Efficacy and Validity of the Elite HRV Smartphone Application During Slow-Paced Breathing

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Abstract

Slow-paced breathing during heart rate variability biofeedback is used to augment cardiac-autonomic modulation. This practice has become widely available with the advent of cost-free smartphone applications such as Elite HRV. However, whether Elite HRV can effectively augment heart rate variability (HRV) and accurately measure HRV during its guided slow-paced breathing feature has not been determined. Therefore, 20 healthy young adults (13 M/8 F) completed a single-visit counterbalanced cross-over protocol involving 10 min each of supine spontaneous (SPONT) and paced (PACED; 6 breaths•min⁻¹) breathing while RR intervals were simultaneously recorded via a Polar H10 paired with Elite HRV and criterion electrocardiography (ECG). HRV values automatically computed by Elite HRV were compared with ECG-derived values filtered and computed using standardized methodology. PACED significantly increased low frequency power (LF) for Elite HRV and ECG (Ps ≤ 0.003) and between-condition difference values for Elite HRV and ECG LF were very largely correlated (Lin’s concordance correlation = 0.73). However, absolute LF values differed, and inconsistent effects were observed for other HRV parameters. For validity, agreement between devices for mean RR was acceptable irrespective of condition (Ps ≥ 0.06, coefficient of variation ≤ 2.2%). Conversely, agreement weakened for time and frequency domain parameters during SPONT and was further weakened for each during PACED. Findings revealed that although slow-paced breathing via Elite HRV effectively increased LF HRV, it weakened agreement with the criterion for conventional HRV parameters (excluding mean RR) relative to spontaneous breathing.

Introduction

The autonomic nervous system (ANS), comprised of the sympathetic (SNS; “fight-or-flight”) and parasympathetic nervous systems (PNS; “rest-and-digest”), regulates involuntarily controlled physiological phenomena such as heart rate (HR), blood pressure, respiration, and digestion (Malik et al., 1996; Waxenbaum et al., 2022). Increased PNS, or vagal activity, decreases HR and increases variability of the inter-beat intervals, i.e., increased heart rate variability (HRV). Higher HRV is associated with greater physiological flexibility, adaptability, and self-regulation (Shaffer et al., 2014), and superior health and lifestyle indicators (Grosicki et al., 2022). Conversely, lower HRV is common in older adults (Natarajan et al., 2020) and is associated with smoking (Hayano et al., 1990), physical inactivity (Rennie et al., 2003) and diabetes (Singh et al., 2000). Low HRV is also associated with increased risk of developing hypertension and cardiovascular disease (Liao et al., 1996; Schroeder et al., 2003; Singh et al., 1998) and mortality (Gerritsen et al., 2001; Kleger et al., 1987; Tsuji et al., 1994). Thus, practical, and cost-effective strategies to increase vagal-mediated HRV may help to reduce disease risk and increase lifespan.

HRV biofeedback (HRVB) is a clinical intervention used to increase vagally-mediated HRV. During HRVB, the individual performs slow-paced breathing at a resonance frequency of ~ 4.5 to 7 breaths•min⁻¹ (Chaitanya et al., 2022; Frank et al., 2010; Lehrer, 2013). During the breath cycle, HR normally increases during inhalation and decreases during exhalation, i.e., respiratory sinus arrhythmia (Hirsch & Bishop, 1981; Larsen et al., 2010). When breathing at a resonance frequency during HRVB, peak-to-trough
differences in HR are maximized, which increases HRV (Dick et al., 2014; Lehrer, 2013; McCraty et al., 2009; Shaffer & Meehan, 2020). Purposely altering breathing rate and depth to maintain resonance frequency during HRVB can be leveraged to improve PNS activity (HRV) and various other indicators of health (Laborde et al., 2022a). For example, HRVB has been used to improve cognition and perceived total stress (Chaitanya et al., 2022), reduce symptoms of trait anxiety (Lee et al., 2015), lower blood pressure and inflammatory markers (Wang et al., 2021), and improve mood (Steffen et al., 2017). HRVB is a clinical technique, but widely available low-cost smartphone applications (apps) offering slow-paced breathing guidance and HRVB (Goessl et al., 2017) could be used outside of the clinic for improving general health and well-being (Laborde et al., 2019). However, investigation into the validity of low-cost HRVB apps is necessary before they can be recommended for personal use.

