# Cardiovascular Response to Whole-Body Vibration on an Automobile Seat

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## Abstract

The study aim was to determine whether a relationship exists between the cardiovascular response, measured by HR and HRV and the magnitude of whole-body vibration. Cardiovascular response of sixty male participants in four groups, was measured during three states i.e. 1) no vibration, 2) a reference vibration and 3) an alternative vibration. The reference vibration was the same for all groups with the alternative vibrations different for each group. Weighted vertical seat vibration was 0.66 $m.s^{-2}$, root-mean-square for the reference and 0.70, 0.73, 0.76 and 0.79 $m.s^{-2}$, root-mean-square for the alternative vibrations. Vibrations only differed in magnitude with the difference between alternative vibrations based on relative difference thresholds. Nonparametric tests compared cardiovascular indicators between groups at State 3 adjusted for state of departure i.e. State 2. No significant differences between groups were found for most of the indicators, suggesting no relationship between cardiovascular response and the magnitude of whole-body vibration.

**Practitioner Summary -** The cardiovascular response to the magnitude of whole-body vibration on an automobile seat was investigated. Results suggest that no relationship exists between the magnitude and cardiovascular response and that the latter may not be as effective as other objective measures (e.g. acceleration) in evaluating the human's response to whole-body vibration.

**Keywords**: whole-body vibration; cardiovascular response; heart rate; heart rate variability; ride comfort

# 1 Introduction

Many environments, such as buildings and vehicles (e.g. cars, trains, planes, ships, etc.), expose humans to vibration. Understanding the effect of vibration on comfort, perception, health and safety is important in order to ensure the environment does not adversely influence these aspects. Quantifying the response of humans to whole-body vibration has been the subject of many studies (Whitham and Griffin, 1978; Parsons et al., 1979; Paddan and Griffin, 2002a; Mansfield and Maeda, 2011; Basri and Griffin, 2012). Standards (such as ISO2631, 1997; BS6841, 1987) have been formulated to guide the evaluation of the effect of vibration on health, comfort, perception and motion sickness. Frequency weightings established in these standards can be used to compare the vibration in different vehicles or different suspension systems in a vehicle. Knowledge of the absolute vibration thresholds (Parsons and Griffin, 1988) provides the magnitudes below which vibration is unlikely to be perceived. Knowledge of difference thresholds provides the smallest change in vibration magnitude that can be detected (Mansfield and Griffin, 2000; Morioka and Griffin, 2000; Forta, Morioka and Griffin, 2009; Gräbe et al., 2020). Most of the human response to vibration research mentioned above, link objective parameters (e.g. measured acceleration) to subjective perception. Measuring physiological response could provide additional, and/or alternative objective measures to quantify human response to vibration.

Most physiological parameters are linked to the autonomic nervous system. The autonomic nervous system maintains internal homeostasis within the human body at a subconscious level via the parasympathetic and sympathetic branches. The parasympathetic branch is responsible for the resting state, controlling the body processes during ordinary situations ("Rest and Digest"). In general, parasympathetic responses increases heart rate variability (HRV), slow heart rate (HR), reduce blood pressure, stimulate the digestive tract to process food and use energy to restore and build tissue

(Task Force, 1996; Cannon, 1939; Hall, 2006). The sympathetic branch is responsible for "Fight or Flight" reactions during stressful situations. Depending on the specific balance between parasympathetic and sympathetic cardiac influence, sympathetic branch activity may decrease HRV, increase HR and the force of cardiac contractions, increase muscle strength and causes the body to release stored energy (Task Force, 1996; Cannon, 1939; Hall, 2006).

Studies have investigated the effect of whole-body vibration on human physiological response considering various physiological parameters. The effect of sinusoidal vertical whole-body vibration on blood pressure, cardiac index, body temperature (Hood et al., 1966), auditory evoked brain potentials (Ullsperger et al., 1986), oxygen uptake, respiratory frequency (Hood et al., 1966; Maikala et al., 2006) and HR (Hood et al., 1966; Ullsperger et al., 1986; Maikala et al., 2006) has been considered. Manninen (1985, 1986) considered the effect of sinusoidal and random whole-body vibration and noise on temporary hearing thresholds, blood and pulse pressure, R-wave amplitude, haemodynamic indices and HR. Hornick and Lefritz (1966) considered the effect of random, long duration vibration at three intensities on HR and respiratory rate. The effect of sinusoidal vertical and random multi-axial whole-body vibration on HRV during simulated driving was investigated by Jiao et al. (2004) and Zhang et al. (2018). Jiao et al. (2004) investigated the effect of whole-body vibration on driving fatigue and Zhang et al. (2018) whether HRV can be used as a measure of drowsiness. Urban driving and its effect on physiological response was investigated by Antoun et al. (2008) considering blood pressure, cortisol, HRV and HR. Many of the studies found changes in various physiological parameters due to whole-body vibration. Maikala et al. (2006) states that "occupational exposure to low-frequency whole-body vibration in the region of 2-20 Hz and between the intensities of 0.1-0.5 g, root-mean-square (r.m.s.) elicits cardiorespiratory responses comparable to moderate exercise." Not only is it important to know whether physiological parameters change due to whole-body vibration and the possible implication on health, but whether a relationship exists between them. If a relationship exists, physiological parameters could be used as additional and/or alternative objective measures in quantifying human response to whole-body vibration. Other than Hood et al. (1966), Hornick and Lefritz (1966) and Ullsperger et al. (1986) that considered the effect of the magnitude of whole-body vibration, most studies considered the effect of frequency. No studies were found that considered the relationship between the magnitude of whole-body vibration and physiological responses.

Human comfort can be affected by various factors. These include psychological effects, ergonomics, noise and vibration exposure. Umemura and Honda (1998) investigated the influence of music and noise on HRV and comfort. It was found that rock music and noise produced increases in the sympathetic cardiac control as measured by HRV and a sense of discomfort. Liu et al. (2008) investigated human thermal comfort with the aid of HRV quantification. Results indicated that sympathetic activity plays an important role in subjects' thermal discomfort and that the LF/HF ratio may be used as an indicator for human thermal comfort.

In the current study the discomfort arising from vibrations are of interest. One study (Chang and Hwang, 2011) investigated the use of electroencephalogram data of drivers to evaluate and improve vehicle ride comfort. They showed that it is feasible to use electroencephalogram data in the evaluation of ride comfort and that it can be used to improve it. They claimed that "this method can predict vehicle performance more precisely in a shorter time leading to the design of vehicles with greater ride comfort". This suggests that using physiological responses as an objective measure in quantifying the effect of vibration on comfort is possible and that it may be beneficial to the process.

