

Economical Estimates of Oxygen Uptake as a Function of Gait Parameters for an Ambulatory Monitoring System

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ABSTRACT

To examine a method to save time and money with empirical equations representing the relationship between oxygen uptake ($\dot{V}O_2$), walking speed (v), step frequency (SF), and step length (SL), we recorded the $\dot{V}O_2$ and SF of 7 young male volunteers walking at an increasing speed from 16.7 to 131.7 m min⁻¹ with 5 m min⁻¹ increments every 1 min, and at a decreasing speed from 106.7 m min⁻¹ for 5 min to 16.7 m min⁻¹ with 5 m min⁻¹ decrements every 1 min on a level treadmill. SL was also computed by dividing walking speed by SF . The $\dot{V}O_2$ during decremental-speed walking was significantly greater compared to that during incremental-speed walking at corresponding speeds. The SF and SL could be expressed as a function of speed by $SF=13.18\sqrt{v}$ and $SL=0.076\sqrt{v}$, respectively, regardless of the different modes of walking with respect to speed. To estimate the $\dot{V}O_2$ during walking at different speeds, the results of the increments and decrements were combined by averaging them with respect to speed ($\dot{V}O_2=1.454 \times 10^{-4}v^2 - 6.5 \times 10^{-3}v + 0.663$, $r=0.999$, $n=7$). In a mathematical model of the cardiorespiratory system, the average values of $\dot{V}O_2$ at a given speed, even though there were on- and off-phase responses, could be predicted within 7.4% of the theoretical steady-state value. These results suggest that the $\dot{V}O_2$ against walking speed can be estimated by averaging the responses between the increments and decrements of moderate speeds. This could improve exercise tests for $\dot{V}O_2$ estimates in terms of time and money. In addition, by using the close relationship between SF and v , $\dot{V}O_2$ can be also expressed as a function of SF .

Key words : Walking speed, Step length, Step frequency, Walking exercise

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INTRODUCTION

Walking is common not only in daily living, but also as exercise to keep healthy. Although exercise training increases muscle strength, postural stability and cardiorespiratory endurance, terrestrial locomotive training such as jogging and running at higher speeds is associated with orthopedic injuries caused by high-impact ground-reaction forces, especially in the elderly^{1,2)}.

The gait parameters of simply-recorded step length (SL) and step frequency (SF) are generally considered fundamental information on the kinematics, biomechanics, and energetics during walking. The rate of energy expenditure during level walking for humans varies with transport speed, which is determined by the products of SL and SF . To date, several studies have reported the relationship between oxygen uptake ($\dot{V}O_2$) and walking speed (v) in humans^{3~5)}. The determination of the $\dot{V}O_2$ -speed relationship requires a lot of time and money for experiments, since subjects must walk at various speeds under conditions in which $\dot{V}O_2$ during walking fully reaches the steady-state levels at individual speeds over relatively long times (e. g., 5 min)^{6,7)}. To date, however, few attempts have been made to overcome these problems.

Therefore, the purpose of this study was to determine methods by which the changes in $\dot{V}O_2$ against v can be economically estimated from the average values of $\dot{V}O_2$ between an incremental speed and a decremental speed. To do this, we systemically examined the relationship between $\dot{V}O_2$, SL , SF , and v . Recently, the estimation of energy expenditure during walking from ambulatory monitoring of gait parameters has stimulated growing interest in the evaluation of physical activity and metabolic rates in health-care promotion, as well as in scientific and clinical studies.

A preliminary report of the results has been presented in abstract form⁸⁾.

METHODS

1 Subjects

Seven healthy young volunteer male subjects, mean age 22 ± 1 years, average height 1.70 ± 0.06 m, average weight 66 ± 7 kg, average leg-length 0.81 ± 0.04 m, and average peak oxygen uptake ($\dot{V}O_{2peak}$) 2.82 ± 0.45 L min^{-1} , participated in the present study having given their informed consent. None of the subjects had a history of circulatory or respiratory disease. Furthermore, no trained athletes participated in this study. The $\dot{V}O_{2peak}$ was determined for each subject not by a walking exercise, but by a stationary cycling exercise over a 15 W min^{-1} incremental ramp exercise until exhaustion⁹⁾ because subjects on a treadmill at higher speeds are in danger of falling, especially at exhaustion. Each subject wore a light T-shirt, shorts, and general gym shoes. The study protocol was approved by the Institutional Human Studies Committee.