Elite HRV is a cost-free smartphone app that offers daily HRV assessment (Flatt & Howells, 2022; Grosicki et al., 2022) and, more recently, HRVB during slow-paced breathing. The app provides proprietary RR filtering and automatic HRV assessment after each reading, along with the option to export raw RR interval data for assessment in separate software. Multiple studies (Chhetri et al., 2021; Gambassi et al., 2020; Himariotis et al., 2022; Moya-Ramon et al., 2022; Perrotta et al., 2017; Stone et al., 2021) have investigated the validity of Elite HRV, but few (Himariotis et al., 2022; Moya-Ramon et al., 2022; Stone et al., 2021) have compared Elite HRV-derived HRV values to a criterion (i.e., electrocardiography [ECG]), and have instead opted to compare HRV metrics generated from exported RR interval data. To our knowledge, in these studies investigating the accuracy of the Elite HRV app, (Chhetri et al., 2021; Gambassi et al., 2020; Himariotis et al., 2022; Moya-Ramon et al., 2022; Perrotta et al., 2017; Stone et al., 2021) acceptable agreement was reported, supporting the use of Elite HRV for measuring resting seated and supine HRV among healthy adults. However, of these investigations, none assessed the agreement between Elite HRV and a criterion during slow-paced breathing. Due to this gap in the literature, it is currently unknown whether Elite HRV can accurately measure the substantial increases in HRV expected to occur during slow-paced breathing. Therefore, we aimed to 1) verify the efficacy of Elite HRV-guided slow-paced breathing as a means to increase HRV, and 2) assess the validity of Elite HRV for quantifying HRV parameters during spontaneous (SPONT) and slow-paced (PACED) breathing. We hypothesized that 1) Elite HRV-guided slow-paced breathing would increase HRV parameters, and 2) Elite HRV would provide acceptable agreement with ECG-derived HRV values during SPONT and PACED breathing.

**Materials and Methods**

**Participants**

We recruited a convenience sample of 22 healthy adults (13 M/8 F). The inclusion criteria was age between 18 and 39 years old. Exclusion criteria were the use of tobacco products and reporting a known cardiovascular, metabolic, or neurological condition. Each participant provided written and informed consent before completing the study. All procedures were conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board.
**Study Design**

This study used a single-visit counterbalanced cross-over design in which participants came to the laboratory between 0700 and 1000 after an overnight fast and having abstained from alcohol and structured exercise for 24 h, and fluids for at least 1 h before their visit (Christiani et al., 2021). Agreement between Polar H10 paired to Elite HRV, and Kubios-filtered ECG (filtered ECG) was assessed via concurrent collection of RR intervals in a supine position during 10 min of spontaneous (SPONT) and app-guided slow-paced (PACED) breathing. Ten min of supine stabilization preceded each condition and 3 min of standing between conditions functioned as a washout period (Laborde, Allen, Borges, Iskra, et al., 2022). Agreement was assessed between ECG-derived HRV values using a standard filtering process (Lipponen & Tarvainen, 2019) and Elite HRV-derived values provided automatically by the app. To determine whether potential differences between filtered ECG (Lipponen & Tarvainen, 2019) and proprietary-filtered Elite HRV parameters could be explained by measuring error (versus filtering), we also assessed agreement between unfiltered (raw) ECG-derived values and raw Elite-HRV derived values.

**RR Interval Collection**

After establishing written and informed consent, height and weight were measured and recorded. Participants were then directed to a dimly lit, temperature controlled (21°C) examination room for the experimental procedures. RR intervals were simultaneously recorded via ECG and Elite HRV using a Polar H10 (Polar Electro Oy, Kempele, Finland) during PACED and SPONT. ECG electrodes were placed in a modified lead II configuration with data transmitted from the integration belt (Biopac BIONOMADIX, BIOPAC Systems Inc., Coleta, CA, USA) to the data acquisition system (Biopac MP 160, BIOPAC Systems Inc., Coleta, CA, USA). The sampling rate was set to 1000 Hz. AcqKnowledge software 5.0 (BIOPAC Systems Inc., Coleta, CA, USA) was used to identify and export RR intervals for subsequent processing in Kubios HRV Premium software (University of Kuopio, Finland) using the auto-correction filter (Lipponen & Tarvainen, 2019). The Polar H10, with a sampling rate of 1000 Hz, was connected via Bluetooth to Elite HRV on an iPad (5th generation, Apple Inc., Cupertino, CA, USA). HRV results from Elite HRV were recorded, and raw RR interval files were exported from the app to the researcher’s email for unfiltered HRV determination in Kubios HRV Premium software. When Elite HRV recordings were started and stopped, a marker was placed on the ECG file in AcqKnowledge to match recording segments during comparisons.

