

Simplified appraisal method for fatigue on sitting for extended periods by using finger plethysmogram

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For the purpose of quantifying and indicating the degree of fatigue as a result of sitting in an automobile seat for long periods of time, a method was developed by using a baseline oscillation and the amplitude of a finger plethysmogram. Between a finger plethysmogram and the degree of fatigue, there is about one hundred times difference in a fluctuation cycle. So, an idea was proposed to convert a finger plethysmogram into a gradient of comprehensive change to make fluctuation cycle scales easily comparable. The gradients of the square of the finger plethysmogram amplitude were converted into absolute values. Then, we drew a fatigue curve based on the results calculated at 18-second integrated values of the time series signals. This curve and the muscle fatigue curve from subjective judgment were in general accord. By using a finger plethysmogram featuring high sensitivity to the fatigue progress, differences in various subjects and seat performances could be found on this fatigue curve using only a 30-minute fatigue test. This new method has made it possible to greatly shorten the measurement time necessary to predict fatigue level by sensory evaluation.

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1. Introduction

Tests have been tried in many fields on how driver's fatigue can be evaluated based on the subject's physical and mental states [1,2]. But measurements utilizing muscle eletrograms, brain- waves, etc. are not suitable for real-time analysis, as the test environment will affect the measurements when they are taken over a very long period of time.

The subject's state is also governed by an oscillator, which attempts to always maintain the same rhythm, and homeostasis, which attempts to return to the original state. Fatigue progression is determined by these two factors along with the level of comfort or discomfort. We previously published a study on capturing variations in blood flow caused by homeostasis that provide signals that a sleep state is about to begin [3]. In addition, evaluating the degree of fatigue as a result of sitting on a seat, we have attempted to define a qualitative appraisal method [4].

The muscle fatigue curve (hereafter termed "pulse wave muscle fatigue curve") is calculated from the integral values of the pulse wave power value's fluctuations; the subject's mental state and degree of arousal (hereafter termed "pulse wave arousal curve") is evaluated by fluctuations of the largest Lyapunov index. The correlation between the pulse wave muscle fatigue curve and the sensory evaluations [5] fatigue curve was analyzed (the sensory evaluations utilized the Borg index, which closely correlates to the integral muscle electrogram), as was the correlation between the pulse wave arousal curve and brain waves' time series frequency. Correlations between the physiological indices and pulse

wave variations were then analyzed based on the results. It was thought that a synchronicity [6] would be found in the rhythms of variation of the power value and largest Lyapunov index in transition stages.

In this paper, we report that the pulse wave muscle fatigue curve showed almost the same tendency as the muscle fatigue curve determined by sensory evaluation, and that the pulse wave arousal curve was associated with the appearance of brain waves and compensatory actions of stimulated sympathetic nerves.

2. Analysis method

The degree of fatigue was measured by the power value indicating fatigue accumulation, and arousal levels based on the largest Lyapunov exponent were employed to verify whether fatigue was compensated for by sympathetic nerve stimulation.

In the following sections, the gradient time series waveforms of the power value and the largest Lyapunov exponent were examined according to the time series signals of the finger plethysmogram. We describe the methods used to deduce a pulse wave muscle fatigue curve from the gradient time series waveforms of the power value, and a pulse wave arousal curve from the gradient time series waveforms of the largest Lyapunov exponent.

2-1. Symbol table

d : parameter embedded dimension

$S(n)$: finger plethysmogram time series signals

Δt : elapsed time

λ : largest Lyapunov exponent

τ : embedded delay time

2-2. Calculating the pulse wave muscle fatigue curve

The pulse wave muscle fatigue curve is calculated from the finger plethysmogram's physiological signals, shown in Figure 1. Calculations of the figures shown in Figure 1 are explained in steps (1)-(8) below. Maximal and minimal values are computed based on Savitzky and Golay's leveling differential method [7]. (1) The maximal and minimal values are divided at 5 second intervals; (2) the squares of the differences between averages is taken as the power values; (3) these power values are then plotted at 5 second intervals to create the power value time series waveform. (4) This waveform is then taken over a 180-second time frame and (5) the power value gradient is calculated by the method of least squares. Next, 162 seconds is overlapped, and the next 180-second interval is calculated in the same manner; the results are then plotted at 18-second intervals. (6) This calculation (termed "slide calculation") is repeated in succession to create a power value gradient time series. (7) The gradient time series waveform is processed by the absolute value method, and (8) the integral values over 18 seconds are plotted in succession as fatigue levels, creating a pulse wave muscle fatigue curve.