2 Experimental design

Each subject completed 2 repetitions of the test during each of the 2 experimental conditions. After resting in a supine position for 30 min, each subject mounted a motor-driven treadmill (AR-160 A ; Minato, Osaka, Japan). The subjects walked on the treadmill during either an increase in speed or a decrease in speed as follows : ①the increments were from 16.7 m min^{-1} to 131.7 m min^{-1} with 5 m min^{-1} increments every 1 min at a 0% grade ; and ②the decrements were from 106.7 m min^{-1} for 5 min to 16.7 m min^{-1} with 5 m min^{-1} decrements every 1 min at a 0% grade. The stepwise increases or

decreases in speed were controlled successively by a personal computer (PC9801RX ; NEC, Tokyo, Japan).

Tests were initiated at approximately 10 : 00 a. m. for all subjects, and the order of testing (e. g., incremental walking vs decremental walking) was randomly assigned. Each subject completed 2 repetitions of the test for each of the 2 experiments, and each trial was performed only once a week to eliminate the influence of exercise training. The subjects ate a small breakfast at least 3h before exercising. All the subjects were familiarized with the test situation in several pilot experiments. All experiments were conducted at an ambient temperature between 21 and 22°C.

3 Measurement of respiratory and gait data

During walking exercise, $\dot{V}O_2$ was measured breath-by-breath using an on-line automated measurement system, as previously described¹⁰. Ventilatory airflow was monitored using a hot-wire-type pneumotachograph (RF-2, Minato ; Osaka, Japan). The composition of expired gas was continuously analyzed using a medical mass spectrometer (WSMR-1400 ; Westron, Chiba, Japan), which was calibrated with a standard reference gas mixture before each experiment. The number of steps in contact with the surface of the treadmill was monitored through foot contact signals generated by a pressure-sensitive mechanical switch attached to the fore-sole of the right shoe. The signals from the foot-switch were fed to a computer. All data for respiratory and gait variables were stored on diskettes for subsequent analysis using a personal computer (PC-9821Xa13 ; NEC, Tokyo, Japan).

4 Data analysis

Respiratory and gait data obtained from 2 repetitions of the walking test for each subject were arranged separately with a 5-sec interval time base using a Lagrange interpolation. These data were then averaged to yield a single data set for each subject. To eliminate the effects of small, if any, day-to-day variability or unexpected artifacts on the measured variables¹¹, consecutive average values for all variables were calculated from the last 20 sec of averaged data obtained at each stage of incremental and decremental v ¹². SL was obtained by dividing v by the corresponding SF . In gait analyses, the basic temporal and spatial factors were assumed to be symmetrical in each stride cycle¹³. It was also assumed that there was consistency between successive gait cycles during walking at each constant speed¹⁴. Least-squares fitting was also applied to the data points on $\dot{V}O_2$ and gait variables. All values are expressed as means \pm SD.

RESULTS AND DISCUSSION

Fig. 1a and **1b** show dynamic changes in $\dot{V}O_2$ during walking on a level treadmill at an increasing speed and a decreasing speed, respectively, of 5 m min⁻¹ every minute in a representative subject. Both the increased and decreased $\dot{V}O_2$ responses and the mean values of the 2 responses were also plotted against v (**Fig. 1c**). The $\dot{V}O_2$ for decremental-speed walking was greater compared to that for incremental-speed walking at corresponding speeds. The differences in $\dot{V}O_2$ between the 2 modes of walking were relatively greater at higher speeds than at lower speeds.

Fig. 2a shows consecutive average values for all subjects during the increasing-speed and decreasing-speed walking and the mean values of the 2 modes of walking against forward speeds. The data points of the mean values of $\dot{V}O_2$ for each subject were well fitted with a quadratic-equation curve, which held for all subjects over speeds ranging from 16.7 to 106.7 m min⁻¹ with a high coefficient of

