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Evaluation of Mental and Physical Load using Inverse Regression on Sinus Arrhythmia Scores

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Abstract

This paper develops a statistical model which estimates mental and physical loads of light work from sinus arrhythmia (SA) scores. During experiments, various levels of mental and physical loads (respectively scored by information processing and finger tapping rates) were imposed on subjects and SA scores were measured from the subjects. Two methods were used in developing workload estimation model. One is an algebraic inverse function of a multivariate regression equation, where mental and physical loads are independent variables and SA scores are dependent variables. The other is a statistical multivariate *inverse regression*. Of the two methods, inverse function resulted in larger mean square error in predicting mental and physical loads. Hence, inverse regression model is recommended for precise workload estimation.

1. Introduction

As many industrial workers are involved with mental work, for example, monitoring, inspection, or computer data entry etc., concerns for mental load evaluation are increased. However any practical mental load evaluation method has not yet been developed.

Many authors studied the relationship between SA and mental load of a binary choice reaction task and concluded that an increase in mental load decreased SA [1, 3, 5, 6, 10, 11, 14]. In their studies, motor action effect was disregarded. However, Luczak [9] suggested "even small motor actions, which should not have measurable effects on the metabolic rate, influence SA over neural pathways". In practice, Lee and Park [8] verified that even finger tapping of a binary choice reaction task influenced SA significantly. Hence, to evaluate mental load using SA, physical load effect should be considered.

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2. Experiments for workloads and SA scores measurement

These authors performed five experiments to collect workloads data and SA scores from subjects. Experimental design and procedures are summarized as follows (for details, see Lee and Park [8]):

List of notations

M	information processing rate (bits/min)
P	finger tapping rate (taps/min)
μ	mean of heart beat intervals (msec)
σ	standard deviation of heart beat intervals (msec)
μ_R, σ_R	μ, σ measured under rest condition
μ_T, σ_T	μ. σ measured under task condition

$\%\mu = (\mu_T - \mu_R)/\mu_R$

$\%\sigma = (\sigma_T - \sigma_R)/\sigma_R$

Subjects and experimental apparatus

Twelve male graduate students were used as paid subjects. Their mean age was 24.3 years (SD 1.2); mean height, 169.8 cm (SD 5.0); mean weight, 61.8 kg (SD 5.3). All subjects were right-handed and in healthy condition, without any cardiac illness.

The ECG was collected from sitting subjects. Electrodes were attached to the two ankles and the left wrist. A bioelectric amplifier (a Hewlett Packard 8811 A) amplified and filtered the ECG signal. Heart beat intervals were measured by a R-peak detector and a timer (measurement accuracy: to 0.49 msec). Details of this heart beat interval measurement system are described in Park and Lee [13].

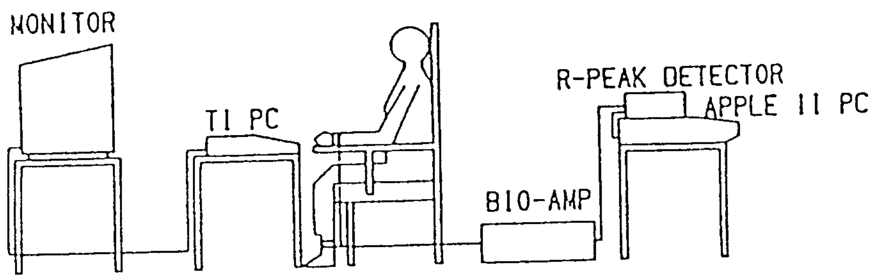

Fig. 1 Layout of apparatus.

The tasks used in the experiments consisted of stimulus identification and button pressing response. A Texas Instrument (TI)-44/9A personal computer (PC) was used to present combined visual and auditory stimuli. A key board of TI PC was used as a response apparatus. Figure 1 shows the layout of apparatus.

Procedure

During five experiments, various mental and/or physical loads were imposed on subjects. In experiment 1, the tasks imposed only a mental load. In experiments 2 - 4, the tasks imposed both mental and physical loads. In experiment 5, the tasks imposed only a physical load. Stimuli, response keys and workloads per stimulus used in five experiments are summarized in table 1.

Table 1. Stimuli, response (keys), and workloads per stimulus used in five experiments.

Experi-ment	Stimuli		Response	Workloads per stimulus	
	Color	Freq(Hz)	(keys)	mental	physical
1	red blue	250 2000	mental counting of total number of blue	identification of two stimuli (1 bit)	–
2	white red blue black	262 523 1047 2095	(I) (J) (M) (K)	identification of four stimuli (2 bits)	single tapping (1 tap)
3	red blue	250 2000	(J) (K)	identification of two stimuli (1 bit)	single tapping (1 tap)
4	red blue	250 2000	(J) (K)	identification of two stimuli (1 tap)	double tapping (2 taps)
5	blue	2000	(K)	–	single tapping (1 tap)

In each experiment, subjects perform five tasks whose stimulus presentation rates were respectively 21 (task 1), 41 (task 2), 62 (task 3), 82 (task 4), 103 (task 5) stimuli/min. At the end of each task, subject's performances of mental and physical loads were scored by programs of TI PC.

Each experiment consisted of a practice period, six measurement periods, and seven relaxation periods. The practice, measurement, and relaxation periods required 10, 3, and 5 min, respectively. Figure 2 shows the schedule of experiment. During six measurement periods, the ECG of subjects was measured under a rest condition (resting without body movement) and five task conditions. The sequence of six conditions was randomized.

Values of μ_R and σ_R were obtained from the heart beat intervals measued under the rest condition; values of μ_T and σ_T were obtained from heart beat intervals measured under each task condition. Values of M, P, $\%\mu$, and $\%\sigma$ for rest condition were set to zero.

