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Improvement of the Prediction Method of Local Muscle Metabolic Rate and its Application to the Determination of Metabolic Rates during Different Working Postures

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Abstract

Our previous prediction method of local muscle energy metabolic rate, which consisted of simultaneous measurements of total metabolic rate and integrated surface electromyogram, was improved. The main points of improvement were the measurement procedures of the total metabolic rate, selection mode of tested exercises, a program for cleaning of data sets and a calculation program of simultaneous equations. The method was applied to determine the metabolic rates of the main seven muscle groups during different fifteen static exercises and postures. The predicted seven muscle groups were the anterior muscles of the abdominal wall, the muscle erector spinae, the muscles of the buttock, the posterior femoral muscle group, the anterior femoral muscle group, the posterior crural muscle group and the anterior crural muscle group. Seven gymnastic exercises, three standing, two half rising, one deep forward bending and two resting postures were tested in the present study. Subjects were seven Japanese normal males. As two of them failed to show metabolic rates of the anterior crural muscle group, a total of 705 metabolic rates were obtained. The present results of active five muscle groups in the static postures showed similar tendencies to our previous results. Therefore the metabolic rates in seven gymnastic exercises, which were not tested in the previous study, were discussed.

Introduction

The human thermoregulation model is a useful assessor for the human thermal environmental system design. The lack of information on local rate of heat generation (Wissler, 1964)[9] as well as the lack of information on the exact neurological integrating system of afferent nerves (Hori and Nakayama, 1981)[2] has prevented the establishment of a precise thermoregulation model. In this paper local muscle energy meta-

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bolic rates, which dominate total energy metabolic rate change (Lehmann, 1953[4]; Janský, 1964[3]), were predicted with our improved method during static work and at rest.

Methods

The principle of our prediction method of local muscle energy metabolic rate was described in the previous paper (Yokoyama, 1980)[12]. Therefore the difference between the present method and the previous one is emphasized in the following.

The sum of the energy metabolic rates in organs other than the muscle is maintained nearly constant regardless of whether measurements were made during rest or exercise (Lehmann, 1953)[4]. Janský (1964)[3] showed that the increase of metabolic heat

Table 1. Metabolic rate during rest and exercise [kcal/h].

	(A) resting	(B) exercising
Total	72.00	216.00
Muscle	27.36	150.00
Liver	8.94	4.74
Stomach-intestine	5.46	3.48
Kidney	5.40	1.56
Spleen	4.56	6.00
Heart	3.18	9.60
Brain	2.16	2.40
Pancreas	0.96	0.42
Blood	0.78	0.78
Salivary gland	0.48	0.18
	31.92	29.16

(Lehmann, 1953)[4]

production during exercise was mainly caused by muscle activities.

Under the condition that the metabolic changes are restricted to n muscle groups, the total energy metabolic rate during ith exercise H_i [kcal/h] can be expressed as follows.

$$H_i = \sum_{j=1}^{n} M_{ij} + B_1 \quad (1)$$

where M_{ij}; energy metabolic rate in jth muscle at ith exercise item [kcal/h],

B_1; energy metabolic rate in organs other than n muscle groups [kcal/h].

M_{ij} can be expressed by using a linear indicator, for which during human static postures the integrated surface electromyogram (m_{ij}) is well adapted (Yokoyama, 1976[11]; Yokoyama, 1980a[12]; Yokoyama, 1982[15]).

$$M_{ij} = C_j \, m_{ij} \quad (2)$$

where C_j is the coefficient, and this value depends on the type of muscle of individuals.

Selecting k ($\geqq n+1$) different exercises in which the total energy metabolic rates are similar and equation (2) can be considered among the active muscles, we can obtain the following equation (3).

$$\begin{bmatrix} H_1 \\ \vdots \\ H_2 \\ \vdots \\ \vdots \\ H_i \\ \vdots \\ H_k \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \cdots\cdots m_{1j} \cdots\cdots m_{1n} & 1 \\ m_{21} & m_{22} \cdots\cdots m_{2j} \cdots\cdots m_{2n} & 1 \\ \vdots & \vdots \quad \vdots \quad \vdots & \vdots \\ m_{i1} & m_{i2} \cdots\cdots m_{ij} \cdots\cdots m_{in} & 1 \\ \vdots & \vdots \quad \vdots \quad \vdots & \vdots \\ m_{k1} & m_{k2} \cdots\cdots m_{kj} \cdots\cdots m_{kn} & 1 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_j \\ \vdots \\ C_n \\ B_1 \end{bmatrix} \qquad (3)$$

