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Sex Differences and Frequency-Specific Responses in Heart Rate Variability from Exposure to Acute Whole-Body Vibration among the Elderly

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Abstract **Purpose:** We investigated sex differences in heart rate variability (HRV; a non-invasive indicator of autonomic nervous system) and its frequency-specific responses to whole-body vibration (WBV) at three distinct frequencies among elderly subjects. **Methods:** Data from 11 males and 13 females were analyzed across four randomized sessions of exposure: WBV at 15, 20, or 25 Hz with a 4 mm peak-to-peak displacement, or control (0 Hz) condition comprising three bouts of 1-minute exposure with 1-minute between-bout rests. HRV measurements were taken before and during the exposure. **Results:** At baseline, low-frequency power/LF (ms^2) were significantly lower in females than males ($P < 0.05$). During exposure, LF (ms^2), high-frequency power (ms^2), standard deviation of normal-to-normal intervals, root mean square of successive differences between RR intervals, standard deviation of the Poincaré plot perpendicular to the line-of-identity, and standard deviation of the Poincaré plot along the line-of-identity significantly increased at 20 Hz for males and 25 Hz for females ($P < 0.05$ to 0.005) compared to respective baselines. **Conclusions:** Elderly females tend to exhibit reduced autonomic nervous system function compared to males. Furthermore, our results indicate that WBV at 20 Hz for males and 25 Hz for females may be considered beneficial for enhancing HRV in the elderly.

Key words: whole body vibration, autonomic nervous system, heart rate variability, elderly, sex difference

Introduction

The global elderly population is steadily increasing, accompanied by a rise in age-related diseases and disorders.[1] It is well-established that aging is linked to a decline in the regulation of the autonomic nervous system (ANS),[2] potentially leading to health issues such as orthostatic hypotension, myocardial ischemia, and other cardiovascular events, necessitating caution and careful consideration.[3,4]

To address health challenges arising from ANS dysfunction, various methods have been proposed, encompassing both pharmacological therapies such as conjugated estrogen replacement therapy, and non-pharmacologic

therapies like aerobic exercise.[5,6] Among non-pharmacologic therapies, whole-body vibration (WBV) exercise has garnered attention due to its reported effectiveness in improving ANS function, peripheral circulation, muscle strength, and balance ability.[7-10] Furthermore, as a simple, safe, easy-to-use, and non-invasive intervention modality, WBV is widely utilized for training and treatment purposes.[10,11] However, despite the potential benefits of WBV for elderly health, optimal vibration parameters, such as frequency, amplitude, and acceleration, remain undefined and urgently need establishment for this purpose.[12] The situation is complicated by the fact that research studies on the impact of WBV on ANS show inconsistent results, with some studies reporting beneficial ANS modulation,[8,13] while others indicate an imbalance in sympathovagal balance caused by exposure to WBV.[14,15]

In humans, sex plays a significant role in various physiological functions, including ANS activity and age-related changes in the latter.[2,16,17] However, there is a severe lack of research exploring the impact of WBV exposure on ANS function among elderly people of different sexes, leaving the potential consequences of sex on ANS activity from exposure to WBV unclear. This lack of research poses challenges to the use of WBV as a tool to enhance ANS function in the elderly. On the other hand, among the vibration-related parameters, it has been proposed that ANS responses to WBV may be more closely related to vibration frequency than amplitude or direction,[14,15] necessitating a careful investigation of the frequency-effect of WBV on autonomic nervous activity.

Considering the above-mentioned issues and existing gaps in the current literature, the present study aims to elucidate sex differences and frequency-specific responses in heart rate variability (HRV), a non-invasive indicator of ANS, induced by exposure to WBV at three distinct frequencies of 15 Hz, 20 Hz, and 25 Hz.

Materials and Methods

Selection and Preparations of Subjects

In this study, we conducted a single-group repeated measures investigation among elderly subjects aged 65 years and older. The present study is part of a larger research project exploring the usefulness of acute WBV exposure among elderly individuals in relation to various physiological parameters, including HRV.

The participants for this study were recruited through poster advertisements and word-of-mouth promotion in nearby communities. The inclusion criteria for the subjects were as follows: no engagement in regular exercise training, regardless of exposure to WBV; non-institutionalized individuals capable of standing; no reported musculoskeletal, neurological, connective tissue, cardiovascular issues (except for hypertension), or other conditions that would prohibit exposure to WBV; no diabetes mellitus and no contraindications to WBV exposure, such as hernias, epilepsy, kidney or gallbladder stones; no joint diseases, metal implants, or prostheses; and no history of surgery within the past year. In total, 42 elderly volunteers enrolled in this study, with 15 males and 15 females ultimately completing all the experimental sessions as described elsewhere.[11]

Before the start of each experimental session, the subjects were instructed to abstain from consuming coffee or tea and eating for at least 3 hours. Additionally, they were asked to refrain from drinking alcohol, smoking, and engaging in strenuous exercise for a minimum of 12 hours prior to the session. Furthermore, subjects were instructed to empty their bladders before entering the laboratory. While in the laboratory, subjects were advised to wear light indoor clothing (two layers for both upper and lower body), regular socks, and shoes. During the acclimatization period of the experimental sessions, all subjects were required to be barefoot. Subjects taking antihypertensive treatment were instructed to maintain their current treatment regimens throughout the study program.