All HRV parameters were derived following standardized guidelines (Malik et al., 1996). For time-domain HRV metrics, we compared mean RR, the root mean square of successive differences (RMSSD), and the standard deviation of normal-to-normal RR intervals (SDNN) between Elite HRV and filtered ECG during SPONT and PACED. For the frequency-domain, we made the same comparisons for low frequency (LF, 0.04–0.15 Hz) and high frequency spectral power (HF, 0.15–0.4 Hz) (Shaffer et al., 2014). Frequency-domain metrics were determined using the fast Fourier transformation method (Li et al., 2019) to be consistent with Elite HRV. RMSSD and HF were considered markers of the PNS, LF a marker of baroreflex activity, and SDNN a marker of global variability (Shaffer & Ginsberg, 2017).

**Respiration Belt**
A strain gauge respiration belt was placed at the mid-point between the navel and xiphoid process. Respiration rate was transmitted from the data integration belt to the acquisition system for analysis in the AcqKnowledge software to confirm compliance with app-guided slow-paced breathing and to quantify respiration rate differences between SPONT and PACED.

**Breathing Conditions**

PACED was guided by Elite HRV using the “Custom Breathing” program which involves continuous RR interval acquisition and subsequent automatic HRV calculation. Inhale and exhale duration were both set to 5 s (6 breaths•min⁻¹) (Laborde et al., 2022b; Lehrer & Gevirtz, 2014). SPONT was assessed using the “Open HRV reading” program which also involves continuous RR interval acquisition and subsequent automatic HRV calculation. The iPad was positioned at a self-selected distance from the participant using a flexible gooseneck tablet holder (enGMOLPHY, City, State, Country) during both conditions. Before beginning PACED, participants were familiarized with the cues for inhaling and exhaling.

**Statistical Analysis**

Normality was assessed via visual inspection of quantile-quantile plots. Readings from the Elite HRV app are automatically rated as “good,” “okay,” or “poor” based on the quantity of artifacts corrected. If readings were rated as “poor,” they were excluded from the analysis. Paired t-tests were used to compare breathing rate between conditions, and HRV between breathing conditions and within measurement tools (ECG SPONT vs. ECG PACED and Elite HRV SPONT vs. ELITE HRV PACED). Lin’s concordance coefficient (LCC) (Lawrence & Lin, 1989) was used to quantify the relative agreement between difference scores (i.e., PACED – SPONT) calculated for filtered ECG-derived and Elite HRV-derived HRV parameters. Relative agreement was qualitatively interpreted as: <0.10 = trivial, <0.3 = small, <0.5 = moderate, <0.7 = large, <0.9 = very large, and >0.9 = near perfect (Hopkins et al., 2009). Statistical analysis was completed using JMP (Version 16; JMP, Cary, NC, USA), SPSS (Version 27, IBM Corp., Armon, NY, USA), and Excel (Version 16, Microsoft Corp., Redmond, WA, USA).

Systematic bias testing was completed via paired t-tests (Atkinson & Nevill, 1998) using a statistical significance threshold of \( P < 0.05 \). Standardized differences were quantified using Cohen's \( d \) effect size (Enzmann, 2015; Lininger & Riemann, 2016) and were interpreted as: <0.20 = trivial, <0.6 = small, <1.2 = moderate, and <2.0 = large (Hopkins et al., 2009). Heteroscedasticity was explored via visual inspection of Bland-Altman figures (Bland & Altman, 1986), and the degree of heteroscedasticity was assessed by calculating Kendall's tau (τ) correlation between the differences and corresponding means; we failed to reject the presence of heteroscedasticity when τ was greater than 0.20 (Brehm et al., 2012). Absolute agreement was computed using the typical error (TE) reported in absolute units and the coefficient of variation (CV) (Hopkins, 2000) reported as a percentage. Relative agreement was assessed via LCC (Lawrence & Lin, 1989) and was interpreted as: <0.10 = trivial, <0.3 = small, <0.5 = moderate, <0.7 = large, <0.9 = very large, and >0.9 = near perfect (Hopkins et al., 2009). Agreement was further assessed using ordinary least products (OLP) regression (Ludbrook, 2012). In this analysis, the slope and intercept along with the 95% confidence interval (CI) for each were used to determine if there were proportional or fixed
biases present. If the 95% CI for the slope and intercept contained 1 and 0, respectively, we rejected the hypothesis of proportional and fixed biases (Ludbrook, 2012).

Results

Twenty-two people volunteered to participate in this study, but one was excluded because the signal quality was rated as “poor” by Elite HRV during PACED. In total, 21 participants (13 M/8 F; 22.8 ± 3.8 years; 24.2 ± 3.9 kg/m²) were included in the analysis. For filtered ECG, the percentage of artifacts corrected was < 4% for 20/21 participants (range: 0–33.0%; median: 0%) during SPONT, and < 3% for 19/21 and < 11% for 20/21 (range: 0–29.0%; median: 0%) during PACED. For Elite HRV, the percentage was < 5% for 20/21 participants (range: 0–5.20%; median: 0.21%) during SPONT, and < 7% for 19/21 and < 12.5% for 20/21 participants (range: 0–17.54%; median: 0.37%) during PACED. In total, 42 (21 SPONT, 21 PACED) Elite HRV readings were included in the analysis, 40/42 were rated as “good” and 2 participants had readings rated as “okay” during PACED. The target breathing rate during PACED was achieved (6.1 ± 0.4 breaths•min⁻¹) and was significantly slower (P < 0.001, d = 4.78) than SPONT (10.7 ± 1.3 breaths•min⁻¹).