The total energy metabolic rate, H_i, can be determined by the indirect calorimetry method (Numajiri, 1970[6]; Sasaki, 1975[7]). For this purpose it is necessary that the expired gas is collected and that the measurement of its volume and analysis of the oxygen and carbon dioxide content are performed. Fig. 1 shows the dynamic characteristics of total energy metabolic rate during moderate exercise. Although the previous collection of expired gas (Yokoyama, 1980b[13]; Yokoyama, 1982[15]) was done during a steady state (time t_1-t_2 in Fig. 1), the present one was performed during the exercise period (t_0-t_2) and recovery period (t_2-t_3). The time t_3, i.e., the time of recovery to a initial resting level was determined with the continuous measurement device of heart rate (Sanei Co., 2E31A). In order to perform accurate measurement of total energy metabolic rate, we measured the expired gas volume with a wet gas meter instead of a dry gas meter and analized the oxygen and carbon dioxide content with a micro Scholander gas analizer in the present study.

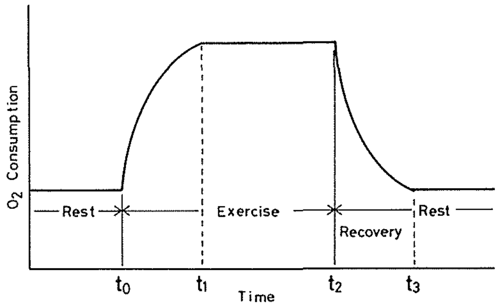

Fig. 1 Schematic representation of dynamic characteristic of O_2 consumption during moderate exercise.

Bipolar surface EMG recordings were obtained from muscles shown in Table 2. The active pairs of electrodes were parallel to the muscle fibers spaced about 25 mm between centers. Each electrode condition was designed to maintain constancy throughout all of the exercise items of individuals. EMG measurements were performed with a ME-135D electroencephalograph apparatus (Nihon Kohden Co.). The exercise items selected for the present study were as follows.

(1) Trunk flexion; The trunk was slightly flexed (5 cm at the point of the opistrodranion) while lying face upward.

(2) Trunk extension; The trunk was slightly extended (5 cm at the point of the gnathion) while lying face downward.

(3) Hip extension; The hip was extended with flexed lower limbs and while

Table 2. The selected muscle groups for the prediction of local muscle energy metabolic rate. Symbol (*) shows the indicator's muscle of each muscle group.

Muscle group	(Local muscle ★1 weight / Total muscle weight) %	Muscle
1 Anterior M. of the Abdominal Wall	5.59	M. rectus abdominis*
2 M. Erector Spinae	5.10	M. erector spinae*
3 M. of the Buttock	9.24	M. gluteus maximus* M. gluteus medius
4 Posterior Femoral M.	4.41	M. biceps femoris* M. semitendinosus
5 Anterior Femoral M.	13.05	M. rectus femoris M. vastus medialis* M. vastus lateralis
6 Posterior Crural M.	5.03	M. gastrocnemius* M. soleus
7 Anterior Crural M.	1.80	M. tibialis anterior*

★1 (Matsushima, 1927)[5)]

lying face downward.

(4) Knee flexion (External load 2.4 kg at the ankles).

(5) Knee extension (External load 2.4 kg at the ankles).

(6) Ankle extension (External load 42 kg at the tiptoes).

(7) Ankle flexion (External load 9.8 kg at the tiptoes).

(8) Standing on tiptoes.

(9) Stiff standing (Standing at attention).

(10) Relaxed standing (Standing at ease).

(11) Half rising at 180°; Half rising with the trunk slightly leaning forward and with knees extended (bending at 180°).

(12) Half rising at 120°; Half rising with the trunk slightly leaning forward and with knees bent at 120°.

(13) Deep forward bending.

(14) Sitting on a chair.

(15) Lying on a bed.

The selection of the item (1)-(7) especially item (1) and (7) enabled us to predict the metabolic rates of the anterior muscles of the abdominal wall and the anterior crural muscle group which could not be predicted in the previous study (Yokoyama, 1982[15)]).

