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# Evaluation of Ride Comfort and Vertical Vibration of Ultra-Compact Mobility Vehicles Using Brain Blood Flow

by

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**Abstract**

Ultra-compact mobility vehicles are intended for short trips by one or two passengers. These vehicles are compact and easy to turn around, so they can enter narrow roads and poor-quality roads that are not paved. However, in such road surface environments, they are susceptible to the influence of vibration caused by steps and unevenness of the road surface, and the ride comfort of the vehicle is expected to be adversely affected, even at low speeds. The authors have analyzed an organoleptic evaluation and biological information to improve the ride comfort based on a proposed control method. In this study, the stress state of the occupant due to the vertical vibration was clarified from the cerebral blood flow, which was used as an indicator of the activity of the central nervous system. As a result, changes in psychological state corresponding to the frequency of vibration could be confirmed by the brain blood flow rate. Furthermore, the results tended to coincide with the subjective evaluation. This result, confirmed that cerebral blood flow rate is useful for evaluating ride quality and vehicle vibration.

***Keywords:*** Ride comfort, Near-infrared spectroscopy, Visual analog scale method, Vertical vibration

## 1. Introduction

Ultra-compact mobility vehicles are vehicles that are intended for the near-distance travel of one to two passengers. In recent years, ultra-compact mobility vehicles have been used for car sharing services and traveling to remote areas where public transportation is inadequate or tourist spots that would be burdensome to walk to. These vehicles are compact and easy to turn around; thus, they can enter narrow roads and bad roads that are not paved. In such road surface environments, they are susceptible to the influence of vibration caused by steps and the unevenness of the road surface, and deterioration of the ride comfort of the vehicle is expected even at low speeds.

To improve ride comfort of ultra-compact mobility vehicles by mitigating vertical vibration, the authors proposed an active seat suspension using a voice coil motor at the seat section of the vehicle[1)]. Moreover, from the psychological state evaluation obtained by analyzing sensory evaluation and biological information, we confirmed that reduction in a passenger's vibration does not necessarily result in optimum ride comfort[2)]. Therefore, reducing vibration by taking physical burden into account and vibration control considering the psychological characteristics of the occupant against the vibration are considered necessary for improving ride comfort. Thus, the authors tried to evaluate ride comfort using the electrocardiogram, which provided biological information reflecting the activity of the autonomic nervous system in the past research; the vibration frequency strongly influenced the human vibration sense that we clarified[3)].

In recent years, research that utilizes brain blood flow rate estimated from near-infrared spectroscopy (NIRS) has been conducted in various fields as a method of evaluating psychological state. It is known that brain blood flow reflects central nervous activity, whereas heart rate variability that can be sorted out from electrocardiogram reflects the activity of the autonomic nervous system. Research on evaluating the human body response to vibration from brain blood flow rate has also been conducted. However, to the best of the author’s

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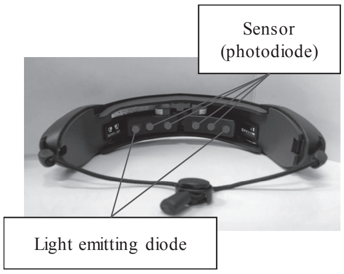
knowledge, research evaluating the influence of vertical vibration of vehicles on cerebral blood flow rate of vehicle occupants has not been conducted. In order to evaluate in detail, it is necessary to clarify the influence of the brain blood flow rate on the frequency of the vertical vibration. Therefore, in this study, we performed an excitation experiment that simulated the environment of the riding condition and clarified the influence of the frequency of vertical vibration on brain blood flow. To clarify whether the change in the brain blood flow rate is an index that can reflect the rider's comfort, subjective evaluation by questionnaire was conducted, and the relationship between the psychological state of the occupant and the brain blood flow rate with respect to the vibration was examined.