Mean RR

Summary statistics for the between-condition comparison (PACED vs. SPONT) of mean RR are reported in Table 1. When measured by ECG, both raw (P = 0.01, d = 0.38) and filtered (P = 0.01, d = 0.37) mean RR was significantly shorter during PACED compared to SPONT. Similarly, when measured by Elite HRV, both raw (P = 0.04, d = 0.33) and app-filtered (P = 0.01, d = 0.44) mean RR was significantly shorter during PACED compared to SPONT. Difference values for filtered ECG and Elite HRV mean RR between conditions demonstrated a near-perfect (LCC = 0.93, 95% CI: 0.89 to 0.99) association.

Summary and agreement statistics for the between-device (filtered ECG vs. Elite HRV) comparison of mean RR are reported in Table 1 and Bland-Altman plots are displayed in Figs. 1a-1d. CVs ranged from 0.34–2.24% and LOAs ranged from ± 9.5 to ± 60.3 ms. The difference between raw ECG and Elite HRV mean RR during SPONT was trivial and non-significant with near-perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. The difference between raw ECG and Elite HRV mean RR during PACED was trivial and non-significant with near perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. The difference between filtered ECG and Elite HRV mean RR during SPONT was trivial and non-significant with near perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. However, there was evidence of heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 1c). The difference between filtered ECG and Elite HRV mean RR during PACED was trivial and non-significant with near-perfect relative agreement and no evidence of fixed or proportional biases based on OLP results.
Table 1 – Time Domain Summary and Agreement Statistics

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean ± SD (ms)</th>
<th>d</th>
<th>P</th>
<th>Mean Bias ± SD</th>
<th>95% LOA</th>
<th>CV (%)</th>
<th>TE (ms)</th>
<th>τ</th>
<th>LCC</th>
<th>Ordinary Least Products Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Raw</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R²</td>
</tr>
<tr>
<td>SPONT Raw</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>-0.01</td>
<td>0.20</td>
<td>1.64 ± 4.0</td>
<td>10.9</td>
<td>-8.1</td>
<td>0.34</td>
<td>3.4</td>
<td>-0.12</td>
</tr>
<tr>
<td>App</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>-0.07</td>
<td>0.17</td>
<td>1.04 ± 25.8</td>
<td>58.1</td>
<td>-46.2</td>
<td>1.97</td>
<td>18.3</td>
<td>0.04</td>
</tr>
<tr>
<td>PACED</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>&lt;0.01</td>
<td>0.87</td>
<td>-0.9 ± 6.4</td>
<td>81.1</td>
<td>-16.7</td>
<td>0.54</td>
<td>15.9</td>
<td>0.23</td>
</tr>
<tr>
<td>App</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>&lt;0.01</td>
<td>0.87</td>
<td>-0.9 ± 6.4</td>
<td>81.1</td>
<td>-16.7</td>
<td>0.54</td>
<td>15.9</td>
<td>0.23</td>
</tr>
<tr>
<td>SPONT Filtered</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>-0.06</td>
<td>0.06</td>
<td>-7.0 ± 50.8</td>
<td>53.3</td>
<td>-47.3</td>
<td>2.34</td>
<td>21.4</td>
<td>-0.01</td>
</tr>
<tr>
<td>App</td>
<td>ECG</td>
<td>1044.9 ± 114.0</td>
<td>-0.06</td>
<td>0.06</td>
<td>-7.0 ± 50.8</td>
<td>53.3</td>
<td>-47.3</td>
<td>2.34</td>
<td>21.4</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

CV = coefficient of variation, TE = typical error, τ = Kendall’s τ, LCC = Lin’s concordance correlation coefficient, RMSSD = root mean square of successive differences, SDNN = standard deviation of normal-to-normal intervals

RMSSD

Summary statistics for the between-condition comparison (PACED vs. SPONT) of RMSSD are reported in Table 1. When measured by ECG, raw (P = 0.046, d = 0.27) and filtered (P = 0.02, d = 0.31) RMSSD was significantly greater during PACED compared to SPONT. When measured by Elite HRV, raw (P = 0.09, d = 0.46) and filtered (P = 0.34, d = 0.19) RMSSD were not significantly different between conditions.