Using HR and HRV instead of electroencephalogram data, or some of the other physiological parameters, has the advantage, at this time of simpler and more readily available equipment. For example, smart watches with wrist-based HR sensors.

The aim of the current study was to determine whether a relationship exists between the cardiovascular response, as measured by HR and HRV and the magnitude of whole-body vibration. If a relationship exists, HR and/or HRV may be an additional and/or alternative objective measure to be used to quantify human response to whole-body vibration in general and in vehicle ride comfort in particular.

## 2 Materials and Methods

### *2.1 Participants*

Participants included 60 males, aged between 20 to 30 years. The sample size required for the study was intended to be determined using the estimates from a pilot study (N = 10). Large variation in the pilot study resulted in large sample size estimates. Hence, in reference to literature (Liu et al., 2008; Umemura and Honda, 1998; Zhang et al., 2018), a more practically feasible sample size of 15 participants per group was decided on. The 60 participants were randomly allocated to four groups of 15 each. Each participant was provided with an informed consent form stipulating the medical conditions that would deem them unfit to participate (e.g. active disease of respiratory system, genitourinary system, cardiovascular system; active disease or defect of the musculo-skeletal system; active chronic disease or disorder of the nervous system; mental health; recent trauma and surgical procedures). Participants were also excluded if they smoked, were using any medication or had any prosthesis. Participants took part on a voluntary basis and were able to withdraw from the experiment at any time. Ethical clearance was obtained from the Research Ethics Committees of the faculties of Engineering, Built Environment and Information Technology and Health Sciences at the University of Pretoria (Ethical approval reference number EBIT/71/2016).

### *2.2 Apparatus*

An automobile seat was mounted on a 25 kN hydraulic actuator (PL 25 N, Instron structural testing systems) via the seat-actuator interface (Figure 1). The seat-actuator interface included a footrest and mounting points for a standard 3-point safety belt. The seat-actuator interface was designed with high structural integrity and with natural frequencies outside the range of interest to whole-body vibration (i.e. 0.5 – 80 Hz). The first two natural frequencies of the interface occur at 81.97 Hz and 92.56 Hz, with each having a rotational mode shape about the vertical axis. The next two natural frequencies at 105.6 Hz and 112.6 Hz showed the structure pivoting left-right and forward-backward about the bolt connection point between the interface and the actuator. Higher frequencies affected the footrest and safety belt mounting points.

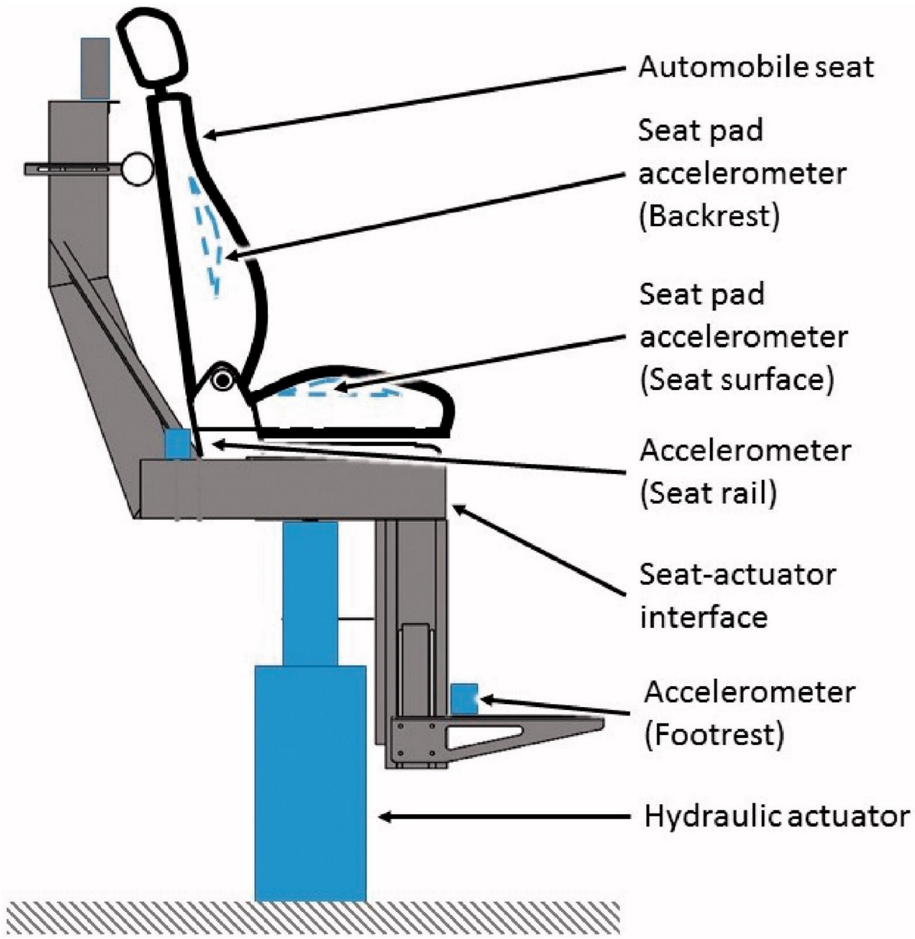


**Figure 1**: Experimental setup of the automobile seat on the hydraulic actuator

Vertical acceleration was measured on the footrest (393B04, PCB Piezotronics) and the seat rail (CXL 10LP3, Crossbow technology). Acceleration in the fore-aft, lateral and vertical directions was measured on the seat surface below the ischial tuberosities of the participant using a seat pad accelerometer (SV39A, Svantek). Acceleration of the backrest was measured in the fore-aft and vertical direction using a seat pad accelerometer (5313A, Dytran Instruments). National Instruments cards (Analog to Digital, PCI-4472; Digital to Analog, PCI-6733 and BNC-2110) and a servo-controller (Control Cube $C^3$ 7500, Zwick / Roell) were used to control the actuator and record the signals from the accelerometers. Data was recorded at 2000 Hz. The cardiovascular measurements were made with a sampling rate of 1000 Hz using the Zephyr™ Bioharness (Medtronic, USA). The Bioharness strap was worn around the chest by participants as recommended by the manufacturer.

The experiment was setup according to ISO13090 (1998). Emergency stop buttons were placed within reach of the experimenter and the participant. Participants wore the seat belt for the entire duration of the experiment. As the environment may have an effect on the cardiovascular state of the participant (Schnell, 2013), the following controls where implemented. Room dividers were placed around the seat setup limiting visual inputs to the participant. Aural input was minimised by stopping all other test in the laboratory and having participants use earplugs. The temperature in the lab was regulated at 24 °C.