2-3. Calculating the pulse wave arousal curve

"Largest Lyapunov Exponent" is an index of instability of orbits; the more stable the orbit, the lower the Lyapunov value. Until now, the relationship between the autonomic nervous system and attractor variance [8,9] has been reported by chaos analysis of the finger plethysmogram; in addition, its relationship to the subject's psychological state and physical condition has also been reported [2,10]. In research on the technology used to measure fatigue, there are also reports on making observations of a person's state of mind based on voice chaos analysis of the person speaking [11]. Based on those reports, it is presumed that a lower Lyapunov exponent indicates a relaxed state, while a larger value indicates a heightened state of adaptability, stress, and concentration. The largest Lyapunov exponent gradient time series waveform is calculated as shown in Figure 2. Calculations of the figures shown in the diagram are explained in steps (11)-(21) below. (11) From the time series signals $S(n)$ ($n = 1, \dots, n$), the time-lag method [12] (Turken's embedding theory) is used to reconfigure the state of dynamic motion (parameter embedded dimension d , embedded delay time $[10]\tau$). In concrete terms, only the embedded dimensional value data ($S(i)$, $S(i+\tau)$, ..., $S(i+(d-1)\tau)$) are selected from the time series starting point, by the weighted ordinate method. (12) The 'd' factors are plotted as points on the d-dimension state space coordinate system. 'i' points are plotted in succession, offset by one point each. (13) The orbit described by the d-dimension state space is the attractor. Here, the delay time for the finger plethysmogram's time series signals is 50ms, when the FNN (False Near Neighbors) formula [13] is utilized

for the embedded dimension, FNN is approximately zero in dimension 3, and is exactly zero in dimension 4; dimension 4 is taken as the optimum embedded dimension.

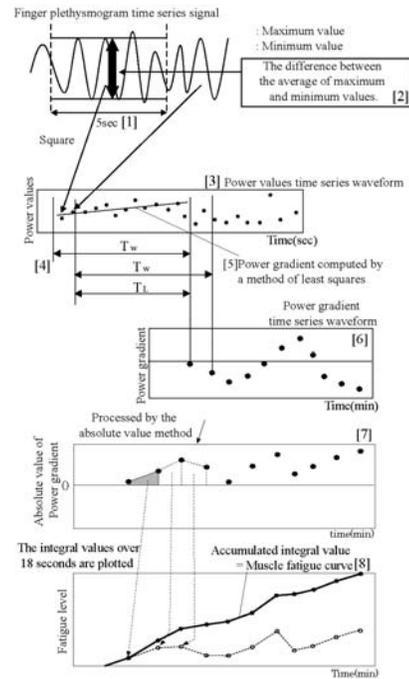


Fig.1 Method for computing the muscle fatigue curve.

The largest Lyapunov exponent, one index that quantifies the attractor's nature, is then calculated. The Lyapunov exponent is the calculated average of the proportions of expansion and contraction of the attractor's orbit, which alternately moves away and then draws closer again. In this case, the Lyapunov exponent was calculated using the Sano-Sawada Method [14]. (14) As shown in Figure 2, a prolate spheroid is created by the points on the attractor; across elapsed time Δt , for example, the prolate spheroid lengthens in one direction and compresses into a rounder, circular form in the other direction. In other words, if the rate of variation in relation to the four straight base vectors is e'_i , then the largest Lyapunov exponent may be calculated from random points on the attractor using the below formula.

$$\lambda_i = \lim_{n \rightarrow \infty} \left(\frac{1}{n\Delta t} \right) \sum \log |e'_i(t)| \quad (1)$$

If the reconstructed attractor's state space is dimension d , then the Lyapunov exponent $\lambda_1, \dots, \lambda_d$ can be calculated in relation to the orthogonal d -point vectors. The largest value in this area is the largest Lyapunov exponent. (15) Reconstruction of the attractor is done over a 30-second time period in relation to continuous data values calculated from finger plethysmogram time series signals, and by sliding the time period in 1-second increments, (16) the largest Lyapunov exponent's time series waveform is created.

The maximal value related to the largest Lyapunov exponent's time series waveform is now found, using Savitzky and Golay's leveling differential method [7]. Next, in order to get a reading of the largest Lyapunov exponent's variation over a wide area, (17) the largest Lyapunov exponent's gradient is found by applying the method of least squares to the greatest values computed over a 180-second time period. (18) The next 180-second time period is then calculated in the same manner, with an overlap of 162 seconds, and the results are plotted. (19) The largest Lyapunov exponent gradient time series waveform is found by repeating this method of calculation. (20) The gradient time series waveform is then processed by the absolute value method, and (21) the integral values at 18-second intervals are plotted in succession as the arousal level to creating the pulse wave arousal curve.