## 2. Measurement and Evaluation Method of Brain Blood Flow

In this study, we focused on a method to estimate the psychological state of the study subjects from the changes in brain blood flow in order to evaluate the ride comfort due to vehicle vibration from the activities of the central nervous system. Figure 1 shows the brain activity measurement device HOT-1000(NeU Co., Ltd.) that was used for brain blood flow measurement. This device is equipped with one sensor unit on each side consisting of a light emitting diode (LED) that emits near-infrared light with a wavelength of 810 nm, and two photodiodes. When measuring the cerebral blood flow rate, near infrared light is irradiated from the LED to the prefrontal cortex of the cerebral cortex. The irradiated near-infrared light scatters and reflects onto the cerebral cortex and reaches the scalp again. The amount of reflected near infrared light is measured by a photodiode. This is based on the property that the hemoglobin contained in blood absorbs light. When brain activity becomes active, the amount of hemoglobin contained in the blood increases. Hemoglobin has the characteristic of absorbing light as described above, and as the activity of the brain increases, the amount of light detected by the photodiode decreases. Therefore, it is possible to estimate the brain blood flow rate from the light quantity.

In the experiment, the measurement of cerebral blood flow that is not representative of the psychological and physical load is required. For this reason, the measurement position was *Fp*2 in the 10–20 electrode placement method that is often used in brain blood flow measurement, and as shown in Fig. 2, the measurement device was attached to the subject. Several studies on cerebral blood flow rate and psychological state have already been reported in other fields. Buijs et al.[4] had proven that the autonomic nervous system activity against stress is revealed that the right side of the prefrontal cortex dominates. Moreover, Tanida et al. [5, 6] showed that subjects who are stressed show more activity in the right brain hemisphere. Furthermore Tanaka et al. [7] showed that there is a correlation between railway vibration and brain blood flow. In this study, we decided to measure cerebral blood flow in the prefrontal cortex of the right brain hemisphere, and evaluate it. As for the method of processing data, the difference from the reference value was used reference to the literature. Details are described in section 5.1.

(a) Front side




(b) Back side

Fig. 1 Brain blood flow measuring device.

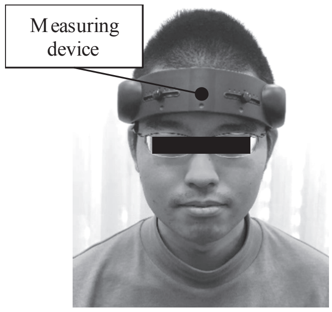



Fig. 2 State of the measurement of brain blood flow.

## 3. Subjective Evaluation Using VAS

The purpose of this study was to clarify whether there is a correlation between the ride comfort that the subject feels and the comfort estimated from the biometric measurement. Therefore, subjective evaluation of comfort using visual analog scale (VAS) was carried out in the experiment, and the comfort that the subject felt was evaluated.

Figure 3 shows an example of the questionnaire sheet used in this experiment. VAS prepares a 10 cm straight line for one question. The answers to the questions are described at both ends of the straight line: The left end shows a negative answer, and the right end shows a positive answer. The subjects were taught how to freely draw a line of intersection at the position indicating the state at that time as the answer to the question. In each question, the center of line means the state that the test subjects themselves does not feel the change comparing the state before the experiment. The both ends means that the test subjects feel best or worst condition. For example, the questions related to drowsiness, the left end was the best drowsiness that can be imagined, and the right end was without drowsiness at all. After that, the distance from the left end to the intersection line was measured, and the score was evaluated as the value of subjective evaluation. It is considered that this score does not change before and after the experiment at the five points in the center; thus, it is possible to think that, if the response is large, the reaction to the question is positive, and if it is small, then the reaction to the question is negative. In this experiment, we set the following question: "Compare with the state before the experiment and show the current comfort." The subject selected the left end if he/she was comfortable and the right end, if he/she was uncomfortable. In this experiment, we asked three more question requiring comparison to the previous experiments. The questions revealed "mood (left end: mood is bad, right end: mood is good)," "sleepiness (left end: sleepy, right end: not sleepy)," and "degree of concentration (left end: not able to concentrate, right end: able to concentrate.).

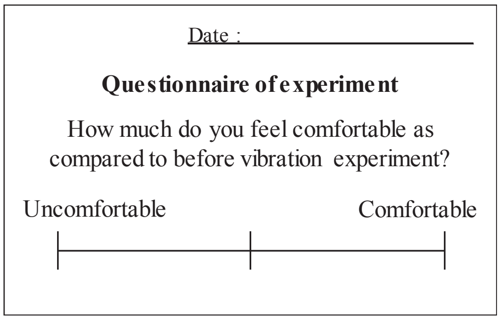



Fig. 3 Questionnaire used in the experiment.