### *2.3 Procedure*

On the day of testing participants were briefed. During State 1 participants were seated on the seat with no vibration input for five minutes. The HR and HRV measurements during the second half represents the participant’s cardiovascular response for this state (Figure 2). At the end of State 1 participants were informed that two vibrating states of the experiment would start. During State 2 the seat was excited with a reference vibration, which was the same for all four groups. Between State 2 and 3 there was a two second pause with no excitation of the seat. During State 3 the seat was excited with the alternative vibration associated with the group to which the specific participant was assigned. All participants were initially subjected to the same reference vibration in State 2 before subjecting the four groups to four different alternative vibrations. This was done, firstly, as the time required for the cardiovascular indicators to normalise was unknown. By not randomizing the order of the reference and alternative vibration, the effect of the duration between them were minimised and biological variation within participants circumvented. Secondly, to have all groups start from the same reference vibration before subjecting them to the alternative vibration. Thus, State 2 is the baseline state from which participants were exposed to alternative vibrations that differed in magnitude.

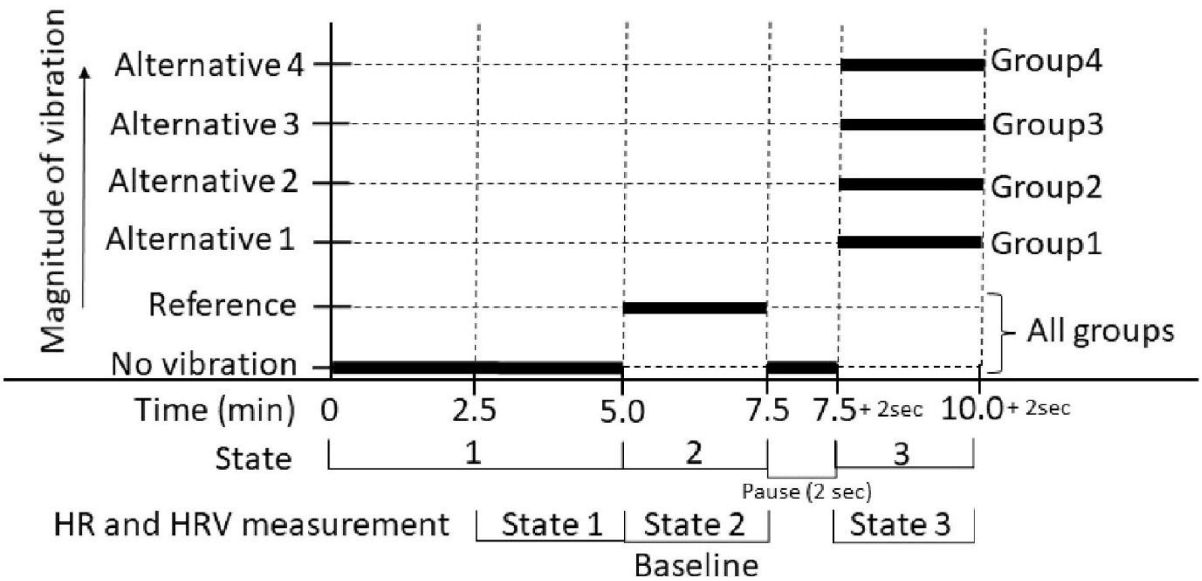


**Figure 2**: Procedure of experiment. State 1 was associated with the first 5 min of the experiment, with participants exposed to no vibration. State 2 was the next 2.5 min, with participants exposed to the reference vibration. State 3 was the last 2.5 min, with participants exposed to the alternative vibration associated with the participant's randomly assigned group.

### *2.4 Whole-body vibration*

The whole-body vibration experienced by participants was evaluated with respect to comfort according to BS6841 (1987). The BS6841 standard was used instead of the more recent ISO2631 (1997) to allow comparison to the difference thresholds reported by Gräbe et al. (2020). Measured accelerations were filtered to remove frequency content below 0.5 Hz and above 80 Hz and weighted in the frequency domain with the applicable weighting function as specified in BS6841 (1987) during post-processing. The frequency weighted accelerations were multiplied by the relevant multiplying factors specified in BS6841 (1987). The accelerations that have been frequency weighted and multiplied by the factors produce the weighted acceleration. The r.m.s. of the weighted acceleration in each of the axis (i.e. fore-aft, lateral and vertical) at the three locations (i.e. footrest, seat surface and backrest) were calculated. The r.m.s. was used to represent the magnitude of the acceleration since the crest factor for all vibrations was below six (BS6841, 1987). The point ride value for each of the three measurement points (i.e. seat surface, backrest and footrest) was calculated by taking the root-sums-of-squares (r.s.s.) of the weighted acceleration in the different axes, i.e. $a_x$, $a_y$, $a_z$, at the specific measurement point (Equation 1). If a weighted value in any axis was less than 25% of the dominant axis at that point, it was omitted from the point ride value (PRV) calculation. An overall ride value was calculated by taking the r.s.s. of the three point ride values, i.e. $PRV_{footrest}$, $PRV_{seat\ surface}$, $PRV_{backrest}$ (Equation 2).

$$\text{point ride value} = \sqrt{a_x^2 + a_y^2 + a_z^2} \tag{1}$$

$$\text{overall ride value} = \sqrt{\text{PRV}_{footrest}^2 + \text{PRV}_{seat\ surface}^2 + \text{PRV}_{backrest}^2} \tag{2}$$

The vibrations used as input to the seat in State 2 and State 3 are based on the vertical vibration measured on the seat rail of a left hand drive Range Rover Evoque eD4 Sports Utility Vehicle on a 4-poster test rig. The vehicle was excited with road profiles corresponding to driving on a test track used for ride comfort evaluations at 80 km/h

(Gräbe et al., 2020). The measured vertical seat rail vibration of the vehicle over the smooth road was used to generate the reference vibration input to the seat in the current study. Four alternative vibration inputs were generated by increasing the magnitude of the reference vibration. The increase was selected to ensure that the difference in the unweighted r.m.s. seat rail acceleration between the alternative vibrations was approximately 5%. The difference between the alternative vibrations was based on the relative difference thresholds reported by Gräbe et al. (2020). The minimum, 25th percentile, median, 75th percentile and maximum relative difference thresholds, considering the vertical component ride value[1] over the smooth road were 6.52%, 8.71%, 10.13%, 13.18% and 22.89% respectively. With the selected increase the resulting relative differences between the alternative vibrations on the seat surface in the vertical direction were 4.3% (Group 2 vs. 1), 8.6% (Group 3 vs. 1) and 12.9% (Group 4 vs. 1). The reference and alternative vibrations are described in Table 1. The frequency content of the accelerations measured on the seat rail of the seat-actuator interface for the reference vibration is shown in Figure 3. The decrease in energy above 40 Hz results from the bandwidth of the 4-poster test rig in Gräbe et al. (2020). The four alternative vibrations differ in magnitude but have the same frequency content as the reference vibration. The durations of the reference and alternative signals were two minutes and thirty seconds each.