Experimental Design

To account for the influence of circadian rhythms, we conducted four experimental sessions randomly on separate days, with a

minimum of 24 hours between each session. These sessions took place at approximately the same time for each subject, between 9:00 am and 4:00 pm. In addition to the recordings of HRV (reported in this paper), we also measured vibrotactile perception threshold (VPT) and skin blood flow (SBF) reported elsewhere.[11]

Briefly, at the start of each session, all subjects underwent a 15-minute acclimation period in an experiment room set at a temperature of 25.0±0.5℃. During this period, subjects were instructed to sit in a comfortable chair with their socks off, and they rolled up the bottoms of their trousers between their knees and heels. Additionally, they were advised to place their feet on the wooden floor and rest their hands on their respective thighs while sitting.

Following the acclimatization period, HRV was measured (followed by VPT) with subjects in a seated position, and these measurements served as the baseline values. Subsequently, subjects were asked to stand on an ethylene vinyl acetate foam pad (3 mm thick) fixed to the rectangular platform of the side-alternating vibration unit. All subjects were instructed to maintain an upright posture, face forward, and grasp the rails provided on the platform. After a rest period of at least 3 minutes in the standing posture, SBF was measured.

Following these measurements, subjects were directed to flex their knees to an angle of approximately 30° (with full knee extension measured as 0°). At this point, they positioned their feet parallel to each other and maintained a distance of 10.5 cm from the center of the platform to the midline of their heels. Subsequently, all subjects underwent an intervention consisting of any of the following four exposure conditions: 1) control (0 Hz), 2) WBV at 15 Hz, 3) WBV at 20 Hz, or 4) WBV at 25 Hz. The peak-to-peak displacement of the vibration platform was 4 mm, and the unweighted and frequency-weighted peak accelerations were 17.75 m/s^2 and 9.64 m/s^2 rms, 31.56 m/s^2 and 14.19 m/s^2 rms, and 49.30 m/s^2 and 17.89 m/s^2 rms at 15 Hz, 20 Hz, and 25 Hz, respectively. The corresponding 8-hour energy-equivalent frequency-weighted acceleration (A(8)) values were 0.76 m/s^2 rms, 1.12 m/s^2 rms, and 1.41 m/s^2 rms, respectively. These values were calculated following the specifications outlined in ISO 2631-1 (1997). The 5-minute intervention protocol included three 1-minute exposure bouts, with 1-minute intervals in between. After each exposure period, during the rest time, subjects were instructed to maintain a steady upright posture. HRV was continuously recorded during this 5-minute exposure period.

Equipment and Measurements

WBV was generated using a commercial side-alternating vibration device (Galileo 900, Novotec Medical GmbH, Pforzheim, Germany). To confirm the vertical (Z axis) peak vibration acceleration level of the unoccupied platform, a triaxial piezoelectric accelerometer (PV-97C, Rion, Japan) was fixed at the midpoint of the area where the subjects' feet were placed and connected to a 3-axis vibration meter (VM-54, Rion, Japan).

For recording of HRV, a portable 2-channel battery-operated heart rate monitoring device (CheckMyHeart, DailyCare BioMedical, Inc., Taiwan) was used. The disposable Ag/AgCl circular surface electrodes (Bioload SDC-H, GE Healthcare, Japan) were placed on the ventral forearms of the subjects.

The room temperature was monitored using digital thermistors (SZL-64, Technol seven, Japan) with a measurement accuracy of ±0.15℃. These thermistors were connected to a highly accurate data logger (K730, Technol seven, Japan) and a scanner (X115, Technol seven, Japan).

Data Processing and Statistical Analyses

In this study, we aimed to evaluate the specific effects of WBV, and therefore, extracted the HRV data during the real exposure period only (three exposures of 1 minute each, totaling 3 minutes). All HRV data underwent visual inspection to eliminate noise and ectopic beats using HRV analysis software (DailyCare BioMedical, Inc., Taiwan).