The subjects were seven Japanese normal males ranging in age from 20 to 31

Table 3. Physical characteristics of subjects.

Subject	Age (yr)	Height (cm)	Weight (kg)	Skin Surface Area * (m^2)
OK	22	162.6	55.3	1.543
FK	23	162.3	56.3	1.553
MM	25	159.2	64.0	1.623
TT	20	170.5	58.0	1.626
YS	31	171.0	69.0	1.760
NN	23	175.3	67.0	1.766
OG	24	177.4	72.0	1.838
Mean	24	168.3	63.1	1.673
S. D.	3.5	7.7	6.5	0.115

* According to Fujimoto et al. (1968).[1)]

years. Their physical characteristics are shown in Table 3. Before solving equation (3), we cleaned individual data sets. The item that the respiratory quotient (R. Q.) was not included in the normal range 0.7–1.0 and that H_i was smaller than the standard basal energy metabolic rate 37.5 [kcal/m²h]×BSA (body surface area ; m²) were excluded from the simultaneous equation (3).

Taking the physiological aspects into account in equation (3), we devised the following procedure. EMGs during the maximum voluntary contraction strength ($m_{j\max}$) were measured with the same electrode conditions as those during the above mentioned exercises (items).

$$p_{ij} = m_{ij} / m_{j\max} \quad (4)$$

Substituting p_{ij} for m_{ij} in equation (3), we get $M_{j\max}$ instead of C_j.

$$M_{j\max} = C_j \ m_{j\max} \quad (5)$$

$$M_{ij} = M_{j\max} \ p_{ij} \quad (6)$$

$M_{j\max}$ means the predicted maximum energy metabolic rate in j muscle group during a sustained isometric contraction. In spite of according special attentions to the measurement, the existence of measuring errors could not be denied in the present data sets. In order to minimize the effect of measuring errors on the solution of $M_{j\max}$, three clear physiological definite criteria were set up.

(1) $M_{1\max}, M_{2\max}, \cdots\cdots\cdots, M_{7\max} > 0$

(2) $M_{7\max} < M_{1\max}, \cdots\cdots\cdots, M_{6\max}$

(3) $M_{5\max} > M_{4\max}, M_{6\max}$

The combinations of eight items which satisfied three physiological criteria were selected for equation (3). The weighting least squares method of which weighting factors were given with frequencies in combinations was used for the present solution of equation (3). Local muscle energy metabolic rate, M_{ij}, was calculated with equation (6).

Experiments on simultaneous measurements of EMGs and total metabolic rates were carried out in Physical Training Center, Hokkaido University. Data cleaning with R. Q. and standard basal metabolic rate, tests for data combination by three physiological criteria, solution of M_{jmax} with weighting least squares method and calculation of M_{ij} were performed with HITAC M-200H in Hokkaido University Computing Center.

Results

Although the prediction method of local muscle rate has been considerably improved, there are still possibilities of the method containing errors in the procedure. Mistakes occasionally occur in the measurement of total metabolic rate. For example,

Table 4. Mean values and standard deviations (S. D.) [kcal/h] of local muscle energy metabolic rate in different excercise items. M_1; Anterior m. of the abdominal wall. M_2; M. erector spinae. M_3; M. of the buttock. M_4; Posterior femoral m.. M_5; Anterior femoral m.. M_6; Posterior crural m.. M_7; Anterior crural m..