Difference values for filtered ECG and Elite HRV RMSSD between conditions demonstrated a moderate (LCC = 0.34, 95% CI: -0.03 to 0.71) association.

Summary and agreement statistics for the between-device (filtered ECG vs. Elite HRV) comparison of RMSSD are reported in Table 1 and Bland-Altman plots are displayed in Fig. 1e-1h. CVs ranged from 20.4–56.6% and LOAs ranged from ±27.6 to ±317.6 ms. The difference between raw ECG and Elite HRV RMSSD during SPONT was trivial and non-significant with near perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. However, there was evidence of heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 1e). The difference between raw ECG and Elite HRV RMSSD during PACED was small and non-significant with moderate relative agreement and evidence of heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 1f). There was evidence of a fixed and proportional bias such that Elite HRV RMSSD was higher compared to ECG and the difference was greater at higher RMSSD based on intercept and slope for the OLP results, respectively. The difference between filtered ECG and Elite HRV RMSSD during SPONT was trivial and non-significant with near perfect relative agreement, but there was evidence of heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 1g). There was evidence of a fixed and proportional bias such that Elite HRV overestimated RMSSD at lower values and...
underestimated it at higher values based on the intercept and slope of the OLP results, respectively. The difference between filtered ECG and Elite HRV RMSSD during PACED was small and non-significant with large relative agreement, evidence of heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 1h), but no evidence of fixed or proportional biases based on OLP results.

**SDNN**

Summary statistics for the between condition comparison (PACED vs. SPONT) of SDNN are reported in Table 1. When measured by ECG, raw \( (P < 0.001, d = 0.89) \) and filtered \( (P < 0.001, d = 0.93) \) SDNN were significantly increased during PACED compared to SPONT. When measured by Elite HRV, raw \( (P = 0.009, d = 0.77) \) but not filtered \( (P = 0.07, d = 0.47) \) SDNN was significantly greater during PACED compared to SPONT. Difference values for filtered ECG and Elite HRV SDNN between conditions demonstrated a moderate \( (LCC = 0.34, 95\% CI: 0.02 to 0.70, P = 0.07) \) association.

Summary and agreement statistics for the between-device (filtered ECG vs. Elite HRV) comparison of SDNN are reported in Table 1 and Bland-Altman figures are displayed in Figs. 1i-1l. CVs ranged from 10.8–40.6% and LOAs ranged from ± 14.7 to ± 201.7 ms. The difference between raw ECG and Elite HRV SDNN during SPONT was trivial and non-significant with near perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. The difference between raw ECG and Elite HRV SDNN during PACED was small and non-significant with small relative agreement. However, there was evidence for heteroscedasticity based on a significant \( \tau \) and visual inspection of the Bland-Altman plot (Fig. 1j) but there was no evidence of fixed or proportional biases based on OLP results. The difference between filtered ECG and Elite HRV SDNN during SPONT was moderate and significant with large relative agreement. There was evidence for a fixed bias such that Elite HRV overestimated SDNN based on the OLP intercept results. The difference between filtered ECG and Elite HRV SDNN during PACED was trivial and non-significant with large relative agreement. There was no evidence for fixed or proportional biases based on OLP results.

**LF**

Summary statistics for SPONT versus PACED LF comparison are reported in Table 2. When measured by ECG, raw \( (P = 0.004, d = 0.89) \) and filtered \( (P = 0.003, d = 0.93) \) LF was significantly greater during PACED compared to SPONT. When measured by Elite HRV, raw \( (P = 0.13, d = 0.47) \) LF was not different between conditions but filtered LF was significantly greater \( (P < 0.001, d = 1.29) \) during PACED compared to SPONT. Difference values for filtered ECG and Elite HRV LF between conditions demonstrated a very large \( (LCC = 0.73, 95\% CI: 0.60 to 0.86) \) association.

Summary and agreement statistics for the between-device (filtered ECG vs. Elite HRV) comparison of LF are reported in Table 2 and Bland-Altman plots are displayed in Fig. 2a-2d. CVs ranged from 20.1–82.3% and LOAs ranged from ± 1415.9 to ± 156980.2 ms². There was evidence of heteroscedasticity for raw and filtered LF during both SPONT and PACED based on \( \tau \) and the Bland-Altman plots (Fig. 2a-d). The difference between raw ECG and Elite HRV LF during SPONT was trivial and non-significant with near perfect relative agreement and no evidence of fixed or proportional biases based on OLP results. The
difference between raw ECG and Elite HRV LF during PACED was small and non-significant with trivial relative agreement and no evidence of fixed or proportional biases based on OLP results. The difference between filtered ECG and Elite HRV LF during SPONT was trivial and non-significant with near-perfect relative agreement and no evidence of fixed or proportional biases. The difference between filtered ECG and Elite HRV LF during PACED was trivial and non-significant with moderate relative agreement and no evidence of fixed or proportional biases based on OLP results.