[1] The vertical component ride value in Gräbe et al. (2020) is equivalent to the r.m.s. of the weighted vertical seat surface vibration in the current study.

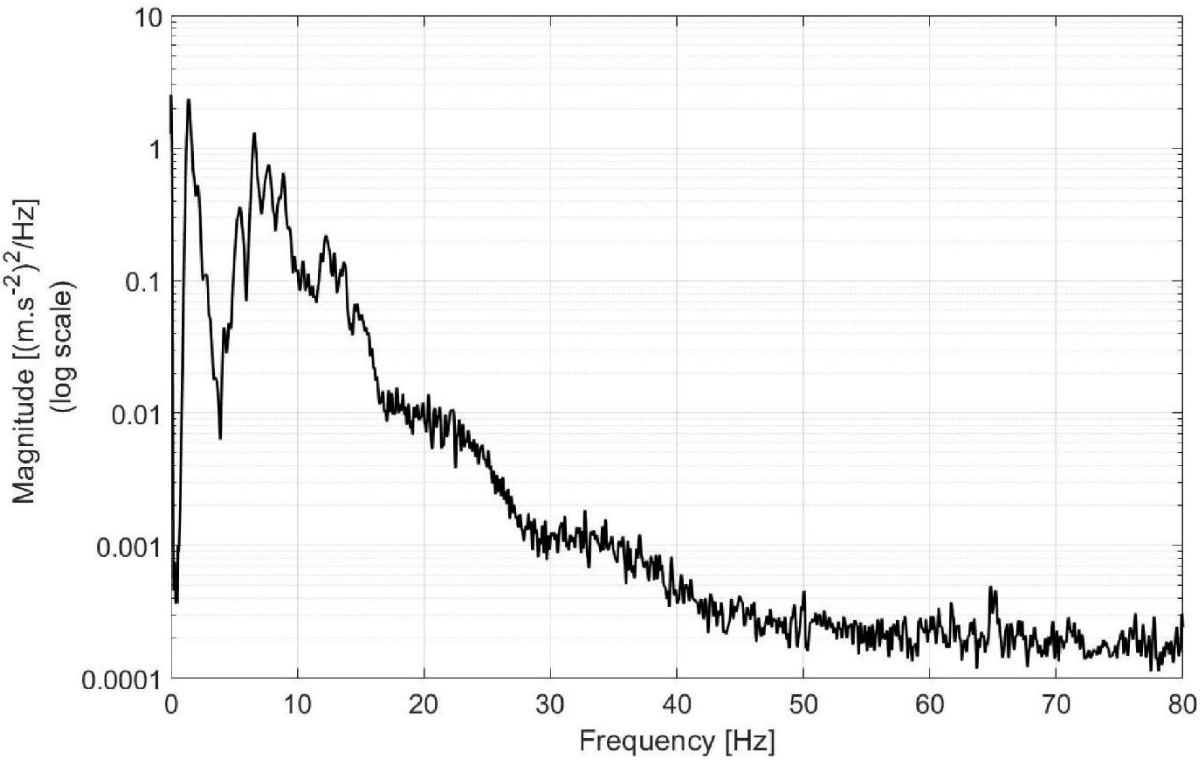


**Figure 3:** Power spectral density of the unweighted acceleration measured on the seat rail of the seat-actuator interface for the reference vibration (0.1 Hz frequency resolution, 42 degrees of freedom).

From Table 1 it is noted that the vertical axis was, as expected, dominant on the seat surface. The other two axes were less than 25% of the dominant axis and therefore omitted from the calculation of the seat surface point ride value. Therefore, the seat surface point ride value is the same as the vertical seat surface vibration. The point ride value for the backrest vibrations was determined from the r.s.s. of the weighted fore-aft and vertical vibration. Considering the overall ride value, the magnitude of acceleration associated with State 2 and 3 falls into the range of fairly uncomfortable to uncomfortable (BS6841, 1987). To put the vibration considered in the current study into context, the weighted vertical seat vibration is compared to the range reported in Paddan and Griffin (2002b). They reported weighted vertical vibration magnitudes for 25 cars ranging from 0.16 – 0.78 m.s$^{-2}$, r.m.s. The vehicles were driven over suitable and appropriate surfaces. The vibration considered in the current study are on the upper end of the reported levels for cars.

**Table 1:** Vibration input to seat (unweighted vibration magnitude measured on seat rail) and vibration to participants (weighted vibration at the seat surface, backrest and footrest as well as the backrest point ride value and overall ride value) in the four groups for State 2 (reference vibration) and State 3 (alternative vibration).

| | | | Median (Interquartile range: 25th percentile – 75th percentile) [m.s$^{-2}$, r.m.s. or r.s.s.[a]] | |
|---|---|---|---|---|
| Location | Direction | Group | State 2 | State 3 |
| Seat rail (Unweighted) | Vertical | 1 | 2.03 (2.02 - 2.03) | 2.16 (2.15 - 2.17) |
| | | 2 | 2.01 (2.01 - 2.02) | 2.21 (2.20 - 2.22) |
| | | 3 | 2.02 (2.01 - 2.04) | 2.32 (2.30 - 2.34) |
| | | 4 | 2.02 (2.01 - 2.04) | 2.47 (2.45 - 2.50) |
| Overall ride value (Weighted) | N/A | 1 | 0.81 (0.79 - 0.84) | 0.85 (0.84 - 0.89) |
| | | 2 | 0.82 (0.78 - 0.85) | 0.89 (0.85 - 0.92) |
| | | 3 | 0.82 (0.79 - 0.84) | 0.94 (0.89 - 0.95) |
| | | 4 | 0.81 (0.78 - 0.84) | 0.97 (0.93 - 0.99) |
| Seat surface (Weighted) | Vertical | 1 | 0.66 (0.64 - 0.71) | 0.70 (0.68 - 0.74) |
| | | 2 | 0.66 (0.63 - 0.70) | 0.73 (0.70 - 0.75) |
| | | 3 | 0.67 (0.65 - 0.70) | 0.76 (0.73 - 0.79) |
| | | 4 | 0.67 (0.62 - 0.68) | 0.79 (0.74 - 0.82) |
| | Lateral | 1 | 0.07 (0.04 - 0.11) | 0.09 (0.05 - 0.11) |
| | | 2 | 0.06 (0.03 - 0.09) | 0.06 (0.03 - 0.09) |
| | | 3 | 0.08 (0.05 - 0.16) | 0.10 (0.06 - 0.17) |
| | | 4 | 0.11 (0.06 - 0.15) | 0.13 (0.07 - 0.18) |
| | Fore-aft | 1 | 0.05 (0.05 - 0.09) | 0.06 (0.05 - 0.10) |
| | | 2 | 0.05 (0.05 - 0.06) | 0.06 (0.05 - 0.07) |
| | | 3 | 0.05 (0.05 - 0.07) | 0.06 (0.05 - 0.08) |