		M_1	M_2	M_3	M_4	M_5	M_6	M_7
(1) Trunk flexion	Mean	89.918	6.363	7.365	2.763	7.489	2.332	0.494
	S. D.	52.495	3.776	5.636	1.810	7.790	2.080	0.374
(2) Trunk extension	Mean	15.273	37.994	23.617	17.635	7.307	6.201	1.036
	S. D.	7.889	17.264	17.423	8.018	5.181	8.296	1.616
(3) Hip extension	Mean	18.016	44.063	70.118	13.513	6.462	4.496	0.737
	S. D.	12.664	24.442	40.701	5.045	4.171	2.883	0.521
(4) Knee flexion	Mean	8.984	16.076	4.793	15.493	5.906	13.100	0.391
	S. D.	5.124	10.758	4.147	5.439	5.501	6.446	0.238
(5) Knee extension	Mean	28.320	6.608	3.290	4.193	46.785	3.948	1.040
	S. D.	20.951	2.075	1.207	1.713	10.618	3.826	0.906
(6) Ankle extension	Mean	12.649	5.836	4.359	1.287	4.731	14.460	0.955
	S. D.	8.230	2.370	4.494	0.674	2.998	10.372	0.588
(7) Ankle flexion	Mean	7.809	6.198	2.565	1.679	8.021	2.516	12.667
	S. D.	3.236	2.331	1.614	0.569	4.054	0.897	14.439
(8) Standing on tiptoes	Mean	11.983	7.051	4.204	3.262	5.364	11.159	4.399
	S. D.	7.103	3.329	3.659	2.702	4.471	6.916	6.731
(9) Stiff standing	Mean	16.944	6.743	21.906	3.063	25.821	4.194	0.875
	S. D.	13.993	3.116	20.394	1.791	20.034	4.224	0.660
(10) Relaxed standing	Mean	8.592	7.897	5.999	2.141	5.077	5.275	2.575
	S. D.	5.663	2.974	3.626	1.794	4.760	5.978	3.732
(11) Half rising at 180°	Mean	12.877	21.952	8.580	6.887	5.706	2.665	2.264
	S. D.	8.819	8.700	6.260	3.848	3.619	1.129	3.140
(12) Half rising at 120°	Mean	11.371	9.831	8.336	2.880	40.583	4.962	0.449
	S. D.	6.642	2.352	4.067	1.662	13.414	3.284	0.305
(13) Deep forward bending	Mean	8.111	4.815	10.804	12.696	4.949	6.340	0.567
	S. D.	6.079	2.535	5.537	3.987	4.242	5.150	0.562
(14) Sitting on a chair	Mean	8.245	4.081	2.260	0.727	2.339	0.952	0.175
	S. D.	6.027	2.067	1.945	0.333	1.824	0.764	0.091
(15) Lying on a bed	Mean	4.421	3.999	2.827	1.241	2.839	0.574	0.214
	S. D.	3.116	2.388	2.337	0.822	1.603	0.484	0.138

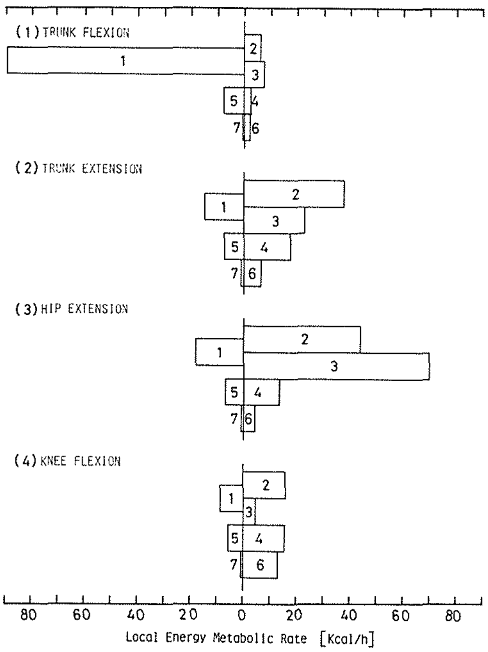

Fig. 2 The mean values of local energy metabolic rates of seven muscle groups at item (1)-(4). 1; Anterior m. of the abdominal wall. 2; M. erector spinae. 3; M. of the buttock. 4; Posterior femoral m.. 5; Anterior femoral m.. 6; Posterior crural m.. 7; Anterior crural m..

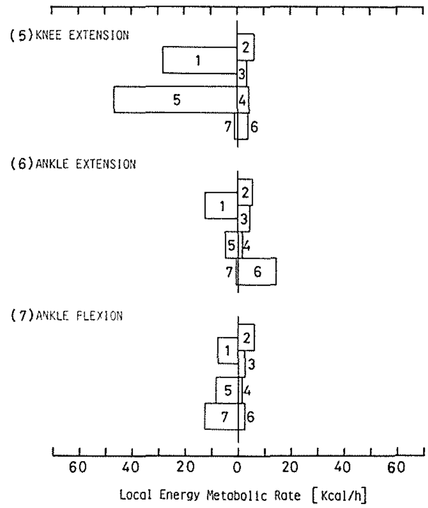

Fig. 3 The mean values of local energy metabolic rates of seven muscle groups at item (5)-(7). Symbols (1 to 7) are explained in Fig. 2.