### Table 2 – Frequency Domain Summary and Agreement Statistics

<table>
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<tr>
<th></th>
<th>Mean ± SD (μm²)</th>
<th>d</th>
<th>P</th>
<th>Mean Bias ± SD</th>
<th>95% LOA</th>
<th>CV (%)</th>
<th>TE (ms²)</th>
<th>x</th>
<th>LCC</th>
<th>Ordinary Least Products Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper</td>
<td>Lower</td>
<td></td>
<td></td>
<td></td>
<td>R²</td>
</tr>
<tr>
<td>LF Raw</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SPONT</td>
<td>8564.4 ± 3157.6</td>
<td>0.06</td>
<td>0.01</td>
<td>-199.9 ± 722.4</td>
<td>1216.9</td>
<td>-351.4</td>
<td>20.1</td>
<td>0.32</td>
<td>0.97</td>
<td>0.91 (0.95 - 1.00)</td>
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<tr>
<td>App</td>
<td>7653.1 ± 3372.0</td>
<td>0.02</td>
<td>0.01</td>
<td>-231.7 ± 559.6</td>
<td>1752.8</td>
<td>-282.9</td>
<td>35.0</td>
<td>0.50</td>
<td>0.96</td>
<td>0.91 (0.95 - 1.00)</td>
</tr>
<tr>
<td>PACED</td>
<td>90000.1 ± 8831.1</td>
<td>-0.58</td>
<td>0.04</td>
<td>-282.0 ± 8099.1</td>
<td>178278.9</td>
<td>-153583.4</td>
<td>82.3</td>
<td>0.33</td>
<td>0.92</td>
<td>-0.03 (-0.06 - 0.03)</td>
</tr>
<tr>
<td>App</td>
<td>90000.1 ± 8831.1</td>
<td>-0.58</td>
<td>0.04</td>
<td>-282.0 ± 8099.1</td>
<td>178278.9</td>
<td>-153583.4</td>
<td>82.3</td>
<td>0.33</td>
<td>0.92</td>
<td>-0.03 (-0.06 - 0.03)</td>
</tr>
<tr>
<td>LF Filtered</td>
<td>844.0 ± 8880.9</td>
<td>0.05</td>
<td>0.05</td>
<td>-158.5 ± 2512.7</td>
<td>8064.5</td>
<td>-825.5</td>
<td>22.4</td>
<td>0.45</td>
<td>0.91</td>
<td>0.01 (-0.09 - 0.06)</td>
</tr>
<tr>
<td>App</td>
<td>8055.1 ± 7273.2</td>
<td>0.13</td>
<td>0.13</td>
<td>-364.5 ± 4311.7</td>
<td>3048.1</td>
<td>-844.4</td>
<td>13.9</td>
<td>0.38</td>
<td>0.98</td>
<td>1.33 (1.33 - 1.33)</td>
</tr>
</tbody>
</table>

HF

Summary statistics for SPONT versus PACED HF comparison are reported in Table 2. When measured by ECG, raw (P = 0.85, d = 0.03) and filtered (P = 0.78, d = 0.03) HF was not different between conditions. Similarly, when measured by Elite HRV, there were no between-condition differences in HF using raw (P = 0.17, d = 0.42) and app-filtered (P = 0.25, d = 0.29) values. Difference values for filtered ECG and Elite HRV HF between conditions demonstrated a trivial and non-significant (LCC = 0.18, 95% CI: -0.27 to 0.57, P = 0.44) association.

Summary and agreement statistics for the between-device (filtered ECG vs. Elite HRV) comparison of HF are reported in Table 2 and Bland-Altman Plots are displayed in Fig. 2e-2h. CVs ranged from 35.5-162.2% and LOAs ranged from ± 738.7 to ± 46410.9 ms². The difference between raw ECG and Elite HRV HF during SPONT was trivial and non-significant with near perfect relative agreement, evidence of heteroscedasticity based on τ, and no evidence of fixed or proportional biases based on OLP results. The difference between raw ECG and Elite HRV HF during PACED was small and non-significant with trivial relative agreement and evidence for heteroscedasticity based on τ and visual inspection of the Bland-Altman plot (Fig. 2f). There was evidence for fixed and proportional biases such that the Elite HRV app overpredicted HF compared to ECG and did so to a greater extent with higher HF values based on the intercept and slope for OLP results, respectively. The difference between filtered ECG and Elite HRV HF during SPONT was trivial and non-significant with near perfect relative agreement, evidence of heteroscedasticity based on τ and the Bland-Altman plot (Fig. 2g), and no evidence of fixed or
proportional biases based on OLP results. The difference between filtered ECG and Elite HRV HF during PACED was small but non-significant with trivial relative agreement, evidence of heteroscedasticity based on $\tau$ and the Bland-Altman plot (Fig. 2h), and no evidence of fixed or proportional biases based on OLP results.