| | | | | |
|---|---|---|---|---|
| | | 4 | 0.05 (0.05 - 0.06) | 0.06 (0.06 - 0.07) |
| Backrest (Weighted) | Point ride value | 1 | 0.32 (0.31 - 0.33) | 0.34 (0.33 - 0.35) |
| | | 2 | 0.32 (0.31 - 0.34) | 0.36 (0.34 - 0.37) |
| | | 3 | 0.32 (0.31 - 0.33) | 0.36 (0.35 - 0.38) |
| | | 4 | 0.32 (0.31 - 0.33) | 0.38 (0.37 - 0.40) |
| | Vertical | 1 | 0.23 (0.23 - 0.23) | 0.25 (0.25 - 0.25) |
| | | 2 | 0.23 (0.23 - 0.23) | 0.25 (0.25 - 0.26) |
| | | 3 | 0.23 (0.23 - 0.23) | 0.27 (0.26 - 0.27) |
| | | 4 | 0.23 (0.23 - 0.23) | 0.28 (0.28 - 0.28) |
| | Fore-aft | 1 | 0.23 (0.21 - 0.24) | 0.24 (0.22 - 0.25) |
| | | 2 | 0.22 (0.21 - 0.25) | 0.25 (0.23 - 0.27) |
| | | 3 | 0.23 (0.20 - 0.24) | 0.25 (0.23 - 0.27) |
| | | 4 | 0.22 (0.20 - 0.23) | 0.26 (0.23 - 0.29) |
| Footrest (Weighted) | Vertical | 1 | 0.33 (0.32 - 0.34) | 0.35 (0.34 - 0.36) |
| | | 2 | 0.34 (0.33 - 0.34) | 0.37 (0.36 - 0.38) |
| | | 3 | 0.33 (0.33 - 0.35) | 0.38 (0.38 - 0.40) |
| | | 4 | 0.34 (0.33 - 0.34) | 0.41 (0.40 - 0.42) |

[a]Units of $m.s^{-2}$, r.s.s. for point ride value and overall ride value. Units of $m.s^{-2}$, r.m.s. for other values.

### *2.5 Cardiovascular response*

Autonomic function and stress responses to the environment can be non-invasively evaluated by observing the cardiovascular response, as measured by HR and HRV. HRV is the variation in time (ms) between the RR intervals of a QRS complex series (i.e. tachogram). HRV reflects the ability of the autonomic nervous system to respond to changes in external influences and/or stressors, thereby maintaining internal homeostasis (Task Force, 1996). Several HRV indicators are linked to the activity of the sympathetic and parasympathetic branches of the autonomic nervous system. High variability indicates the ability of the autonomic nervous system to adapt to the environment while low values present an even heartbeat, without variation, unable to preserve internal physiological homeostasis (Task Force 1996; Montano et al. 2009; Malliani 2000; Kim et al. 2018). Indicators considered in the current study were included based on their ability to indicate the activity of the parasympathetic and sympathetic branches of the autonomic nervous system, especially during a stressor. Table 2 presents the indicators considered in the current study and the expected change in them during a stressor as indicated in literature (Task Force 1996; Montano et al. 2009; Malliani 2000; Kim et al. 2018).

The cardiovascular measurements in State 1 consisted of a two and a half minutes stabilization period followed by two and a half minutes RR interval data sampling and HRV quantification period. Similarly, RR interval data sampling and HRV quantification was performed over the two and a half minutes in State 2 and 3. RR interval series (tachogram) of at least 1 minute is recommended to assess high frequency (HF) power and 2 minutes for the low frequency (LF) component (Task Force, 1996). Low frequency ranges from 0.04 – 0.15 Hz and the high frequency ranges from 0.15 – 0.4 Hz. The frequency-domain results were obtained from the Fast Fourier Transform spectrum. The Bioharness data obtained was converted into a MATLAB® (R2017b, MathWorks) structure which was imported into Kubios (Version 3.0.2, Kubios) for HRV quantification. Kubios software was used to analyse the tachograms by calculating the HRV indicator values over a two minute window. The window shifted on by 10 seconds until the end of the two and a half minute tachogram. The data from the four two minute analysis windows were averaged to give a single value for HR and HRV indicators during the three states.

**Table 2**. Heart rate and heart rate variability indicators and their expected response to a stressor (Task Force 1996; Montano et al. 2009; Malliani 2000; Kim et al. 2018)

| | Origin of autonomic control (Parasympathetic or sympathetic branch) | Response to a stressor |
|---|---|---|
| Indicator [unit] | | |
| Heart rate [bpm] | Parasympathetic (short term) and sympathetic (long term) influence on HRV | Increase |
| Mean RR [ms] | The mean of the RR intervals between successive QRS complexes, result of vagal (short term) and sympathetic (long term) influence on HRV. | Decrease |
| Variability indicator [unit] | | |
| STDRR [ms] | Standard deviation of RR intervals between successive QRS complexes, indicator of vagal (short term) and sympathetic (long term) influence on HRV (Overall HRV). | Decrease |
| RMSSD [ms] | Root-mean-square of the standard deviation between RR intervals, indicator of vagal influence (short term). | Decrease |
| pNN50 [%] | The percentage of successive RR interval differences larger than 50ms computed over the entire recording, indicator of vagal influence (short term) on HRV. | Decrease |
| LF Power [$ms^2$] | Indicator of sympathetic influence including a parasympathetic component. | Decrease |
| HF Power [$ms^2$] | Indicator of only parasympathetic influence. | Decrease |
| LF/HF [-] | Indicator of autonomic balance | Increase |

### *2.6 Statistical methods*

In the current study we observed repeated measures derived from a longitudinal study to assess the cardiovascular response from baseline (State 2) to State 3 following an increase in the magnitude of vibration. To determine whether a relationship exists between cardiovascular response and the magnitude of whole-body vibration, the responses of groups were compared at State 3, adjusted for the response at state of departure (i.e. State 2), using nonparametric multivariable linear regression. Nonparametric multivariable linear regression does not make assumptions about the functional form and makes use of bootstrapping for estimation. In the regression, 'magnitude of vibration' was the predictor and 'cardiovascular indicator response at state of departure' the covariate. Other possible covariates may be smoking status, age, sex and medication. However, recruiting only men within the range 20 to 30 years, that did not smoke or used any medication and furthermore as a result of randomization of participants in four groups, it was not deemed necessary to include these covariates. Randomization of participants within groups was confirmed at State 1 using the Kruskal-Wallis test (i.e. nonparametric one-way analysis of variance). To deal with the small sample size and potentially skewed data, non-parametric testing was done. The 0.05 level of significance was employed. Statistical software Stata® (15, StataCorp) was used in the data analysis.