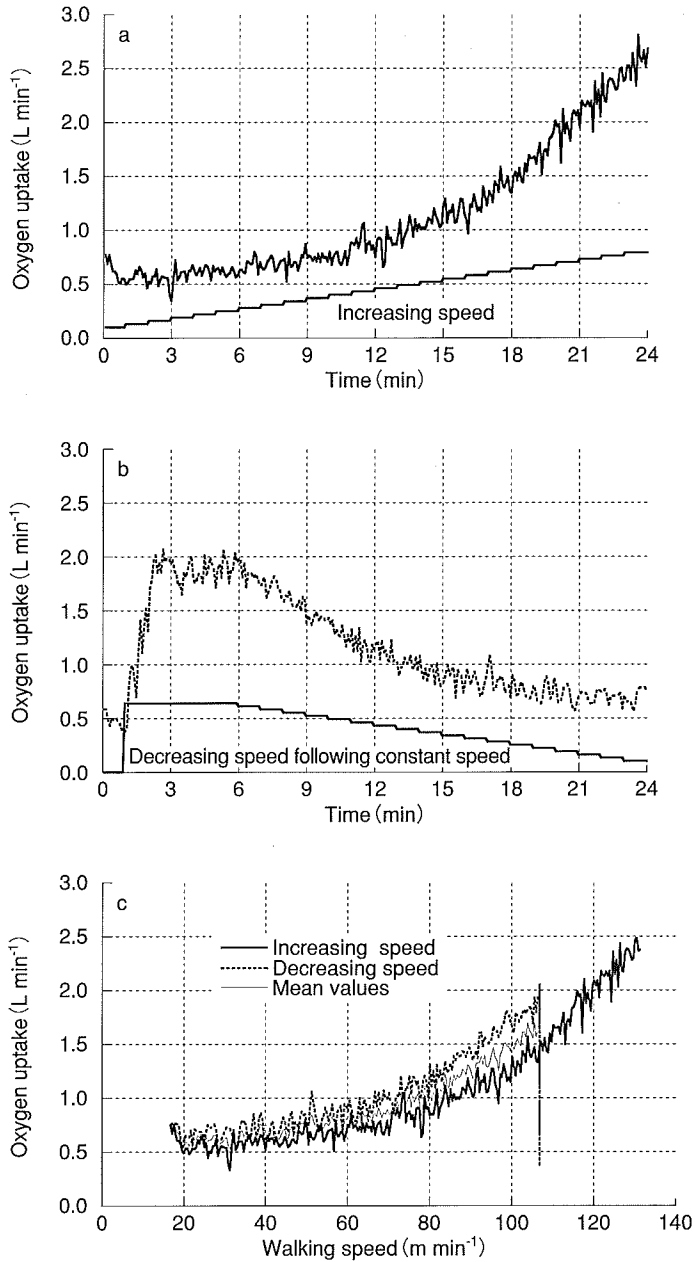


Fig. 1 a : Oxygen uptake ($\dot{V}O_2$) responses to 1-min increment treadmill exercise in a representative subject

The speed of the level treadmill was increased from 16.7 to 131.7 m min⁻¹ with 5 m min⁻¹ increments every 1 min.

b : Oxygen uptake ($\dot{V}O_2$) responses to a 1-min decrement treadmill exercise

The speed of the level treadmill was a constant at 106.7 m min⁻¹ for 5 min and then decreased from 106.7 to 16.7 m min⁻¹ with 5 m min⁻¹ decrements every 1 min.

c : Oxygen uptake ($\dot{V}O_2$) for increment- and decrement-speed walking and the mean values at the corresponding speeds

The dash-dotted vertical line at 106.7 m min⁻¹ indicates the data obtained during walking at the initial constant speed in decremental-speed walking tests.