**Discussion**

The purpose of this investigation was to 1) verify the efficacy of Elite HRV-guided slow-paced breathing as a means to increase HRV, and 2) assess the validity of Elite HRV for quantifying HRV parameters during spontaneous (SPONT) and slow-paced (PACED) breathing. The main findings for our first aim were Elite HRV-guided breathing effectively increased LF as measured by filtered ECG and Elite HRV, and individual changes in LF demonstrated very large relative agreement between measurement tools. However, absolute values differed, and Elite HRV- and ECG-derived changes in other HRV parameters (RMSSD, SDNN, and HF) in response to PACED showed weaker agreement. Regarding our second aim, Elite HRV provided acceptable agreement with filtered ECG for mean RR, irrespective of respiration rate or RR filtering. However, weaker agreement was observed for other HRV parameters, particularly during PACED.

**Comparison of SPONT and PACED HRV**

There was a small but significant reduction in mean RR during PACED, irrespective of filtering, and there was a near perfect correlation between difference values of filtered parameters. However, RMSSD significantly increased for ECG but not for Elite HRV during PACED, irrespective of filtering, with a moderate and non-significant correlation between filtered difference values. Similarly, SDNN significantly increased for ECG during PACED, irrespective of filtering whereas Elite HRV-derived SDNN significantly increased only for unfiltered values, highlighting potential differences between Elite HRV's proprietary algorithm and the Kubios auto-correction. Furthermore, filtered SDNN difference values were moderately but non-significantly correlated. No differences in HF between conditions was observed, irrespective of filtering for both ECG and Elite HRV. Additionally, filtered difference values demonstrated small and non-significant associations. Our findings for mean RR, RMSSD, SDNN, and HF are in line with some, but not all, previous research on HRV and slow-paced breathing. For example, when comparing breathing at 6 breaths·min$^{-1}$ with and without biofeedback (Laborde et al., 2022b), RMSSD and SDNN increased, HF increased at the group level with a wide range of error, but mean RR increased. We observed similar changes in SDNN, but RMSSD only changed for filtered ECG, and we noted a decrease in mean RR. Melo et al. (Melo, 2018) found that participants had higher RMSSD and SDNN during slow-paced breathing (6 breaths·min$^{-1}$) which also matched our results for ECG- but not for Elite HRV-derived values. A possible explanation for the reduction in mean RR and limited increases in RMSSD and HF in the current study could be that participants were more relaxed during SPONT versus PACED. Lack of familiarity with slow-paced breathing possibly kept them vigilant in adhering to the breathing cadence, resulting in stronger
inhalations which contribute to HR accelerations and collectively may have limited the magnitude of decelerations.

LF significantly increased for ECG during PACED, irrespective of filtering, but Elite HRV-derived LF significantly increased only for filtered values. Filtered LF difference values demonstrated very large and significant associations. The observed increase in LF matches many previous investigations (Laborde et al., 2022b; Melo et al., 2018; Saboul et al., 2013) and is pertinent to assessing the accuracy of Elite HRV during slow-paced breathing or HRVB because LF is the primary HRV parameter of interest during breathing practices (Sakakibara et al., 2020; Sevoz-Couche & Laborde, 2022; Shaffer & Meehan, 2020). LF reliably increases during slow breathing in various populations (Laborde et al., 2022a) and is a key metric used to determine one’s resonance breathing frequency (Shaffer & Meehan, 2020). The increase in LF for filtered Elite HRV and the strong relationship of the change values between conditions (PACED – SPONT) for ECG and Elite HRV supports the utility of its guided breathing feature for acutely improving LF HRV. However, it should be noted that Elite HRV-derived values for LF differed from ECG-derived values filtered using the standard method (Lipponen & Tarvainen, 2019).

Comparison of Filtered ECG- and Elite HRV-derived HRV

We observed excellent agreement between Elite HRV and ECG for raw and filtered mean RR during SPONT, with mean bias and 95% LOA values comparable with previous investigations (Himariotis et al., 2022). However, an important finding was that the raw and filtered mean bias and 95% LOA’s for PACED were higher than current SPONT and previously reported SPONT values (Himariotis et al., 2022). Thus, based on these findings, the average RR interval length during the 10 min reading was accurately characterized, but, for some participants, the mobile system did not achieve the same accuracy when characterizing fluctuations of the RR intervals across the same reading.