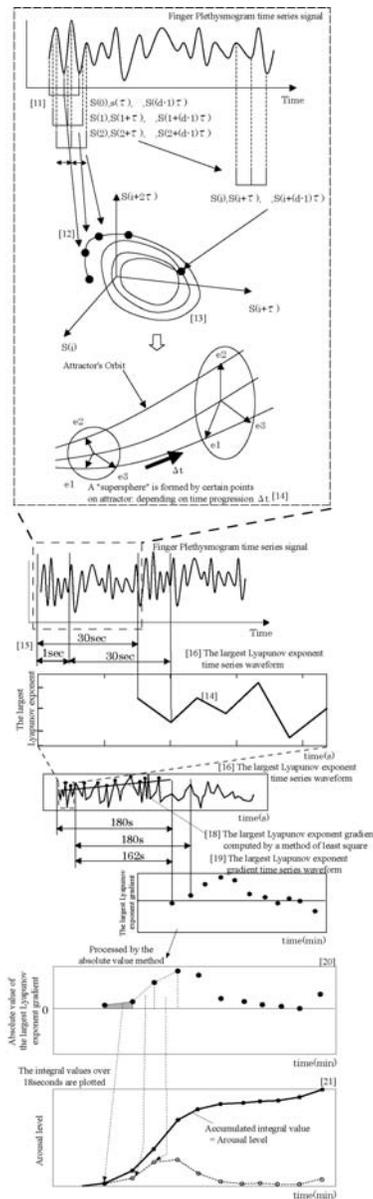


Fig.2 Method for computing the arousal curve.

3. Materials and Methods

The measuring device utilized in the experiments' finger plethysmograms was composed of an infrared diode and phototransistor. After A/D conversion was done, the measured data was processed on a PC. The sampling frequency is 200Hz, with a resolution of 12 bits. Sensory evaluation was performed every 30 minutes throughout the experiment. Sensory evaluation was carried out according to Borg's scale.

The first test was a one-hour long sitting fatigue test that utilized a seat with a hard cushion (hereafter termed "stable posture-maintaining seat") and a seat with a softer cushion (hereafter termed "body pressure dispersion seat"); a sensory evaluation was performed and pulse waves were measured with the subject in the relaxed posture. As it was thought that feelings of discomfort would increase the sense of fatigue over a three-hour period, the test subject watched a video movie to decrease the effects of feelings of discomfort.

The experiments were carried out on three males in their 20s and 30s. The latent time for them to fall asleep was 10 – 15 min.

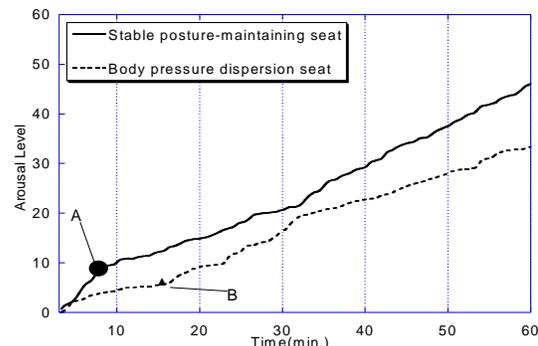
In Experiment 2, with the same two kinds of seats used in Experiment 1 tests to detect fatigue levels in a sitting position in the environment of whole-body vibration were carried out by sensory evaluation and measurements of pulse waves.

The test utilized random stimulus waves, including shock vibration; shock wave acceleration on top of the platform was 1.3Hz frequency/0.5G amplitude (peak-to-peak), with a crest factor of 3.

4. Results and discussion

Since sitting experiments took about one hour, the degree of fatigue was defined as follows:

- (1) No fatigue
- (2) Despite some level of fatigue, compensation is possible under constant conditions. This is the state where fatigue is compensated for by sympathetic nerve stimulation, and the fatigue may not be detected objectively by short-term examinations.
- (3) Due to fatigue, errors and delay in response time are observed.



(a) Pulse wave arousal curve

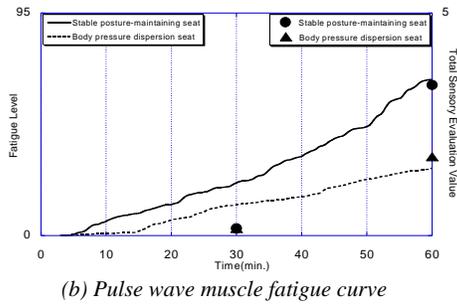
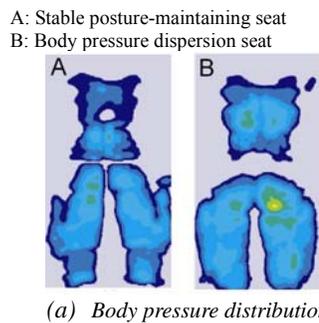
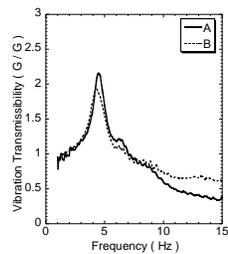


Fig.3. Comparison of muscle fatigue curve and subjective judgment: experiment on sitting in a static position over a long time period of one hour.