## 3 Results

HR and HRV indicators are summarized by group and state in Table 3. The groups at State 1 did not differ significantly for any of the cardiovascular indicators, which confirms the randomization of participants at State 1. Reported in Table 4 are cardiovascular responses (predicted means) within groups and the comparison of groups with respect to the cardiovascular response at State 3, adjusted for response at state of departure (i.e. State 2), using nonparametric linear regression. The cardiovascular responses (predicted means) within groups reported in Table 4 are graphically presented in Figure 4. The pure parasympathetic (vagal) cardiac control indicators (RMSSD, pNN50 and HF power) indicate a decreasing trend when increasing the magnitude of whole-body vibration. This is similar to what is expected to happen during a stress response (Table 2). The indicators

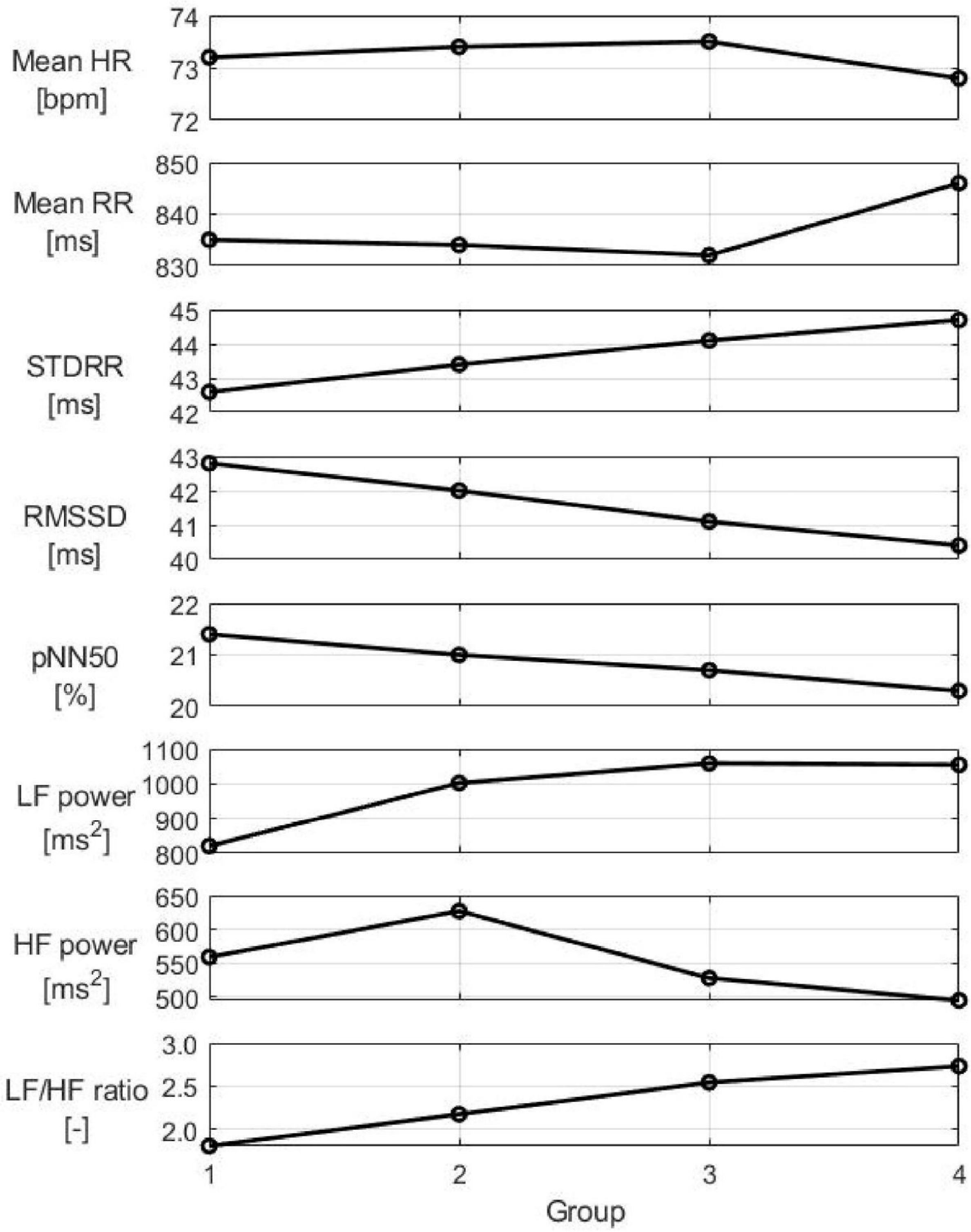


**Figure 4**: Relationship between the cardiovascular indicators and magnitude of whole-body vibration (i.e. Group). The cardiovascular indicator values are the predicted means at State 3 adjusted for State 2 using nonparametric linear regression.

**Table 3:** Median (Interquartile range: 25th percentile – 75th percentile) values for the cardiovascular indicators over the four groups and three states