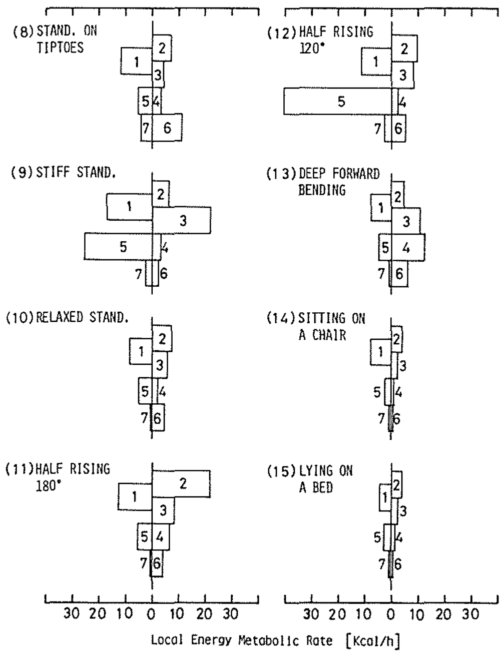

Fig. 4 The mean values of local energy metabolic rates of seven muscle groups at item (8)-(15). Symbols (1 to 7) are explained in Fig. 2.

in subject NN, 30 measurements were reduced to 17 after data cleaning with R. Q. and the standard basal metabolic rate. Fortunately from the remaining 17 measurements simultaneous equations could be constructed, which enabled prediction of the metabolic rates of seven muscle groups. In subject FK and MM, item (7) was excluded from each data set. Therefore from their data sets metabolic rates of only six muscle groups without the anterior crural muscle group could be predicted.

Consequently a total of 705 metabolic rates were predicted. Table 4 summarizes the means and standard deviations of local muscle energy metabolic rates. The sample number in the anterior crural muscle group was five and that in the other six muscle groups was seven. The means of seven muscle groups in each item are shown in Fig. 2–Fig. 4. In Fig. 2–Fig. 4 the array of seven muscle groups is compared to the human body. The left and the right hand in each figure corespond to the front and the rear of the body, respectively.

The predicted values were on both sides in each muscle group.

Discussion

A comprehensive study of human local muscle energy metabolic rate has not been reported in the literature except the works by one of the authors (Yokoyama, 1980b[13]; Yokoyama, 1982[15]). The present method was more advanced compared to the previous method (Yokoyama, 1980a[12]). The number of items covered in the present study was larger than that in the previous report. In our previous paper, the measurement of O_2 consumption and CO_2 production, which was necessary for the indirect calorimetry method, was done during a steady state, because the steady state of O_2 consumption and CO_2 production during various human static postures was previously examined with continuous measurement (Yokoyama, 1974[10]). On the other hand, in the present study the measurements were done during the work and recovery process, because of the selection of item (1)–(8) other than static postures and because of taking into account of the accuracy in the present study.

Three physiological criteria were set up in order to predict better metabolic rates. Among three physiological criteria (1) $M_{j\max}$ ($j=1, \cdots\cdots, 7$) >0 is obvious during static work and at rest. The criterion (2) has been supported by Matsushima's work (1927)[5] (see Table 2) and many other muscle mass studies. The criterion (3) has been also supported by the above mentioned studies and especially "$M_{5\max}>M_{4\max}$" is demonstrated by measurements of maximum voluntary contraction strength (Yokoyama and Mito, unpublished data[17]).

Taking into account the prediction of accuracy, it was necessary that the predicted muscle groups were large (Yokoyama, 1980a[12]). According to Table 2, the present seven muscle groups were well adapted.

The energy metabolic rates of the anterior muscles of the abdominal wall and the anterior crural muscle group did not remarkably change throughout static postures (Table 4 and Fig. 4). Therefore it was as a matter of course that metabolic rates for no more than five muscle groups could be predicted among static postures in the previous study. Metabolic rates of five muscle groups during static postures were similar to those in the previous study. For example, in the half rising posture at 120° the metabolic rates of the anterior femoral muscle group (M_5) were 40.583 ± 13.284 [kcal/h] ($n=7$) in the present study and 42.61 ± 20.68 [kcal/h] ($n=5$) in the previous study (Yokoyama, 1982[15]).