For this study, we performed frequency-domain, time-domain, and non-linear analyses of HRV data, using detrended values obtained from normal-to-normal (NN) interval data via the application of fast-Fourier transformation. The sampling frequency for HRV data was set at 250 Hz.[19]

For frequency-domain analysis, we measured the following parameters: 1) low-frequency power (LF, 0.04 to 0.15 Hz); 2) high-frequency power (HF, 0.15 to 0.4 Hz); 3) the ratio of LF-to-HF power (LF/HF). Additionally, we normalized LF and HF using very low-frequency power (VLF, between 0.0033 to 0.04 Hz) and the following formulas: (1) LF in normalized units (nu) = LF ÷ (total power - VLF); and (2) HF in normalized units (nu) = HF ÷ (total power - VLF), where total power represents the variance of NN intervals over the temporal segment (below approximately 0.4 Hz).[20] Subsequently, LF/HF was calculated using these LF (nu) and HF (nu) values. For time-domain analysis, we assessed the following parameters: 4) standard deviation of NN intervals (SDNN); 5) the root mean square of successive differences between normal heartbeats (RMSSD).[20] In non-linear measurements, we analyzed: 6) standard deviation of Poincaré plot perpendicular to the line-of-identity (SD1); 7) standard deviation of Poincaré plot along the line-of-identity (SD2); 8) the ratio of SD1-to-SD2 (SD1/SD2).[21]

The normal distribution of each data set was verified using Kolmogorov-Smirnov tests and Shapiro-Wilk tests. Continuous variables in this study were presented as medians and interquartile ranges (IQR) in the tables and figures. To compare baseline values of HRV between males and females, we computed the median of the four values obtained for each subject (male, n=11; female, n=13) under four experimental conditions. The group differences were assessed by applying Mann-Whitney exact test and Wilcoxon signed-rank test as appropriate. All statistical tests were considered two-tailed, and the significance level was set at $P < 0.05$. Statistical analyses were performed using the SPSS software package version 28 for Windows (SPSS Inc., Chicago, IL, USA).

Ethical Statement

The protocol of this study received approval from the relevant institutional review board of Yamaguchi University School of Medicine (approval no. H30-057-2, dated 25-09-2019). This study was conducted in compliance with the Declaration of Helsinki. Prior to enrolling in this study, written informed consent was obtained from all participants.

Results

After a thorough examination to eliminate noise and identify ectopic beats, our final analysis incorporated HRV data obtained from 11 male and 13 female participants. The median values, along with IQR, for age and BMI among male participants were 73.0 (10.0) years and 25.9 (3.23) kg/m^2, respectively. Correspondingly, for female participants, the median values (IQR) for age and BMI were 70.0 (6.50) years and 22.6 (5.37) kg/m^2, respectively.

Comparison of the HRV baseline values for males and females revealed a significant difference, with LF (ms^2) being significantly lower in females compared to males ($P < 0.05$; Table 1). In contrast, HF (ms^2), LF (nu), HF (nu), LF/HF, SDNN, RMSSD, SD1, SD2 and SD1/SD2 did not exhibit significant differences between males and females.

The measured HRV results before and during WBV in terms of frequency-domain parameters have been depicted in Figures 1 and 2. In Figure 1, data analysis indicated a significant increase in LF (ms^2) and HF (ms^2) during WBV at 20 Hz for males ($P < 0.05$). Conversely, as shown in Figure 2, LF (ms^2) was significantly elevated under all conditions except control (0 Hz) ($P < 0.05$ to 0.01), and HF (ms^2) increased significantly at 25 Hz for females ($P < 0.05$). However, no significant changes were observed for LF (nu), HF (nu), and LF/HF (Figures 1 and 2).

The HRV values before and during WBV in terms of time-domain parameters have been presented in Figure 3. As revealed, SDNN and RMSSD showed significant increases, but only during 20 Hz for males ($P < 0.005$ and $P < 0.05$, respectively). Conversely, for females, these parameters were significantly enhanced solely during 25 Hz (both $P < 0.05$).

In Figure 4, non-linear measurements of HRV before and during exposure to WBV are displayed. Among males, SD1 increased significantly only during 20 Hz ($P < 0.05$), and SD2 during 15 Hz and 20 Hz ($P < 0.05$ and $P < 0.005$, respectively). In contrast, for females, SD1 and SD2 demonstrated significant increases solely during 25 Hz (both $P < 0.05$).

Table 1 Comparison of baseline values for heart rate variability between males and females

HRV parameters	Median (IQR)		P-value
	Male (n=11)	Female (n=13)	
LF (ms^2)	53.5 (258)	18.0 (32.8)	**0.047**
LF (nu)	58.8 (25.7)	59.8 (23.1)	0.865
HF (ms^2)	35.0 (420)	15.0 (18.5)	0.228
HF (nu)	41.2 (25.7)	40.2 (23.1)	0.865
LF/HF	1.44 (1.97)	1.54 (1.60)	1.000
SDNN (ms)	22.0 (31.7)	15.7 (9.16)	0.119
RMSSD (ms)	14.2 (27.3)	9.79 (6.57)	0.424
SD1 (ms)	10.0 (19.3)	6.92 (4.64)	0.424
SD2 (ms)	29.6 (39.0)	21.3 (11.6)	0.119
SD1/SD2	0.38 (0.17)	0.38 (0.16)	0.955

LF (ms^2), absolute power of the low-frequency band; LF (nu), relative power of the low-frequency band in normal units; HF (ms^2), absolute power of the high-frequency band; HF (nu), relative power of the high-frequency band in normal units; LF/HF, ratio of LF-to-HF power; SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive RR interval differences; SD1, standard deviation of Poincaré plot perpendicular to the line-of-identity; SD2, standard deviation of Poincaré plot along the line-of-identity; SD1/SD2, ratio of SD1 to SD2.
P values indicate the levels of significant differences for the corresponding baseline values between males and females by Mann-Whitney exact test. Bold P value indicates a significant difference between males and females.