| Indicator [unit] | Group | Median (Interquartile range: 25th percentile – 75th percentile) | | |
|---|---|---|---|---|
| | | State 1 | State 2 | State 3 |
| Mean HR [bpm] | 1 | 73.7 (69.1 - 84.4) | 76.0 (70.3 - 88.2) | 78.4 (70.3 - 86.2) |
| | 2 | 74.4 (59.4 - 84.2) | 78.0 (61.9 - 85.0) | 77.2 (64.3 - 84.7) |
| | 3 | 70.0 (61.2 - 75.9) | 71.9 (63.2 - 78.3) | 71.4 (65.2 - 80.5) |
| | 4 | 67.9 (56.5 - 74.1) | 70.8 (60.4 - 80.9) | 69.5 (57.4 - 79.1) |
| | *p*-value[a] | .248 | | |
| Mean RR [ms] | 1 | 786 (716 - 868) | 784 (683 - 824) | 766 (697 - 847) |
| | 2 | 822 (740 - 1019) | 775 (717 - 975) | 793 (717 - 942) |
| | 3 | 864 (801 - 988) | 839 (769 - 956) | 846 (748 - 925) |
| | 4 | 853 (790 - 1069) | 853 (747 - 994) | 865 (764 - 1049) |
| | *p*-value[a] | .270 | | |
| STDRR [ms] | 1 | 57.6 (41.9 - 67.2) | 44.5 (26.1 - 50.1) | 42.7 (29.7 - 46.1) |
| | 2 | 67.5 (48.9 - 99.5) | 50.1 (32.8 - 62.8) | 44.5 (35.8 - 52.7) |
| | 3 | 56.9 (51.9 - 79.5) | 42.5 (37.6 - 56.5) | 44.2 (38.6 - 52.2) |
| | 4 | 64.7 (46.9 - 85.6) | 51.5 (32.8 - 74.0) | 42.6 (35.6 - 56.2) |
| | *p*-value[a] | .365 | | |
| RMSSD [ms] | 1 | 54.4 (35.0 - 69.0) | 33.8 (25.4 - 52.5) | 34.5 (25.3 - 44.3) |
| | 2 | 54.6 (42.8 - 89.2) | 43.3 (26.2 - 57.5) | 44.7 (31.1 - 54.8) |
| | 3 | 51.8 (46.2 - 58.2) | 37.1 (30.9 - 47.4) | 33.9 (30.5 - 41.5) |
| | 4 | 69.8 (39.8 - 89.6) | 43.1 (28.7 - 88.8) | 39.7 (33.2 - 58.0) |
| | *p*-value[a] | .490 | | |
| pNN50 [%] | 1 | 37.7 (14.3 - 44.7) | 13.7 (4.8 - 28.0) | 12.4 (3.5 - 22.5) |
| | 2 | 36.8 (20.1 - 55.3) | 18.5 (4.0 - 37.5) | 18.5 (4.8 - 34.5) |
| | 3 | 32.4 (23.5 - 36.8) | 17.7 (11.1 - 31.7) | 12.8 (10.8 - 17.5) |
| | 4 | 39.0 (16.6 - 58.0) | 27.4 (7.2 - 48.7) | 23.2 (10.7 - 41.6) |
| | *p*-value[a] | .560 | | |

| | | | | |
|---|---|---|---|---|
| LF Power | 1 | 1050 (630 - 1720) | 970 (560 - 1800) | 520 (300 - 1310) |
| [ms$^2$] | 2 | 1920 (900 - 4560) | 630 (480 - 2100) | 820 (480 - 1990) |
| | 3 | 1510 (960 - 2410) | 990 (760 - 1300) | 1120 (680 - 1260) |
| | 4 | 1780 (740 - 3180) | 1020 (600 - 1290) | 650 (530 - 1770) |
| | *p*-value[a] | .270 | | |
| HF Power | 1 | 1360 (700 - 1910) | 410 (280 - 570) | 390 (160 - 550) |
| [ms$^2$] | 2 | 1330 (580 - 2220) | 630 (330 - 1050) | 590 (330 - 980) |
| | 3 | 1370 (970 - 1810) | 880 (360 - 1110) | 480 (270 - 670) |
| | 4 | 1980 (780 - 3430) | 630 (320 - 2390) | 450 (230 - 810) |
| | *p*-value[a] | .509 | | |
| LF/HF | 1 | 0.99 (0.39 - 1.91) | 2.53 (1.64 - 3.64) | 2.53 (1.88 - 3.51) |
| [-] | 2 | 1.29 (0.74 - 2.16) | 1.41 (1.04 - 2.08) | 1.71 (1.24 - 2.70) |
| | 3 | 1.09 (0.51 - 2.04) | 1.42 (0.69 - 3.46) | 2.17 (1.26 - 3.88) |
| | 4 | 0.83 (0.34 - 1.53) | 1.24 (0.47 - 3.52) | 0.74 (0.41 - 4.83) |
| | *p*-value[a] | .485 | | |

[a] Groups did not differ significantly at State 1 for any of the cardiovascular indicators (Kruskal-Wallis test, i.e. nonparametric one-way analysis of variance)

representing a combination of the parasympathetic (vagal) and sympathetic HR control (STDRR and LF power) increased. These observations, together with an increase in the autonomic balance indicator (LF/HF), present evidence of autonomic changes similar to a physiological stress response. However, considering the comparison of groups at State 3 with respect to the cardiovascular indicators, no significant differences (*p*-values < 0.05) between the groups were found for any cardiovascular indicators except for mean RR (between Group 3 and 4), LF power (between Groups 1 and 2) and HF power (between Groups 2 and 3). Marginally significant differences (*p*-values 0.05-0.1) were found for HF power (between Group 1 and 2, Group 2 and 4) and LF/HF (between Group 1 and 2, Group 1 and 3).

**Table 4**: Comparison of groups with respect to cardiovascular response at State 3 adjusted for response at state of departure (i.e. State 2), using nonparametric linear regression.

| | | At State 3 adjusted for State 2 | | | |
|---|---|---|---|---|---|
| | | Predicted mean | *p*-value | | |
| Indicator [units] | Group | | vs 1 | vs 2 | vs 3 |
| Mean HR [bpm] | 1 | 73.2 | - | - | - |
| | 2 | 73.4 | .648 | - | - |
| | 3 | 73.5 | .639 | .716 | - |
| | 4 | 72.8 | .703 | .457 | .128 |
| Mean RR [ms] | 1 | 835 | - | - | - |
| | 2 | 834 | .750 | - | - |
| | 3 | 832 | .638 | .723 | - |
| | 4 | 846 | .308 | .141 | .032* |
| STDRR [ms] | 1 | 42.6 | - | - | - |
| | 2 | 43.4 | .537 | - | - |
| | 3 | 44.1 | .538 | .523 | - |
| | 4 | 44.7 | .538 | .523 | .509 |
| RMSSD [ms] | 1 | 42.8 | - | - | - |
| | 2 | 42.0 | .398 | - | - |
| | 3 | 41.1 | .395 | .422 | - |
| | 4 | 40.4 | .395 | .423 | .395 |
| pNN50 [%] | 1 | 21.4 | - | - | - |
| | 2 | 21.0 | .666 | - | - |
| | 3 | 20.7 | .670 | .674 | - |
| | 4 | 20.3 | .597 | .556 | .438 |
| LF power [ms$^2$] | 1 | 820 | - | - | - |
| | 2 | 1002 | .037* | - | - |
| | 3 | 1058 | .102 | .565 | - |
| | 4 | 1054 | .286 | .760 | .970 |
| HF power [ms$^2$] | 1 | 559 | - | - | - |
| | 2 | 627 | .092$^†$ | - | - |
| | 3 | 528 | .566 | .042* | - |
| | 4 | 495 | .411 | .071$^†$ | .497 |
| LF/HF ratio [-] | 1 | 1.80 | - | - | - |
| | 2 | 2.17 | .088$^†$ | - | - |
| | 3 | 2.54 | .073$^†$ | .107 | - |
| | 4 | 2.73 | .148 | .228 | .455 |

$^†$*p*-value .05-.1: marginally significant; **p*-value < .05: significant difference at 5% level

# 4 Discussion

## *4.1 Relationship between cardiovascular response and the magnitude of whole-body vibration*

The results seem to suggest that there is no relationship between cardiovascular response, as measured by HR and HRV, and the magnitude of whole-body vibration. It is difficult to compare the results to previous studies. Some of these difficulties arise from differences between characteristics of participants (e.g. age, sex), test conditions and procedures, sensory stimuli (e.g. vibration, noise), whole-body vibration (e.g. magnitude, frequency, duration), tasks performed by participants and the aims of the study.