The quantitative results of Table 4 and Fig. 2–4 confirm a number of findings by the previous reporters mainly from the view points of electromyography. Those with reference to human static postures, item (8)–(15), were discussed in our previous papers (Yokoyama, 1980b[13] : Yokoyama, 1982[15]).

Item (1)–(7) were frequently observed in daily gymnastic exercises and physical weight training programs. Item (1), trunk flexion, has been adopted to harden the anterior muscles of the abdominal wall. In fact, metabolic rate of the muscles was the mean 89.918 kcal/h, which was the greatest among seven muscle groups in the exercise and among all items in the muscle group.

Though item (2), trunk extension, and item (3), hip extension, caused the corporation of the muscle erector spinae, the muscles of the buttock and the posterior femoral muscle group, metabolic rate of the muscle erector spinae and that of the muscles of the buttock were the greatest in item (2) and item (3), respectively.

In item (4) knee flexion and item (5) knee extension, the same external momentum load was added. In knee flexion the metabolic rate of the posterior femoral muscle group increased together with those of the muscle erector spinae and the posterior crural muscle group. Conversely in knee extension the metabolic rate of the anterior femoral muscle group increased together with that of the anterior muscles of the abdominal wall. The sum of metabolic rates of seven muscle groups in item (5) knee extension was greater than that in item (4) knee flexion, in which ligamentous apparatus in knee joint would act to reduce metabolic rates.

The metabolic rates of the posterior crural muscle group in item (6) ankle extension and of the anterior crural muscle group in item (7) ankle flexion increased steadily, as well known.

Local muscle energy metaboldc rate can quantitatively evaluate physiological loads not only among different exercises in a muscle group but also among different muscle groups during a exercise. It will be applied to the survey of exercise physiology, industrial hygiene (Yokoyama, 1981[14]) and so on. On the other hand, local muscle energy metabolic rate is useful to construct a human thermoregulation model (Stolwijk and Hardy, 1977[8] ; Yokoyama and Tajima, 1981[16]), because it gives the main source of heat production in human body, which is a fundamental parameter for a human thermoregulation survey in biological engineering or ergonomics. Accordingly we hope that this kind of study will be continued in order to obtain more precise values.

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References

1) Fujimoto, S. et al.: Jap. J. Hygiene, **23** (1968), p. 443–450.
2) Hori, T. and T. Nakayama: Onnetsu Seirigaku (Thermal Physiology), (1981), p. 253–280, Rikohgakusha.
3) Janský, L.: Acta Univ. Carolinae-Biologica, **1965** (1964), p. 1–91.
4) Lehmann, G.: Praktische Arbeitsphysiologie, (1953), p. 122–163, Georg Thieme Verlag.
5) Matsushima, H.: Igaku-Kenkyu, **1** (1927), p. 43–48.
6) Numajiri, K.: Rodo no tsuyosa to tekiseisagyoryo (Work Intensity and Optimal Work Amount), 8th ed., (1970), p. 201-253, Inst. Sci. Labour.
7) Sasaki, T.: Shin Seirigaku [2] (Current Physiology [2]), 4th ed., (1975), p. 467–503, Igakusyoin.
8) Stolwijk, J. A. J. and J. D. Hardy: Reactions to Environmental Agents, (1977), p. 45–68, Amer. Physiol. Soc.
9) Wisslar, E. H.: Bull. Math. Biophysics, **26** (1964), p. 147–166.
10) Yokoyama, S.: J. Anthrop. Soc. Nippon, **82** (1974), p. 96.
11) Yokoyama, S.: J. Anthrop. Soc. Nippon, **84** (1976), p. 174–183.
12) Yokoyama, S.: J. Anthrop. Soc. Nippon, **88** (1980a), p. 97–108.
13) Yokoyama, S.: Man and his Environment, (1980b), p. 88–92, Concept Publ. Company.
14) Yokoyama, S.: Jap. J. Hygiene, **36** (1981), p. 208.
15) Yokoyama, S.: J. Anthrop. Soc. Nippon, **90** (1982), p. 25–35
16) Yokoyama, S. and A. Tajima: Jap. J. Ergonomics, **17** (1981), p. 98–101.
17) Yokoyama, S. and C. Mito: unpublished data.