3. Evaluation of mental and physical loads from SA scores

Two methods are available for estimation. One is to derive a inverse function of a multivariate regression where workloads (scored by M and P) are independent variables and SA scores

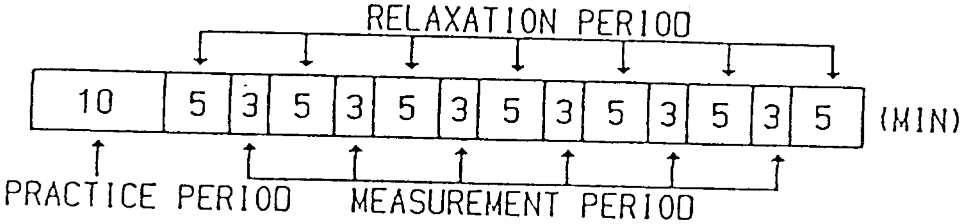

Fig . 2 Schedule of experiment.

(scored by $\%\mu$ and $\%\sigma$) are dependent variables. In the previous study [8], these authors developed the following multivariate regression equation which illustrates workloads effects on SA scores.

$$\begin{pmatrix} \%\mu \\ \%\sigma \end{pmatrix} = \begin{pmatrix} 0.0002189 \\ -0.08618 \end{pmatrix} + \begin{bmatrix} -0.00003585 & -0.0003441 \\ -0.004558 & -0.0007073 \end{bmatrix} \begin{pmatrix} M \\ P \end{pmatrix}, \qquad (1)$$

where $0 \leqslant M \leqslant 121$ (bits/min), and $0 \leqslant P \leqslant 118$ (taps/min).

From equation (1), inverse function is derived as follows:

$$\begin{pmatrix} M \\ P \end{pmatrix} = \begin{pmatrix} -19.3118 \\ 2.6218 \end{pmatrix} + \begin{bmatrix} 455.4479 & -222.9297 \\ -2952.9606 & 22.9214 \end{bmatrix} \begin{pmatrix} \%\mu \\ \%\sigma \end{pmatrix}, \qquad (2)$$

where $-0.1586 \leqslant \%\mu \leqslant 0.1141$, and $-0.8075 \leqslant \%\sigma \leqslant 0.7083$.

The other method is to develop a multivariate inverse regression using M and P as dependent variables and $\%\mu$ and $\%\sigma$ as independent variables. From a model:

$$\begin{pmatrix} M \\ P \end{pmatrix} = \begin{pmatrix} a_0 \\ b_0 \end{pmatrix} + \begin{bmatrix} a_1 & a_2 \\ b_1 & b_2 \end{bmatrix} \begin{pmatrix} \%\mu \\ \%\sigma \end{pmatrix} + \begin{pmatrix} e \\ e' \end{pmatrix},$$

a multivariate inverse regression is developed as follows:

$$\begin{pmatrix} M \\ P \end{pmatrix} = \begin{pmatrix} 16.0808 \\ 30.1514 \end{pmatrix} + \begin{bmatrix} 52.5123 & -76.6032 \\ -146.1822 & -17.6765 \end{bmatrix} \begin{pmatrix} \%\mu \\ \%\sigma \end{pmatrix}, \qquad (3)$$

$$R^2 = \begin{pmatrix} 0.3535 \\ 0.0776 \end{pmatrix}, \quad P = \begin{pmatrix} 0.0000 \\ 0.00001 \end{pmatrix}, \quad \text{sample size} = 360.$$

where $-0.1586 \leqslant \%\mu \leqslant 0.1141$, and $-0.8075 \leqslant \%\sigma \leqslant 0.7083$.

In general, it is known that the inverse regression method is superior to the inverse function method in viewpoint of mean square error (MSE) or the percentage of unexplained variation [2, 7]. In this study, we used MSE as a criterion to judge the prediction accuracy of each method. Table 2 shows that inverse function method had larger MSE than inverse function method in

Table 2. Comparison between inverse function and inverse regression methods by MSE.

Method	MSE_{mental} + $MSE_{physical}$ = MSE
Inverse function	2221.27 + 18725.20 = 20946.47
Inverse regression	713.13 + 1030.00 = 1743.13

predicting either mental or physical load. Therefore, inverse regression equation (3) is recommended as a workload evaluation model.

4. Discussion

When mental and physical loads are predicted using the inverse regression equation (3), the followings are especially noteworthy:

1. The output estimates of equation (3) are useful only when applied to the tasks which do not require severe motor actions. The results of a study conducted by Opmeer [12] suggested that it may be impossible to estimate mental load of a task using SA, if motor actions of the task increase the mean heart rate of human operator to more than 140 beats/min.
2. To avoid excessive errors of overextrapolation, it is wise to restrict prediction to the region where original data were obtained. The inverse regression model is developed on the basis of experimental data ($\%\mu$, $\%\sigma$) whose ranges are respectively $-.1586 \leqslant \%\mu \leqslant .1141$, and $-.8075 \leqslant \%\sigma \leqslant .7083$.
3. There are many factors which reflect workload effects. However, only SA scores are considered in this study. Hence, multiple correlation coefficients of inverse regression model are small but statistically significant. For the prediction of mental load, the square of multiple correlation coefficient (R^2) is .3535 ($p < .00001$). For the prediction of physical load, R^2 is only .0776 ($p = .00001$). As pointed out by Firth [4], other physiological variables, performances, and subjective responses should also be considered. Ultimately we should solve workload evaluation problem by multivariate analyses using multivariables. In this case, multivatiate inverse regression will effectively be used for modeling.

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