13}\) Even though the PFT algorithm may have been adjusted to improve the estimate of \(\dot{V}O_2\)peak, these findings are in line with the present bias of 4.4 ± 3.1 mL·kg⁻¹·min⁻¹ and thus further highlight that PFT overestimates \(\dot{V}O_2\)peak compared with CPET. When the validity of the Seismofit and PFT \(\dot{V}O_2\)peak estimations was compared, they both showed an inadequate agreement; however, the difference in LoA was smaller by 2.4 mL·kg⁻¹·min⁻¹ and the MAPE lower by 2.8% points for the Seismofit, indicating a better agreement than PFT. The Seismofit estimation is entirely objective, in contrast to PFT where self-reported weekly hours influence the estimated \(\dot{V}O_2\)peak. This is a strength in the Seismofit model as people often tend to overestimate their activity level, and perhaps this is the reason for PFT overestimating \(\dot{V}O_2\)peak.

**Reliability of \(\dot{V}O_2\)peak measurement and estimation**

Reliability assessment in method comparison studies is often lacking, probably due to requirements of an extended study design. However, when incorporated it provides important knowledge in the understanding of the quality of the method. Directly measured \(\dot{V}O_2\) during a graded CPET is considered the most accurate method for determination of \(\dot{V}O_2\)peak, and reproducibility typically is reported with CoV around 5%.\(^{41-47}\) Reliability of CPET in the present study was high, with excellent ICC and within-subject CoV of 3.4% between test days observed. Therefore, CPET was considered

**Comparison of methods for \(\dot{V}O_2\)peak estimation**

A recently published meta-analysis covering 8 studies validating the PFT showed an average overestimation of 2.2 ± 1.9 mL·kg⁻¹·min⁻¹ (mean ± 95% CI) with LoA ranging from −13.1 to 17.4 mL·kg⁻¹·min⁻¹ compared with CPET.\(^{42}\) In addition, 3 of the 4 most recently published studies using PFT algorithms probably are most comparable to the PFT algorithm applied in this study. These studies showed bias and 95% CI between 3.0 ± 3.1 mL·kg⁻¹·min⁻¹ and 4.7 ± 3.4 mL·kg⁻¹·min⁻¹,\(^{15-17}\) whereas the fourth study found a bias of −0.5 ± 2.8 mL·kg⁻¹·min⁻¹ compared with CPET.\(^{13}\) Even though the PFT algorithm may have been adjusted to improve the estimate of \(\dot{V}O_2\)peak, these findings are in line with the present bias of 4.4 ± 3.1 mL·kg⁻¹·min⁻¹ and thus further highlight that PFT overestimates \(\dot{V}O_2\)peak compared with CPET. When the validity of the Seismofit and PFT \(\dot{V}O_2\)peak estimations was compared, they both showed an inadequate agreement; however, the difference in LoA was smaller by 2.4 mL·kg⁻¹·min⁻¹ and the MAPE lower by 2.8% points for the Seismofit, indicating a better agreement than PFT. The Seismofit estimation is entirely objective, in contrast to PFT where self-reported weekly hours influence the estimated \(\dot{V}O_2\)peak. This is a strength in the Seismofit model as people often tend to overestimate their activity level, and perhaps this is the reason for PFT overestimating \(\dot{V}O_2\)peak.

**Figure 4** Data (n = 20) from 3 separate tests for each participant (mean ± 95% CI). A: Scatter plot with linear regression between \(\dot{V}O_2\)peak estimations performed with a nonexercise model using seismocardiography (SeismoFit 1 and SeismoFit 2). Red dotted line represents the line of identity (r = 1.0). B: Bland-Altman plot of the agreement between SeismoFit 1 and SeismoFit 2. Blue line represents the bias. Blue dotted line represents the 95% CI of the bias. **Red dotted line** represents the 95% LoA. Abbreviations as in Figure 3.
acceptable as a reference method. Based on excellent ICC and within-subject CoV of 4.5% (SeismoFit 1) and 3.8% (SeismoFit 2), SeismoFit VO₂peak estimation is highly reliable between test days. Furthermore, the test–retest also proved that SeismoFit repeatability was high. The consistency in within-subject VO₂peak estimations is vital because it confirms that SCG signal recording, features, and fiducial point extraction and processing by the SeismoFit are reliable. This indicates that the lack of accuracy probably is algorithm-dependent and not related to SeismoFit SCG signal recording. SCG algorithm version 4.3 is trained using data from <150 healthy subjects within a relatively small age span, who performed a resting SCG recording and a CPET cycle ergometer test.26,27

PFT has previously been concluded to be reliable based on Pearson r = 0.91 between 2 test days.43 In the present study, PFT was proved highly reliable between 3 test days, with within-subject CoV of 3.0% ± 1.4% and ICC of 0.97.

Study limitations
The lack of a familiarization test day for the participants to use the equipment and exercise testing is a limitation. However, it was prioritized to include a third test day instead, as few method validation studies include more than 2 test days. There were no differences in the measured VO₂peak values between test days. The recruitment of the trained elderly participants is a limitation as they might not reflect the trained elderly population in general, but rather the very top end. Lastly, an obvious limitation is missing the 2 CPET tests due to measurement error and not including a fourth test day within a reasonable timeframe.

Conclusion
In the current study, SeismoFit VO₂peak estimation correlated to the gold standard CPET but underestimated VO₂peak with a significant systematic error. Compared to PFT, SeismoFit showed better agreement based on a smaller random error and MAPE. The reliability of SeismoFit VO₂peak estimation was high both within test days and between test days, with CoV being low and ICC excellent, indicating that the SeismoFit system is dependable in recording and processing the SCG signal. Consequently, because the VO₂peak estimation model is cloud-based, it is possible that SeismoFit VO₂peak estimation could improve and eventually be considered applicable in clinical settings when more data are available for training the algorithm. Thus, based on the present findings, the SeismoFit VO₂peak estimation model needs further improvement if it is to be considered for use in a clinical setting.

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Disclosures
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Authorship
All authors attest they meet the current ICMJE criteria for authorship.

Patient Consent
All patients provided written consent.

Ethics Statement
The study conforms to the Helsinki Declaration and was approved by the Science Ethical Committee of the Greater Region of Copenhagen, Denmark (H-19081375).

Data availability
All data that were used in the current study are available upon reasonable request. The estimated and measured VO₂peak values on the 3 test days from all the participants are given in Supplemental Table 3.

Appendix Supplemental data
Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.cvdhj.2023.08.020.

References