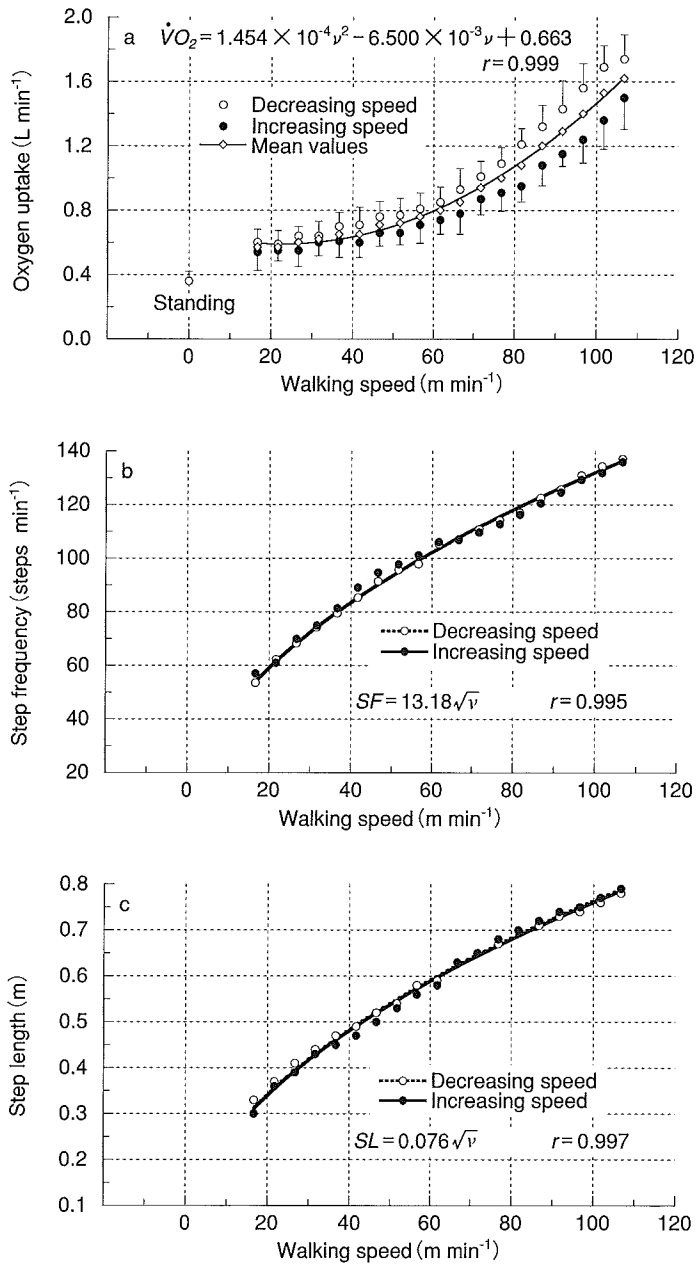


Fig. 2 a : Group mean values of oxygen uptake ($\dot{V}O_2$) for 7 subjects during level walking at increment and decrement treadmill speeds and the mean values at the corresponding speeds
b : Group mean value of step frequency (SF) for 7 subjects during level walking at increment and decrement treadmill speeds
c : Group mean value of step length (SL) for 7 subjects during level walking at increment and decrement treadmill speeds

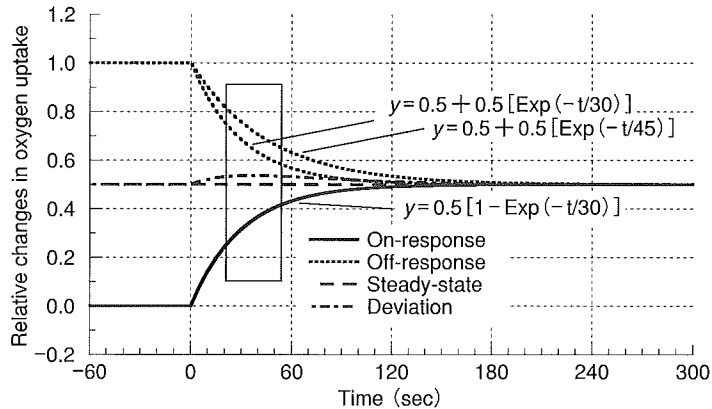


Fig. 3 Time courses of oxygen uptake ($\dot{V}O_2$) responses during the transition from different baselines to a new exercise intensity

The solid line shows the exponential increase with a time constant (TC) of 30 sec, and the dotted lines with TC s of 30 and 45 sec show an exponential decrease.

determination ($0.991 < r < 0.998$). **Fig. 2b** and **2c** show the corresponding changes in SF and SL , respectively, against v . The SF and SL increased almost linearly with increasing-speed walking and decreased almost linearly with decreasing-speed walking, while the changes in the 2 variables were very similar between the 2 modes of walking. Both the changes in the mean SF (steps min^{-1}) and in the mean SL (m) could be expressed as a function of forward speed by a single equation each, regardless of the different modes, as follows :

$$SF = 13.18\sqrt{v} \quad (1)$$

$$SL = 0.076\sqrt{v} \quad (2)$$

which satisfied the relation $v = SF \cdot SL$.