However, SD1/SD2 did not exhibit significant changes under any exposure condition for both males and females.

Discussion

HRV is considered to be an effective and useful measure of ANS activity.[20] In this study, we examined the sex differences and frequency-specific responses in HRV to WBV exposure among elderly individuals by exploring frequency-domain, time-domain, and non-linear analyses of the collected data. Each of the investigated HRV parameters has specific implications: LF, SDNN, and SD2 reflect both sympathetic and parasympathetic measures, HF, RMSSD, and SD1 are primarily associated with parasympathetic activity, while LF/HF and SD1/SD2 offer insights into sympathovagal balance.[20,21] It should also be mentioned that HF, SDNN, RMSSD, SD1 and SD2 can be assessed with at least 1 minute of recording time, and LF necessitates a minimum of 2 minutes.[21,22]

Comparing baseline values between elderly males and females, we observed that LF (ms^2) was significantly lower in females, while the other HRV parameters did not exhibit significant differences between males and females. These results probably suggest that although sympathovagal balance is not significantly different between elderly males and females, overall ANS function is more attenuated in females. Our findings are comparable with those of a meta-analysis conducted by Koenig and Thayer (2016), who reported lower LF (ms^2 and nu), LF/HF, and SDNN, and higher HF (ms^2 and nu) in females compared to males, indicating a parasympathetic dominance in females. However, in our investigation, we observed decreased ANS activity among females compared to the findings reported by Koenig and Thayer (2016). This disparity may be attributed to our exclusive inclusion of elderly females experiencing a menopause-related decline in estrogen levels, a factor known to play a crucial role in suppressing the sympathetic nervous system

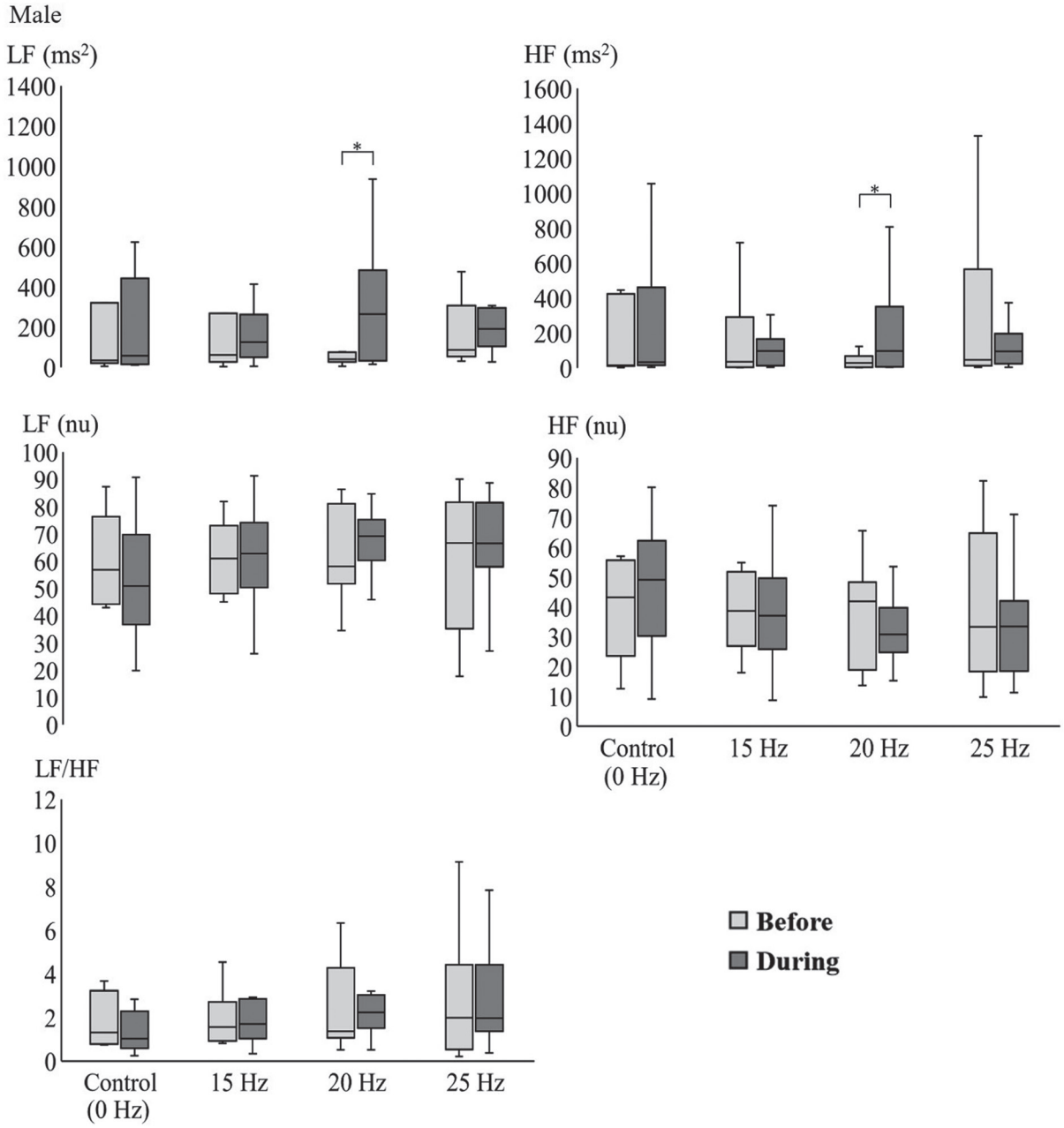

Fig. 1 Boxplots displaying median with 25th and 75th percentiles for measured HRV frequency-domain parameters under four conditions (control (0 Hz), 15 Hz, 20 Hz, and 25 Hz) for males. Levels of significant differences between before and during intervention: *P < 0.05. n= 11, 10, 11, and 11 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively.
LF (ms^2), absolute power of the low-frequency band; LF (nu), relative power of the low-frequency band in normal units; HF (ms^2), absolute power of the high-frequency band; HF (nu), relative power of the high-frequency band in normal units; LF/HF, ratio of LF-to-HF power.

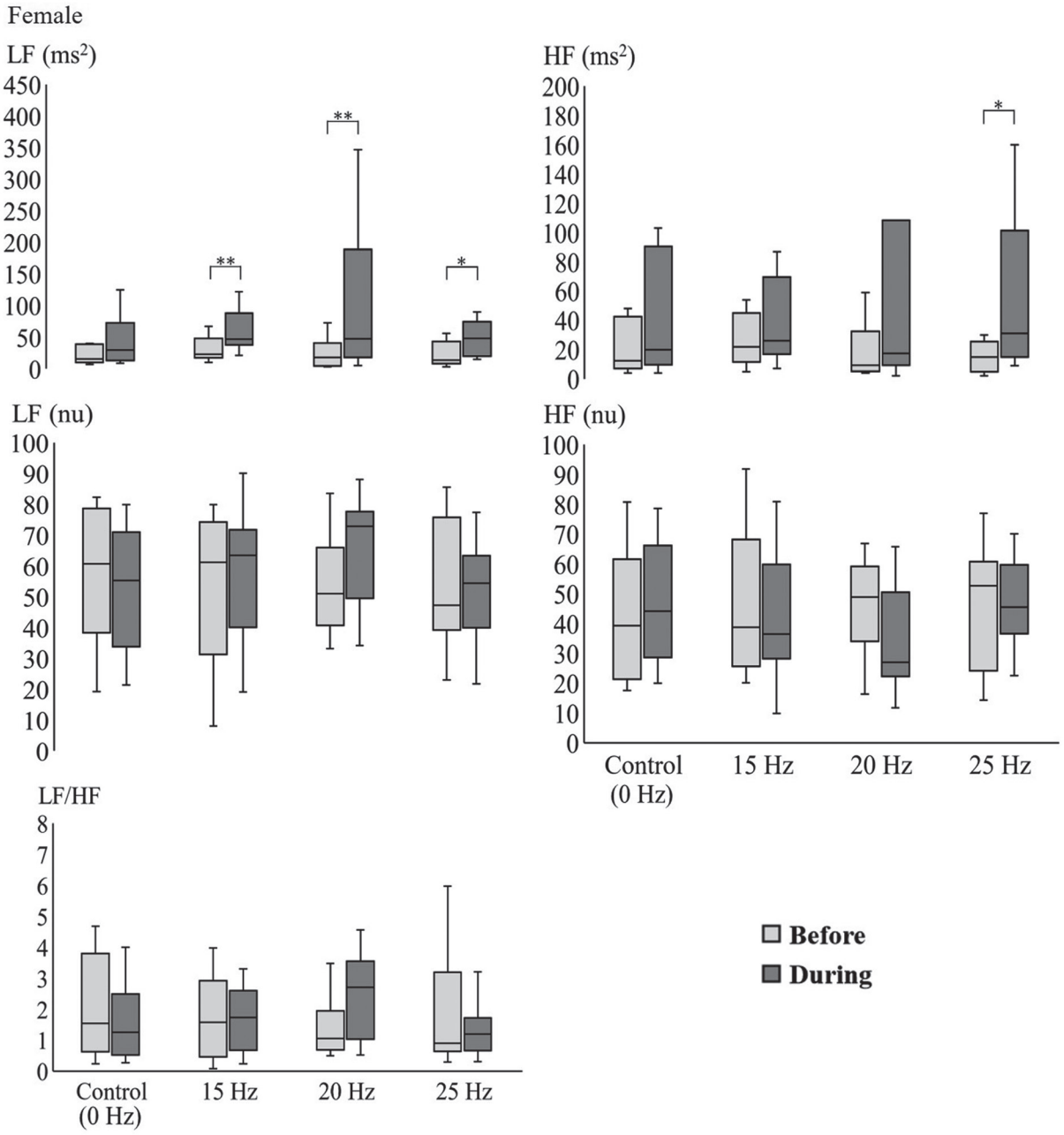

Fig. 2 Boxplots displaying median with 25th and 75th percentiles for measured HRV frequency-domain parameters under four conditions (control (0 Hz), 15 Hz, 20 Hz, and 25 Hz) for females. Levels of significant differences between before and during intervention: *P < 0.05, **P < 0.01. n= 12, 13, 10, and 12 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively.
LF (ms^2), absolute power of the low-frequency band; LF (nu), relative power of the low-frequency band in normal units; HF (ms^2), absolute power of the high-frequency band; HF (nu), relative power of the high-frequency band in normal units; LF/HF, ratio of LF-to-HF power.

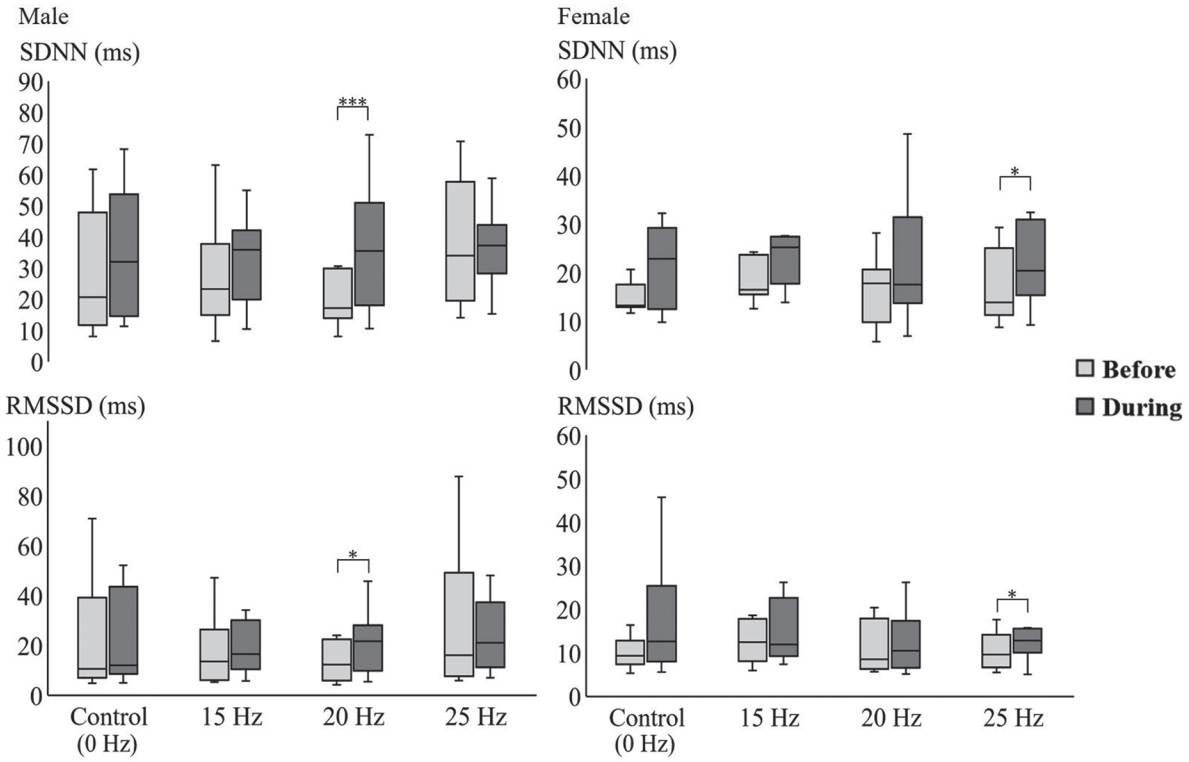

Fig. 3 Boxplots displaying median with 25th and 75th percentiles for measured HRV time-domain parameters under four conditions (control (0 Hz), 15 Hz, 20 Hz, and 25 Hz) for males and females. Levels of significant differences between before and during: *P < 0.05, ***P < 0.005. For males: n= 11, 10, 11, and 11 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively. For females: n= 12, 13, 10, and 12 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively.
SDNN, standard deviation of NN intervals; RMSSD, root mean square of successive RR interval differences.

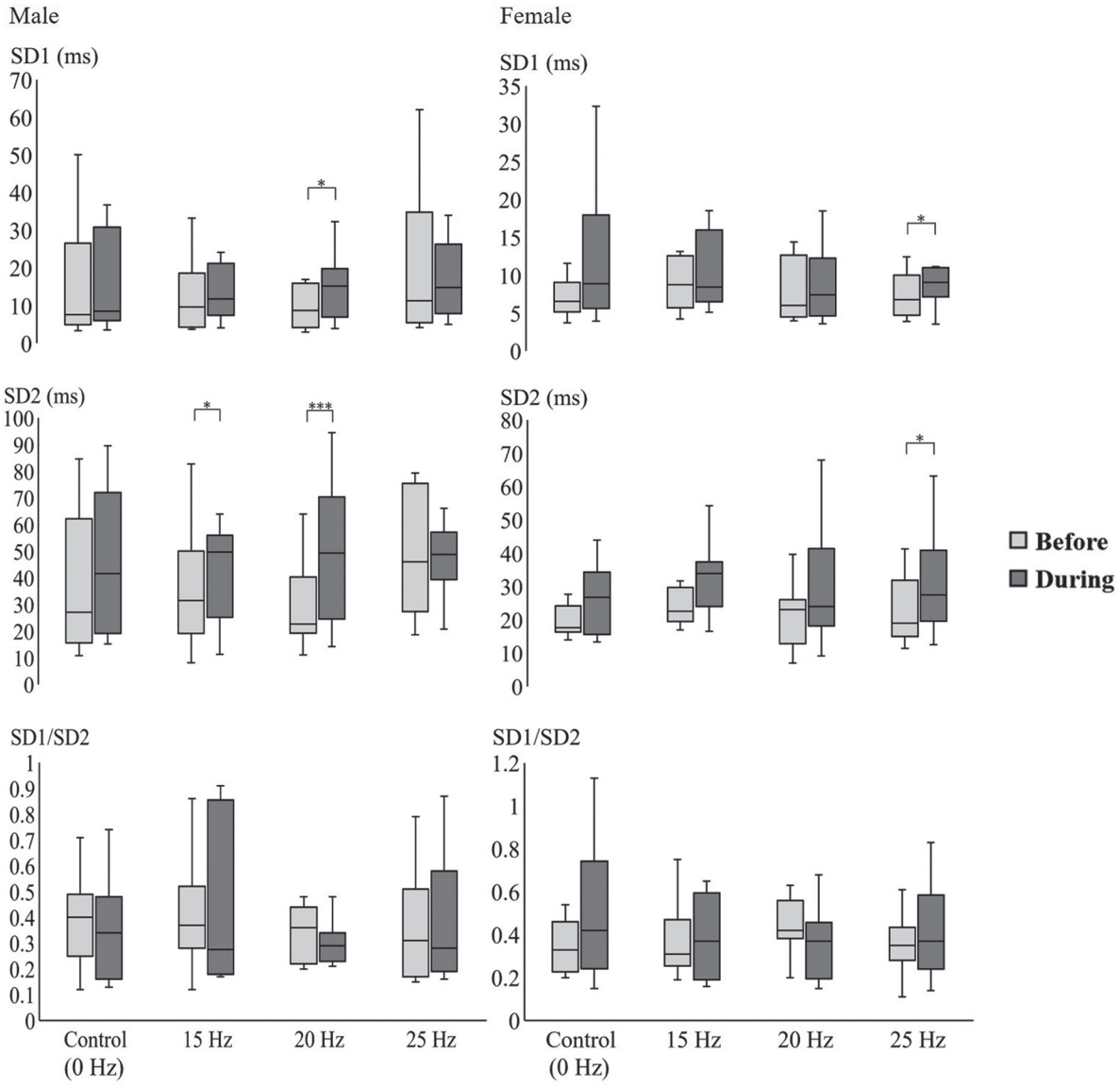

Fig. 4 Boxplots displaying median with 25th and 75th percentiles for measured HRV non-linear measurements parameters under four conditions (control (0 Hz), 15 Hz, 20 Hz, and 25 Hz) for males and females. Levels of significant differences between before and during: * $P < 0.05$, *** $P < 0.005$. For males: n= 11, 10, 11, and 11 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively. For females: n= 12, 13, 10, and 12 for control (0 Hz), 15 Hz, 20 Hz, and 25 Hz conditions, respectively.
SD1, standard deviation of Poincaré plot perpendicular to the line-of-identity; SD2, standard deviation of Poincaré plot along the line-of-identity; SD1/SD2, ratio of SD1 to SD2.

(SNS) and activating the parasympathetic nervous system (PNS).[5] In contrast, Koenig and Thayer's study included subjects with a broader age range, spanning from 5 months to 70 years.

Considering the commonly observed changes in HRV parameters induced by exposure to WBV, we observed a significant increase in LF (ms^2), HF (ms^2), SDNN, RMSSD, SD1, and SD2 under 20 Hz in males and 25 Hz in females. These findings suggest that 20 Hz for males and 25 Hz for females might be the most effective frequencies for the purpose of stimulating the ANS (especially PNS) and increasing HRV. On the other hand, our findings indicate that the applied vibration was not probably enough to alter the sympathovagal balance. The effects of WBV on HRV observed in our study are in line with the findings of Licurci et al. (2018), who reported improvements in time-domain parameters such as SDNN and RMSSD in the elderly following WBV at 20 Hz. However, no significant changes were noted in frequency-domain parameters, including LF, HF, and LF/HF. In their study, Licurci et al. (2018) did not consider the effect of sex and the subjects were also relatively younger. These factors may partially account for the observed variations in the responses in HRV.[2,23] In contrast to our study, Jinakote et al. (2023) reported that SDNN, RMSSD, SD1 and SD2 were significantly reduced while LF (nu), HF (nu), LH/HF and SD1/SD2 were not significantly changed during 25 Hz WBV exposure in young healthy subjects. Their study subjects were younger than ours (median (IQR) age, 21 (3.75) years) and they did not account for sex differences. Their reported results may emphasize the importance of age and sex considerations when performing WBV exercises. In a study, Jalilian et al. (2019) investigated the effects of WBV exposure with varying frequencies (3-20 Hz) and intensity (0.5 m/s^2) on HRV among young males. They observed increases in LF (nu), HF (nu), and LF/HF but decreases in SDNN and RMSSD. They suggested that WBV caused stimulations of both the SNS and PNS with a disruption in sympathovagal balance. In contrast, our findings show that WBV did not cause any significant change in sympathovagal balance at any exposure frequency. The differences may be attributed to variations in subject characteristics and the random frequency waves (3-20 Hz) employed in the study by Jalilian et al. (2019). Sañudo et al. (2013) exposed young healthy males to WBV of 25 Hz after intense cycle exercise, and found an increase in total power, although no changes were noted in LF (nu), HF (nu), or LF/HF. However, total power is associated with overall ANS function and can increase due to vagal activation.[20,25] Therefore, this observation by Sañudo et al. (2013) supports the findings of our study that showed a pronounced PNS stimulation by exposure to WBV.

Our study design does not allow us to elucidate the mechanisms by which WBV improves HRV. Potential theories include an increase in baroreflex sensitivity and nitric oxide (NO) levels, coupled with a reduction in cardiac muscle overload, and/or decreased angiotensin II levels.[10,26-29] It is plausible that enhanced baroreflex sensitivity leads to the partial or complete restoration of sympathetic inhibition, causing vagal activation and thereby modulating the ANS.[10,30] Additionally, research has demonstrated that vibration stimulation induces an elevated production of NO, potentially resulting in improvements in peripheral components of the cardiovascular system, such as enhanced vascular function and increased blood flow to skeletal muscles.[31] Furthermore, the endothelial release of NO inhibits central and peripheral SNS activity while increasing central and peripheral PNS activity.[32,33] A reduction in angiotensin II levels, combined with the suppression of the renin-angiotensin-aldosterone system, may contribute to the attenuation of the sympatho-excitatory process.[34] The alterations in various HRV parameters observed in our study may be attributed to the combined effects of the aforementioned factors induced by exposure to WBV.

Limitations

Several potential limitations should be considered in the present study. The sample size of this study was relatively small. In this study, the participants were apparently healthy Japanese elderly individuals. These limitations may impact the generalizability

of the current findings. In our investigation, a limitation might be the presence of missing HRV data under various exposure conditions due to movement and mechanical artifacts. The existence of these missing values may have affected the precision of our data analysis. However, the deletion of inconsistent RR-intervals as a means of addressing such discrepancies is considered to be a simple but valid approach, as documented in the literature.[35] Our study focused solely on three specific WBV frequencies (15 Hz, 20 Hz, and 25 Hz) and did not investigate the effects of other vibration-related parameters such as amplitude or acceleration. Future research should explore a wider range of WBV frequencies, amplitudes, and accelerations to determine their impact on the ANS function more comprehensively.

Conclusions

Our findings indicate that elderly females tend to exhibit reduced ANS function compared to males. Moreover, WBV frequencies of 20 Hz for elderly males and 25 Hz for elderly females appear to be effective in enhancing ANS function without significantly altering the sympathovagal balance. Therefore, when exposing elderly subjects to WBV, it is advisable to recommend the selection of an appropriate vibration frequency based on sex.

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Conflicts of Interest

The authors declare no conflict of interest.

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