For raw and filtered RMSSD and SDNN, wide LOA’s and high CV’s (> 10%) were observed, especially during PACED. Relative agreement (LCC correlation) ranged from large to near perfect during SPONT but weakened (small to large) during PACED. Filtering did not meaningfully change agreement for RMSSD during SPONT but worsened it for SDNN. Agreement for these parameters improved with filtering during PACED but remained weak. Visual inspection of the Bland-Altman plots for RMSSD (Fig. 1e, 1f, 1g) and SDNN (Fig. 1i, 1l) showed that a majority of the sample demonstrated individual bias values near zero, indicating that a limited number of participants were driving the sub-optimal agreement results. Our findings for filtered RMSSD are in line with previous work comparing Elite HRV and ECG. During 5-min SPONT HRV readings in the seated position, Stone and colleagues noted a non-significant difference and very large relative agreement with LOAs (-34.74 to 20.87 ms) similar to ours (-28.0 to 27.3 ms) for filtered RMSSD during SPONT (Stone et al., 2021). Other previous work has found acceptable agreement for Elite HRV during spontaneous breathing, but no analyses that included SDNN used automatic Elite HRV-derived values (Chhetri et al., 2021; Gambassi et al., 2020). In a study comparing a photoplethysmography (PPG)-based wrist band versus ECG (Menghini et al., 2019), there were small mean biases for both RMSSD and SDNN during SPONT and PACED, but LOAs were slightly wider during PACED.
Frequency domain parameters (HF and LF) demonstrated wide 95% LOA's and high CV's (> 20%), especially during PACED. Relative agreement (LCC correlation) was near perfect during SPONT but weakened (trivial to moderate) during PACED. Filtering had varying effects on outcomes. During SPONT, agreement was largely unchanged for both LF and HF. For PACED, agreement was improved for LF and HF but remained poor for both variables. Only one previous investigation explored the validity of Elite HRV for measuring frequency domain parameters (Gambassi et al., 2020), but LF and HF were manually computed after RR data export into Kubios. In line with our findings, Menghini et al. (Menghini, 2019) compared PPG- and ECG-derived LF and HF and found that 95% LOAs were wider during paced versus spontaneous breathing. However, they observed a near perfect relationship for LF and HF during both breathing conditions while we did not.

Limitations and Strengths

This study was not without limitations. The ECG recordings were marked at the moment that Elite HRV recordings started but there is a possibility of very minor error in synchronizing the RR interval collection (e.g., < 1 s). However, strong agreement for mean RR, irrespective of condition or filtering, suggests this had minimal effects. Participants completed this study in a quiet and temperature-controlled room, but the environment may not represent a comfortable home setting in which app-guided breathing would regularly be performed. Moreover, although participants were familiarized with the breathing cadence for PACED, they may not have been adequately familiarized with appropriate relaxation during slow-paced breathing which could have affected HRV responses to PACED versus SPONT. Finally, this study used a standard and popular filtering method (Lipponen & Tarvainen, 2019) to derive reference values but note that there is currently no universally agreed-upon criterion filtering algorithm. This study also had a few notable strengths. The testing procedures were in the morning after an overnight fast which created standardized conditions, and male and female participants were included in the study. Also, slow-paced breathing had not been previously used to validate Elite HRV or similar apps.

Conclusions

Elite HRV provided acceptable agreement with the criterion for mean RR, irrespective of breathing rate, potentially supporting its ability to provide accurate HR during guided breathing and HRVB protocols for most individuals. However, slow-paced breathing at 6 breaths•min⁻¹ generally worsened the agreement between Elite HRV- and ECG-derived HRV, with and without filtering. Moreover, there was inconsistent agreement between Elite HRV- and ECG-derived changes in HRV when comparing spontaneous to slow-paced breathing. Although Elite HRV's guided slow-paced breathing feature effectively increased LF, as measured by Elite HRV and the criterion, absolute values differed. Therefore, Elite HRV users should be mindful of the current results when interpreting HRV values or when comparing them with non-Elite HRV-derived norms. These findings also support a need to investigate the validity of other mobile devices and applications for measuring HRV during slow-paced breathing.

Declarations
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**Figures**
Figure 1

Time Domain Bland-Altman Plots

ECG = (Kubios-filtered) electrocardiogram; App = Elite HRV app; RMSSD = root mean square of successive differences; SDNN = standard deviation of normal-to-normal intervals

Triangles represents participants with “okay” signal quality during PACED
Figure 2

Frequency Domain Bland-Altman Plots

ECG = (Kubios-filtered) electrocardiogram; App = Elite HRV app; RMSSD = root mean square of successive differences; LF = low frequency spectral power; HF = high frequency spectral power

Triangles represents participants with “okay” signal quality during PACED