In the current study no significant differences were found for most of the cardiovascular indicators between the groups exposed to different magnitudes of whole-body vibration. This is similar to the results of Ullsperger et al. (1986). They found that the RR intervals did not show a dependence on magnitude. RR intervals did show a dependence on frequency, however there was no significant difference in mean RR and STDRR between the vibration conditions. Hood et al. (1966) showed increases in the HR due to the magnitude of vibration, with the largest HR values at the higher magnitude. Hornick and Lefritz (1966) noted that the mean HR remained elevated over the duration of the test for the lowest of the three magnitudes considered. Hood et al. (1966) and Hornick and Lefritz (1966) did not state whether the differences were significant.

Ullsperger et al. (1986) investigated the effect of vertical sinusoidal whole-body vibration with different magnitudes and frequencies on central nervous processes. They considered nine vibration conditions consisting of no vibration and vibration at four frequencies and two intensities at each frequency (1 Hz: 1.13, 5.53 $m.s^{-2}$, r.m.s.; 2 Hz: 0.79, 5.0 $m.s^{-2}$, r.m.s.; 4 and 8 Hz: 0.57, 3.6 $m.s^{-2}$, r.m.s.). Hood et al. (1966) investigated the cardiopulmonary effects of sinusoidal whole-body vibration at six frequencies and two magnitudes at each frequency (2, 4, 6, 8, 10, 12 Hz at 5.89 and 11.77 $m.s^{-2}$ peak acceleration). Besides the differences mentioned between the current study and Hood et al. (1966), it should also be noted that participants in their study were laying semi-supine on a table. In the study of human response to prolonged random vibration by Hornick and Lefritz (1966), they considered random vibration with a frequency bandwidth of 1-12 Hz and three magnitudes (0.98, 1.47 and 1.96 $m.s^{-2}$, r.m.s.). The magnitude and frequency of the random whole-body vibration considered in Hornick and Lefritz (1966) are the closest to that considered in the current study. However, their vibration duration of 4 hours was much longer than the 2.5 minutes per state in the current study. HR and HRV can change over the duration of vibration. Hornick and Lefritz (1966) commented on the response of HR over the duration of the test, stating "heart rate data assume the classical form where elevation in the rate occurs at the onset of the simulation…, and a gradual return to the normal resting state…occurs". Zhang et al. (2018) investigated the effect of sinusoidal vertical and random multi-axial whole-body vibration on HRV during 60 min of simulated driving. They showed that the mean LF/HF ratios increased significantly over time compared to a no vibration condition, with significant increases after the first 15 min of exposure to vibration. RMSSD and pNN50 significantly decreased over time during vibration compared to the no vibration condition. They state that the increase in mean LF/HF ratios "indicates that sympathetic activity increases during extended periods of exposure to low frequency vibration". They contributed the changes in HRV to the increased mental workloads and/or stress during vibration exposure. Besides the differences in magnitude, frequency, waveform and duration of the vibration between the studies, the participants performed different tasks during testing. In the current study participants performed no task. Participants in the study of Ullsperger et al. (1986) had to count the omitted lights on a modified Mackworth-clock, perform piloting tasks associated with low-altitude high-speed flight in Hornick and Lefritz (1966) and do passive limb movement and leg exercises in Hood et al. (1966). Antoun et al. (2018) investigated the effect of urban driving on physiological response. They considered three conditions: a control task, a driving task and an excersice plus driving task. The driving tasks' duration ranged between 22 – 50 min. They found that HR was elevated and HRV was reduced during the driving task compared with the control. They suggest that the changes in HR and HRV are predominantly due to changes in the parasympathetic branch of the autonomic nervous system, with intermittent sympathetic activation, in the response to driving stress.

Overall it seems that no relationship between physiological response and the magnitude of whole-body vibration have been established, and specifically not between cardiovascular response, as measured by HR and HRV indicators, and the magnitude of whole-body vibration considered in the current study. The current study used a randomized four arm parallel design. Time and resources permitting, the study may be improved by performing the study as a four period crossover design.

### *4.2 Applicability of cardiovascular response as an objective measure in the quantification of ride comfort*

As stated in section 2.4, the relative differences between the alternative vibrations on the seat surface in the vertical direction are 4.3% (Group 2 vs. 1), 8.6% (Group 3 vs. 1) and 12.9% (Group 4 vs. 1). The relative difference in the vertical seat surface vibration between Group 1 and 4 of 12.9% exceeds the median relative difference threshold of 10.13% and is close to the 75$^{th}$ percentile of 13.18%, reported in Gräbe et al. (2020). It would therefore imply that at least 50% and up to 75% of the participants would have a

79.4% probability[2] of identifying the alternative vibration experienced in Group 4 as the larger vibration compared to the vibration of Group 1. However, the results in the current study showed no significant differences in most of the cardiovascular indicators between the groups exposed to the alternative vibrations. This seems to suggest that even though the difference in vibration magnitude on the automobile seat was subjectively perceivable, there was no significant difference in cardiovascular response between the alternative vibrations, at least for the magnitudes considered. Therefore, the evidence seems to be against HR and HRV being possible additional or alternative objective measures to quantify human response to whole-body vibration and to vehicle ride comfort in particular.

## 5 Conclusion

For the whole-body vibration considered in this study no relationship was found between cardiovascular response, as measured by HR and HRV, and the magnitude of whole-body vibration. It was also shown that even though the difference in vibration magnitude on the automobile seat was subjectively perceivable, there was no significant difference in most of the cardiovascular indicators between the alternative vibrations. The results seem to suggest that cardiovascular response may not be as effective as other objective measures (e.g. acceleration) in quantifying the response of humans to whole-body vibration with respect to comfort, as cardiovascular response seems to have no relationship to the magnitude of whole-body vibration and is less sensitive than objective measures, such as acceleration, and subjective perception.

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[2] The level of detection probability (i.e. 79.4%) results from the psychophysical method used in determining the relative difference threshold in Gräbe et al. (2020).

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## 7 Declaration of interest statement

The authors declare that they have no conflict of interest

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