Cardiorespiratory responses, including pulmonary gas exchange and cardiac variables, to physiological stimuli generally change in a way such that their responses during the on-phase and the off-phase can be expressed as an exponentially increased and decreased function, respectively^{6,7,9,15}. **Fig. 3** shows a numerical simulation of $\dot{V}O_2$ responses for a theoretical system with respect to a step function of work rate. When a linear transfer function between the stimulus exercise and the output response was assumed, a first-order exponential function with a time constant (TC) could be fitted to the responses. The TC s were used to compare the kinetics of the different responses. Despite their transient phases, the on-response and off-response with the same TC of 30 sec to an identical intensity, but from different baselines, were settled to an asymptote in a mirror-image way so that the averaged values of the 2 responses could give the steady-state value. On the other hand, the kinetics of the off-response with a TC of 45 sec were slower than with the TC of 30 sec. The change in the average values of the on-response and the slower off-response in the early transient phase slightly deviated from the steady-state value. However, the maximum deviations, appearing within 25 to 55 sec, were 7.4% at the most. Thus, even though the kinetics of the off-response were 50% slower than those of the corresponding on-response, the estimate of $\dot{V}O_2$ at any speed by averaging the counteractive changes would not have had any serious effects. In the simulation of $\dot{V}O_2$ responses, the cardiorespiratory system was

assumed to have linearity of responses to the stimuli. Since the mean value of 1.69 ± 0.14 (L min^{-1}) for $\dot{V}O_2$ at 106.7 m min^{-1} was approximately 60% $\dot{V}O_{2\text{peak}}$ and the respiratory exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) was 0.89 ± 0.14 , the respiration remained under conditions below the anaerobic threshold so that systemic linearity was satisfied in the exercise protocols of this study.

Since the quantity of $\dot{V}O_2$ estimated from the gait parameters was evident in this study, ambulatory monitoring techniques make it possible to quantify the rate of metabolic energy expenditure during transport. For example, using the equation predicting $\dot{V}O_2$, the metabolic rate during walking can be estimated from SF computed from the number of steps per unit time with an accelerometer (Digital Walk, FM-180, Fukuda, Tokyo, Japan). The gait parameters recorded using the accelerometer with the ECG monitoring system could be used subsequently by a medical specialist or a special adviser to check and analyze the physical conditions during walking for health and in everyday life.

CONCLUSIONS

The changes in $\dot{V}O_2$ against v were estimated from the average values of $\dot{V}O_2$ responses between the increments and decrements within a range of moderate v in 2 exercise tests with a substantial time and cost saving. The estimates of $\dot{V}O_2$ could be correctly expressed as a function of v by a quadratic equation. By using the close relationship between SF and speed, the $\dot{V}O_2$ in the above expression could be replaced by an equation as a function of SF , $\dot{V}O_2$ (L min^{-1}) = $4.82 \times 10^{-9} SF^4 - 3.74 \times 10^{-5} SF^2 + 0.663$.

REFERENCES

- 1) Pollock ML, Wilmore JH. Exercise in Health and Disease. Philadelphia : W. B. Saunders Company ; 1990.
- 2) Takahashi T, Okada A, Hayano J, Takeshima N. Responses of heart rate and vagal tone to treadmill walking on land and in water in healthy older adults. JAPA 2003;11:18-26.
- 3) Zarrugh MY, Radcliffe CW. Predicting metabolic cost of level walking. Eur J Appl Physiol 1978;38:215-23.
- 4) Takahashi T, Okada A, Tamura T, Miyamoto Y. Cardiorespiratory responses to walking and running at an incremental speed of treadmill. Adv Exp Med Biol 2001;499:363-8.
- 5) Bastien GJ, Willems PA, Schepens B, Heglund NC. Effect of load and speed on the energetic cost of human walking. Eur J Appl Physiol 2005;94:76-83.
- 6) Niizeki K, Takahashi T, Miyamoto Y. A model analysis of asymmetrical response of pulmonary $\dot{V}O_2$ during incremental and decremental ramp exercise. J Appl Physiol 1995;79:1816-27.
- 7) Takahashi T, Niizeki K, Miyamoto Y. Effects of base line changes in work rate on cardiorespiratory dynamics in incremental and decremental ramp exercise. Adv Exp Med Biol 1995;393:159-64.
- 8) Takahashi T, Yanagida H, Niizeki K, Wang S, Matsuo T, Watanabe S, et al. