Dynamic Characteristic of Human Energy Metabolism Observed from Transition of Walking

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Abstract The dynamic characteristic of human energy metabolism was investigated during natural walking experiments in eighteen Japanese young adults. The trait was expressed in terms of a time constant obtained from the regression of the energy cost at walking to the first order lag model. The analysis showed that the mean value of time constant for the males was 1.38 minutes with a standard deviation of 0.28 minutes, and that for the females was 2.29 minutes with that of 0.99 minutes. A sex difference was shown in the trait indicating male more rapid response.

INTRODUCTION

Through the long process of evolution, animals have acquired the present state of adaptability of their respiratory, circulatory, digestive, energy metabolic and other systems. In the energy metabolic system, the adaptability is shown by the ability to provide energy needed for the animal's actions. The ability may be represented by two kinds of characteristics, that is dynamic and static.

The problems of energy metabolism as related to body size and to respiratory surface were first discussed by RUBNER (1883) and then summarized by HEMMINGSEN (1960). Many interesting problems related to this subject have been reviewed by some authors as KLEIBER (1961), SCHMIDT-NIELSEN (1975) and so forth. And there are also a number of studies on the theme of energy metabolism in locomotion. Many comparative

studies have revealed the characteristics among the locomotion types (SCHMIDT-NIELSEN, 1972 a), the specificity of bipedalism (TAYLOR, SCHMIDT-NIELSEN and RAAB, 1970) or the comparison of energy cost between quadrupedal and bipedal walking (TAYLOR and ROWNTREE, 1973). These were always concerned with the static characteristics, and there are still few studies on the dynamic characteristics of energy metabolism.

The purpose of this study is to analyse one of the most important characteristics of the dynamic aspect of human energy metabolism, that is the response time of the human energy metabolic system when the step input is given to the system. Measurements of the energy cost in the time series were performed during natural walking, that is walking not on the treadmill, and the data obtained were regressed to the first order lag model (the response pattern of the first order

lag system, as the step input is given to the system), and finally time constant as the index of the response time was estimated. It means that the human energy metabolic system has been assumed as the first order lag system, which was proved appropriately later.

The human energy metabolic system may be actually much more complicated because the system is sustained by many other systems: respiration, circulation, body temperature regulation and others, each of which has a control system. But the attempt to fit these time series data to the first order lag model, which is the simplest model, is often available as the first step for elucidating the dynamic characteristics of a system.

METHOD

In these experiments nine male and nine female healthy young subjects were made to walk outdoors on the irregularly hexagonal concrete course with a lap of 102.8 meters. These natural walking experiments were held in July 1975, usually during the cool of the morning. Before the experiments, the subject's stature and weight were measured, and their physical conditions (overeating, fatigue and post-absorptive state) were checked to eliminate the factors disturbing the experiments. Table 1 shows the age of the subject, the measurements stated above and the mean value of air temperatures which were measured every minute during the experiments. The air temperature was slightly higher for the experiments.

Table 1. Age, stature and weight of nine male and nine female subjects and air temperature during the experiments.

Subject	sex	age	stature (cm)	weight (kg)	air temperature during exp. (°C)
A	male	28	168.7	60	30.4
B		23	166.5	57	27.2
C		23	166.7	56	30.5
D		22	173.2	56	31.3
E		25	172.3	63	33.2
F		25	167.3	54	30.8
G		19	160.0	58	31.9
H		23	166.5	56	31.2
I		19	175.5	65	27.8
J	female	20	161.3	53	25.6
K		24	158.5	51	28.6
L		21	165.7	56	28.7
M		21	152.1	43	25.1
N		18	164.3	55	28.4
O		20	161.6	51	26.2
P		20	155.6	56	28.7
Q		20	154.4	48	30.7
R		26	153.1	50	30.6

Fig. 1. The equipment used by the subject. The sample gases were collected into the rubber bags (4) through the bifurcated gas cock (3) attached to the duct (2), which was connected to the mask (1) and the Max Planck gas meter (5). Then the gases were kept in the 50 cm³ disposable syringes.

Sample gases were collected in the rubber bags every minute, through the bifurcated gas cock attached to the tube connecting the mask and the Max Planck gas meter. The equipment used on the subject is shown in Fig. 1. Then the gases were kept in the 50 cm³ disposable syringes and finally analysed by the Scholander gas analyser, to calculate the energy cost. The energy cost measured on the subject at the start point, with a gas meter of 3.8 kg on his back, standing at ease for five minutes, was used as the initial value. Then he began to walk naturally for twenty-five minutes at any given speed but speed must be constant during the walk. It means that the constant speed walking was given to the human energy metabolic system as the step input.

The experiment was tentatively divided into three parts: the initial state (for

5 minutes), the transient state (for 15 minutes) and the steady state (for 10 minutes). All time series data were checked to prove the acquisition of the steady state within at least 15 minutes from the start, by testing the gradient of the regression line of the data during the last 10 minutes of walk.

To estimate time constant, the data at the transient state were regressed to the first order lag model, although the dynamic characteristics are, of course, concerned with the data in the steady state. The mathematical form of the first order lag model is:

$$y = Qe^{-\frac{t}{\tau}} \dots\dots\dots(1),$$

where t is time and the independent variable, y is the dependent variable, Q is the initial value of y , e is constant and the base of natural logarithm, τ is the time constant. The convergent value of y is zero. In this case the residual variance around the first order lag model is provided as the random variance on the model.

The graphical form of this model is shown in Fig. 2. The tangent line at any contact point cuts the convergent value of y after a time constant from the contact point. Fig. 2 shows that the tangent line at the start point cuts the convergent value of y after a time constant from the start. Therefore, the index time constant is generally used to express the response time of the system. The larger time constant means a slow response and the small one means a rapid response. In addition, another feature of the time constant is that the y value after a time

Fig. 2. This figure shows three cases of the response pattern of the first order lag model as against the step input. The time is shown on the abscissa and the energy cost per unit time is shown on the ordinate. In case of a the time constant is 1 (arbitrary unit), in case of b it is 2 and in case of c it is 4. It is shown that the larger the time constant is, the slower is the response time.

constant from the start covers about 63.2 % $\left(1 - \frac{1}{e}\right)$ of the whole changing range of y (in Fig. 2, this is Q).

For the actual calculation of regression, the formula (1) was changed into the logarithmic form to be used as the form of the linear regression, that is:

$$\ln y = -\frac{1}{\tau}t + \ln Q \dots \dots \dots (2)$$

With this formula, the time constant was statistically obtained as the reciprocal number of the gradient of the linear regression line, when the original data of the transient state were put into y and t . Q is the difference between the initial value and the convergent value.

The level of fitness of the data to this model was indicated by the correlation coefficient, which was calculated by the

method of SNEDECOR and COCHRAN (1967).

The statistical formula is:

$$\Sigma d^2 = (1 - R^2) \Sigma y^2$$

where d is the residual, y is the original datum and R is the correlation coefficient.

RESULTS AND DISCUSSIONS

The first order lag model was used to elucidate the dynamic characteristic of human energy metabolic system, as the first step to analyse the dynamic characteristics of the system. Male and female examples of the fitness to the first order lag model are shown in Fig. 3 and Fig. 4, showing good fitness. The results, time constant of the energy cost per minute, that of minute volume (indicated V_E in Table 2), that of oxygen consumption per minute ($\dot{V}O_2$) and that of the expired

Fig. 3. This figure shows the fitness between the energy cost of a male G and the model. The value of the correlation coefficient is 0.998. The time constant is calculated as 1.50 minutes, being slightly higher than the mean value for the males. The time (the unit is minute) is shown on the abscissa and the energy cost per minute (kcal/minute) is shown on the ordinate.

Fig. 4. This figure shows the fitness of a female Q with the correlation coefficient of 0.997. The time constant is calculated as 3.61 minutes. The time (minute) is shown on the abscissa and the energy cost per minute (kcal/minute) is shown on the ordinate.

Table 2. Time constants, correlation coefficients and sex differences.

Subject	sex	time constant of energy cost (min.)	correlation coefficient about energy cost	time constant of $\dot{V}E$ (min.)	time constant of $\dot{V}O_2$ (min.)	time constant of $\dot{V}CO_2$ (min.)
A	male	1.229	0.995	1.567	1.068	1.225
B		1.329	0.988	1.416	1.129	1.212
C		1.236	0.996	1.855	1.065	1.084
D		1.176	0.998	1.273	1.016	1.130
E		1.208	0.997	1.573	0.974	1.123
F		2.084	0.993	2.178	1.783	2.012
G		1.499	0.998	1.873	1.365	1.445
H		1.291	0.995	0.849	1.052	1.163
I		1.352	0.994	1.065	1.164	0.813
Mean		1.378		1.517	1.180	1.245
S. D.		0.282		0.419	0.253	0.331
J	female	2.209	0.993	2.089	1.658	2.181
K		1.325	0.997	2.244	1.214	1.252
L		2.869	0.995	2.621	2.758	1.567
M		3.894	0.985	1.580	1.563	2.373
N		1.505	0.997	2.342	1.323	1.389
O		1.243	0.997	1.404	1.081	1.129
P		1.610	0.997	2.038	1.242	1.954
Q		3.609	0.993	3.682	3.354	4.305
R		2.371	0.992	1.456	2.088	3.843
Mean		2.293		2.162	1.809	2.221
S. D.		0.985		0.706	0.782	1.136
Sex Diff. Significance Level		95%		95%	95%	95%

carbon dioxide per minute ($\dot{V}CO_2$), are forms.

listed in Table 2, the unit of which is minute. The table also shows the correlation coefficients of energy cost, when the original data were fit to the model, the high value of which proves the adequate fitness to the model. It means that the human energy metabolic system is appropriately taken as the first order lag system. It is tentatively able to be assumed that the transfer function of the human energy metabolic system is $\frac{1}{1+\tau s}$. Where s is the parameter of the Laplace trans

The analysis showed that the mean male time constant was 1.38 minutes with a standard deviation of 0.28 minutes and the female one was 2.29 minutes with that of 0.99 minutes. The sex differences in the time constant of these four measurements were detected by the t -test at a five percent significance level, indicating a more rapid response in the male than in the female, which was in accordance with our experiences. These male and female ranges of energy cost (from

Fig. 5. The male and female ranges of the first order lag models finally obtained from the data on nine males and nine females. The horizontally striated area shows the male range (from the male mean value minus one standard deviation to that plus one standard deviation). The vertically striated area shows the female range. The male mean value (m) and the female mean value (f) of time constant are shown on the abscissa.

the mean time constant minus one standard deviation to that plus one standard deviation) and the sex difference are shown in Fig. 5.

Energy metabolism during exercise is a results of integration of energy requirement in the muscular system, physical energy distribution, respiratory control, circulatory control and body temperature regulation. Energy metabolic system contains these many sub-systems, each of which have transfer characteristics, on which, however, there are still few studies. The result of this study means the approximate total dynamic characteristic of human energy metabolic system including these many sub-systems. The attempt to

fit to the model, on the supposition that all residual variance is a random variance around the model, is sufficiently available, as each characteristic is not yet clear.

It may be imagined that an animal like a horse, which must be provided sufficient energy quickly for running, has a shorter time constant, which means a shorter response time, and that an animal like a tortoise, which has another method of escape than running or fighting, has a longer time constant meaning a longer response time. Further investigations of this kind will show the different time constants for animals having different life patterns. With regard to the human response time of energy metabolic system,

it is also suggested that the time constant will be affected by training or aging, and it will show the difference among the groups scattered around the world.

CONCLUSION

It can be concluded that the human energy metabolic system can be regarded to be the first order lag system, and that the response time of the human energy metabolic system can be expressed by the time constant. There is a sex difference in the time constant at a five percent significance level, showing a more rapid response in the male than in the female.

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歩行の過渡状態からみたヒトのエネルギー代謝系の動特性

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本研究は、ヒトのエネルギー代謝系の動特性を解析する第一段階として、この系のステップ入力に対する応答時間を測定する事を目的とした。その為、定速の自然歩行をこの系に対するステップ入力として用い、一分毎にエネルギー消費量を測定して解析を行なった。

実験期間は、1975年6月から7月に互る一ヶ月余りの間であり、主に気温変化の少ない午前中に実験を行なった。場所は、コンクリート舗装された一周約100mのコースである。実験は、日本人青年男女各12名を被験者として、まず5分間の直立安静を保たせた後、25分間の定速自然歩行を行なわせ、一分毎のエネルギー消費量を測定した。測定法は、間接測定法の開放系である。歩行以外の種々の影響（緊張等々）のみられるものを除く為、被験者が歩行開始後15分以内に定常状態に達しているかどうかを検定し、最終的には男女各9名づつを解析に用いた。検定は、歩行後半の10分間のエネルギー消費量が有意に上昇あるいは下降していないかどうかを、回帰直線を取り、その傾きが0と有意に異なるかどうかで判定して行なった。

目的とするヒトのエネルギー代謝系の応答時間を得る為、一分毎のエネルギー消費量を一次遅れ系のステップ応答パターン（一次遅れモデル） $y = Qe^{-\frac{t}{\tau}}$ に当てはめ、この時定数 τ をヒトのエネルギー代謝系の（ステップ入力に対する）応答時間として用いた。この時定数は、一次遅れ系のステップ応答時間を表す良い指標として、一般によく用いられているものである。

その結果、男子の時定数は、 1.38 ± 0.28 分（1標準偏差）、女子のそれは、 2.29 ± 0.99 分と計算され、5%の危険率で性差がみられ、男子の応答時間の短い事が示された。すなわち、男子のエネルギー代謝系の方が早く運動状態に移行できるという事であり、これは我々の経験とよく一致する事である。又、エネルギー消費量と一次遅れモデルとの相関係数を計算すると、いずれも非常に高い値を示し、ヒトのエネルギー代謝系のステップ応答が一次遅れモデルによく当てはまる事が示された。すなわち、この結果から見る限り、ヒトのエネルギー代謝系は一次遅れ系に近似してよく、その伝達関数は $1/(1+\tau s)$ と考えてさしつかえないと結論された。