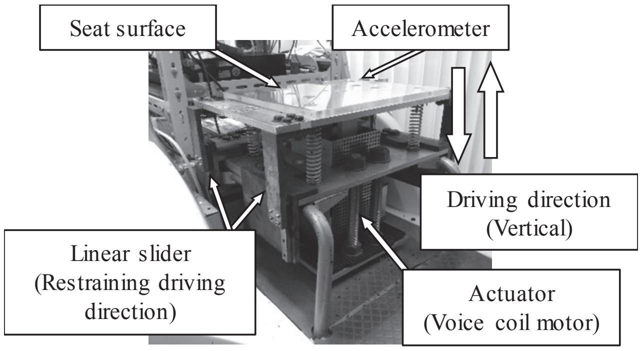



Fig. 4 Photograph of active seat suspension.

Fig. 5 Photograph of ultra-compact mobility vehicle.

## 4. Experimental Method

### 4.1 *Experimental conditions*

In this study, vibration tests were conducted to confirm the effect of vibration frequency on a person's psychological state using an ultra-compact electric vehicle equipped with active seat suspension (Fig. 4, 5). The movement direction of the seat surface of active seat suspension is restrained in the vertical direction by the four linear sliders installed in the surroundings. During the experiment, as shown in Fig. 6, a test subject wearing a brain blood flow device was made to get in the car, and the driving posture was reproduced. In the experiment, vibrations having a single frequency were excited for 3 min using the active seat suspension in the procedure shown in Fig. 7, and the cerebral blood flow rate in the right brain hemisphere in that section was measured. Before the vibration test a screen, as shown in Fig. 8, was displayed on the monitor put in front of experimental vehicle, and subjects were asked to perform some mental arithmetic tasks to regulate their mental condition for 1 min.

The experiment was approved by the Ethics Committee on the "Research targeting people" (approval number: 17009). Before participating in the experiment, subjects were informed about the study, such as the study contents. Then, subjects who agreed to participate signed a consent form approved by the committee. The subjects were five college students.

### 4.2 *Vibration condition*

Ultra-compact mobility has short wheelbase and tread and It is known that vibration input to rolling and pitching is very small as compared with general cars. Also Yoshida et al. research[8)], it has been clarified that vertical vibration affects to psychological state. Therefore, in this experiment, we focus on the vibration in the vertical direction and conduct a

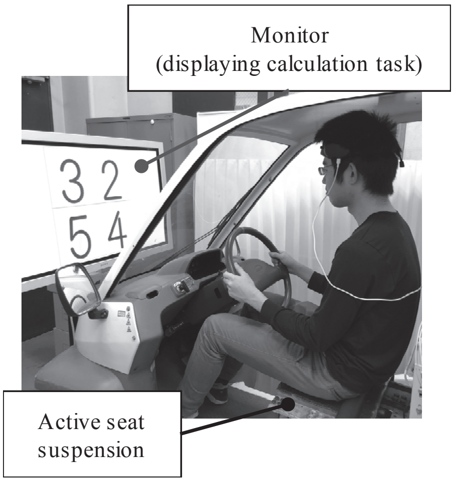



Fig. 6 State of the calculation task carried out before the vibration task.

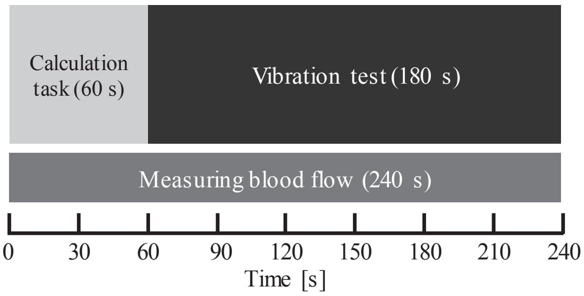



Fig. 7 Experimental flow in each vibration frequency.