(a) Body pressure distribution



(b) Vibration transmissibility

Fig.4. Seat characteristic

Conventional evaluation of fatigue based on the power value alone was applied to definition (1). With the introduction of dynamic and hour-long tests to evaluate fatigue definitions (2) and (3) were often applied. Therefore, to determine the compensation by sympathetic nerve stimulation, arousal levels measured from the largest Lyapunov exponent were combined for calculation. The timing to consider compensation by sympathetic nerve stimulation was a point where arousal levels changed sharply, and compensation by sympathetic nerve stimulation calculated with the largest Lyapunov exponent was added for fatigue evaluation.

4-1. Evaluation of fatigue from different sitting postures (Experiment 1)

Fig. 3 shows the results of experiments to evaluate fatigue while sitting under static conditions. Figure 3(a) shows the comparison of arousal levels based on a finger plethysmogram, while Figure 3(b) shows the comparison

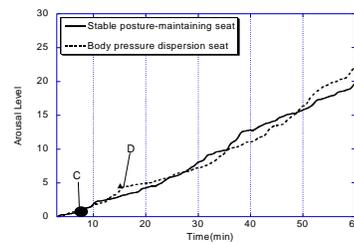
of fatigue levels based on a finger plethysmograms and sensory evaluation.

In the curve for arousal levels in Figure 3(a), the slope of the arousal levels with the stable posture- maintaining seat changed at point A five minutes after beginning. In fatigue curves incorporating the results of arousal levels in Figure 3(b), the two seats showed comparable slopes for fatigue levels until 30 minutes, when the slope for the stable posture- maintaining seat became steeper. This is the same tendency found with sensory evaluation based on Borg's rating scale. It was presumed that compensation by sympathetic nerve stimulation was observed with both seats, but that with the body pressure dispersion seat, the subjects showed decreased levels of fatigue due to compensation, then shifting to be in a resting state. These results seemed to occur because the burdens on the antigravity muscles were reduced by leaving the body support to the seat, not by maintaining the posture with antigravity muscles.

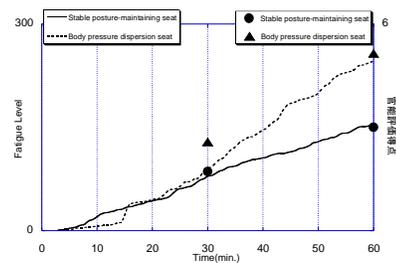
On the other hand, with the stable posture- maintaining seat, the burdens on the antigravity muscles to maintain the posture is heavy and fatigue levels were heightened despite the compensation. Lastly, Figure 4(a) shows the characteristics of body pressure distribution with both seats used in the experiment.

4-2. Fatigue from sitting under whole -body vibration (Experiment 2)

Fig. 5 shows the results of experiments under whole-body vibration. Figure 5(a) shows the comparison of arousal levels by a finger plethysmogram, while Fig. 5(b) shows the comparison of fatigue levels by a finger plethysmogram and sensory evaluation.



(a) Pulse wave arousal curve



(b) Pulse wave muscle fatigue curve

Fig.5. Comparison of fatigue curve and subjective judgment: fatigue test on a long period of sitting corresponding to whole body vibration of various seats.

In the curve for arousal levels in Figure 5(a), the slope for arousal levels with the stable posture- maintaining seat changed at point C five minutes after beginning. With the body pressure dispersion seat, the slope changed at point D 15 minutes later.

In the fatigue curve in Figure 5(b) incorporating the results of arousal levels, the results under whole-body vibration were opposite to those observed during static sitting. This is because differences between the seats in absorbing vibrations of 10 Hz or higher affected the levels of fatigue. Figure 4(b) shows the vibration conduction rates by vertical vibration input with both seats used in the experiment.

5. Conclusion

These results indicate that fatigue levels appraised by subjective sensory evaluation might possibly be calculated by the integration of gradient time series waveforms of power values representing muscle fatigue and time series waveforms combining slopes of the largest Lyapunov exponent representing fatigue levels compensated for by sympathetic nerve stimulation.

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