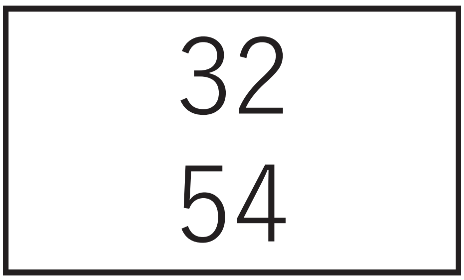
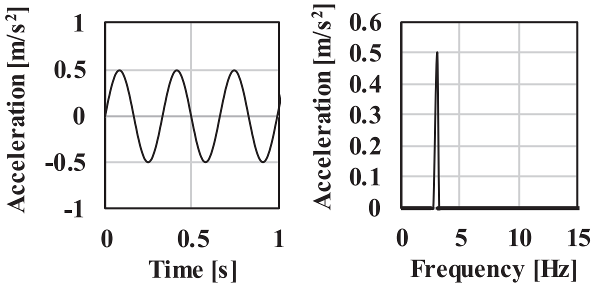
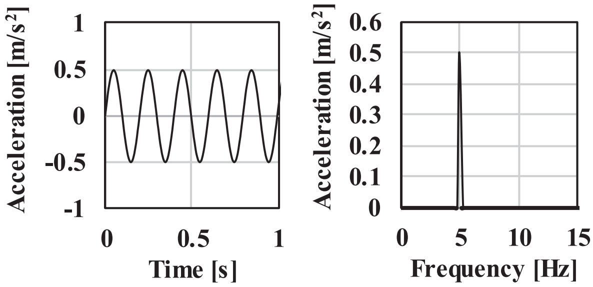


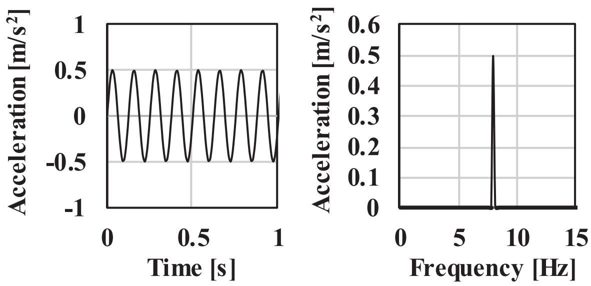

Fig. 8 Example of calculation tasks displayed on the monitor.



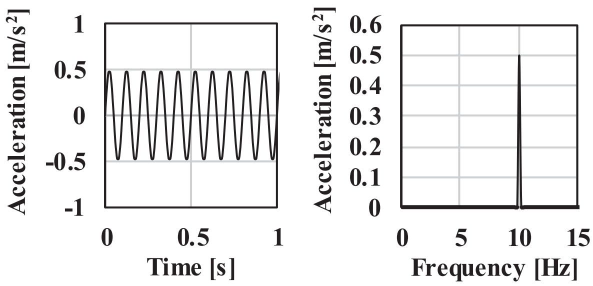

(a) 3 Hz




(b) 5 Hz




(c) 8 Hz




(d) 10 Hz

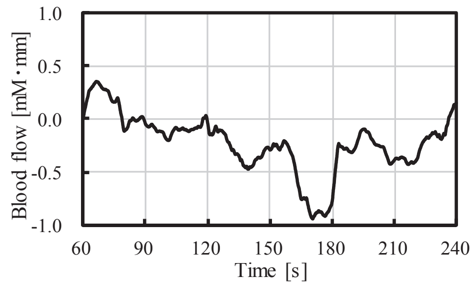
Fig. 9 Time histories of seat acceleration.

study. In this experiment, it is necessary to excite with a vibration that can be felt so that ride comfort differs with the vibration condition. Takei et al.[9)] reported that the sense of vibration differs from 0.2 to 3 Hz at a fluffy feeling, 3 to 8 Hz at a robust feeling, and 8 to 20 Hz at a flapping feeling. In addition, Janeway and ISO[10)] state a vibration of 4 to 8 Hz is a vibration sensitive to humans. For this reason, in this experiment, four types of sinusoidal vibrations each having a single frequency characteristic of 3, 5, 8, and 10 Hz, and constant acceleration amplitude shown in Fig. 9 with different ride comfort levels were set. In the vibration experiments, we eliminated the body resonance of the vehicle by jacking the vehicle up.

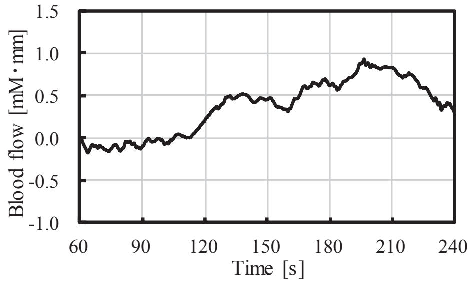
## 5. Experimental Results and Considerations

### 5.1 *Changes in brain blood flow due to vibration*

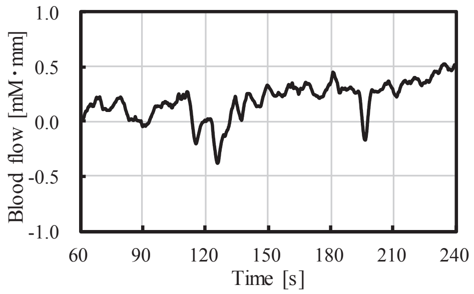
Figure 10 shows an example of the time history of brain blood flow changes in the right brain hemisphere acquired during excitation in this experiment. The same figure shows the variation with respect to the brain activity quantity at 0 s, respectively. As can be seen from Fig. 10 (a), the cerebral blood flow rate gradually decreases after excitation starts at 3 Hz excitation. On the other hand, at the 5 Hz and 8 Hz



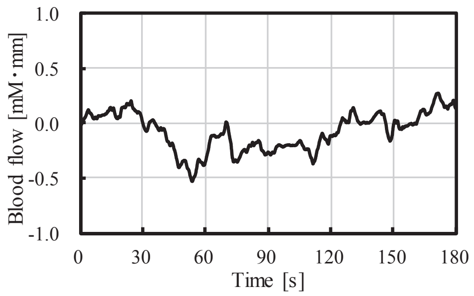

(a) 3 Hz




(b) 5 Hz




(c) 8 Hz




(d) 10 Hz

Fig. 10 Time histories of brain blood flow.

Table 1 Averages of brain blood flow.

(a) 3 Hz

| Section | Subjects | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 60 - 90 s | 0.13 | 0.08 | -0.60 | 0.09 | -0.60 |
| 210 - 240 s | -0.10 | -0.10 | -1.99 | -0.48 | -1.99 |

(b) 5 Hz

| Section | Subjects | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 60 - 90 s | -0.10 | 0.10 | -0.03 | 0.02 | -0.03 |
| 210 - 240 s | 0.58 | -0.03 | 0.36 | -0.15 | 0.36 |

(c) 8 Hz

| Section | Subjects | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 60 - 90 s | 0.10 | 0.01 | -0.13 | 0.00 | -0.07 |
| 210 - 240 s | 0.40 | 0.48 | -0.23 | 0.15 | 0.65 |

(d) 10 Hz

| Section | Subjects | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 60 - 90 s | 0.10 | 0.04 | -0.16 | -0.10 | -0.44 |
| 210 - 240 s | 0.10 | 0.16 | -0.39 | -0.21 | -1.66 |

excitations shown in Figs. 10 (b) and (c), it gradually increases from the start of excitation, indicating that the activity of the brain is activated. From basal experiments on cerebral blood flow rate, the change in resting position for 3 minutes was about 0.020 mM · mm, when stress was given by mental arithmetic for 3 minutes, it increased by 0.30 mM･mm or more, is significantly increased. In addition, although it decreased at the 10 Hz excitation shown in Fig. 10 (d), it gradually increased and returned to a value close to the onset of vibration at around 240 s.

To clarify the change in the cerebral blood flow rate of the right brain that appeared after excitation for 3 min, in terms of 3 minutes the 30 s (60–90 s) which immediately occurred after the start of excitation and 30 s (60–90 s) immediately before the end of the vibration, the average value of the cerebral blood flow rate in the right brain was calculated for each experiment and is shown in Table 1. The subject A is the same as the subject in Fig. 10. From the same table, it can be confirmed that the tendencies of blood flow rate increase and decrease of all the subjects were the same in each excitation condition when the blood flow rate immediately after the start of excitation was compared with that immediately before the end of excitation.

Therefore, the average values of the increases and decreases in the cerebral blood flow rate in the right brain hemisphere for all the subjects at each stimulation condition are shown in Fig. 11. The increase and decrease in the brain blood flow rate was calculated by subtracting the average value of the blood flow rate immediately after the start of vibration from that immediately after the end of vibration. From the same figure, it was confirmed that the brain blood flow rate decreased at 3 Hz and 10 Hz, and

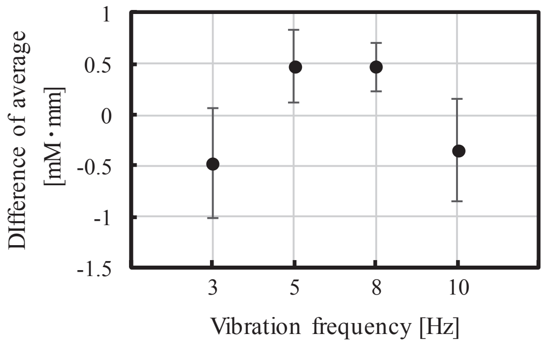



Fig. 11 Change amount in brain blood flow rate for each vibration frequency.

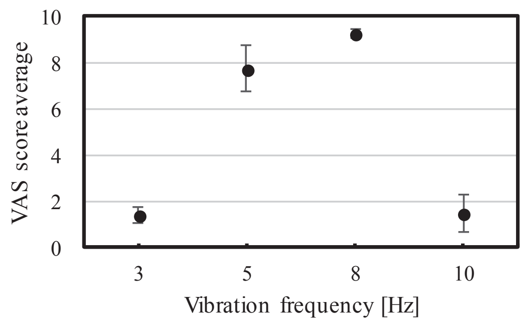



Fig. 12 VAS score of each vibration frequency.

the brain blood flow rate increased at 5 Hz and 8 Hz, and the brain activity was activated.

### 5.2 *Influence on subjective evaluation (VAS) by vibration*

Figure 12 shows the data on the comfort associated with the most cerebral blood flow rate among the subjective evaluation results of all four items of the VAS obtained in this experiment. In the figure, a VAS value of 5, indicates that comfort has not changed before the experiment. If it is more than 5, it can be evaluated that the subjects are uncomfortable and are more comfortable if it falls further below 5. In the same figure, a VAS value of 5 indicates that the comfort has not changed before the experiment, but a higher value indicates discomfort while a value lower than 5 indicates comfort. At excitations of 3 Hz and 10 Hz, it was found that the VAS value was lower than 5; thus, the ride was comfortable. On the contrary, at the vibration conditions of 5 Hz and 8 Hz, the VAS value was greater than 5, and the ride was uncomfortable.

### 5.3 *Consideration*

In this experiment, to compare the change in brain blood flow rate obtained in this experiment with the subjective evaluation, brain activity was inactivated at excitations of 3 Hz and 10 Hz, and subjective evaluations showed that the subjects were comfortable. On the other hand, when brain activity was activated at vibrations of 5 Hz and 8 Hz, the subjects evaluated themselves as being uncomfortable. From this, it was confirmed that there is a relationship between the stress state index due to the activity state of the brain and the subjective psychological state evaluation with respect to the frequency of the vertical vibration.

The ISO states that vibrations of 4 Hz to 8 Hz appear to be the most unpleasant. In addition, Matsumoto et al.[11] reported that the natural frequency of the human body in a sitting position is about 5 Hz. Thus, this experiment shows that, following the input of a vibration with frequency that is burdensome, the right brain hemisphere is activated. By measuring this activity, stress can be evaluated.

## 6. Conclusion

In this study, we focused on brain blood flow in the right brain hemisphere, which reflects the activities of the central nervous system, to evaluate the ride comfort against the vertical vibration of ultra-compact mobility vehicles. We confirmed experimentally the change in the brain blood flow rate in the prefrontal cortex, which has been used as a stress index for the frequency of vibration considered to affect the ride comfort.

It was confirmed that the brain blood flow rate in the right brain hemisphere increased when the vertical vibration frequency was 5 Hz and 8 Hz, which human beings find uncomfortable. In this experiment, we focused on clarifying the response of the brain blood flow rate to a limited oscillation frequency for a relatively brief time. For that reason, future research will clarify the vibration frequency, acceleration amplitude, exposure to develop quantitative indices by clarifying the vibration frequency, acceleration amplitude, and the response appearing in the brain blood flow rate when human subjects are exposed to vibrations for a long time.

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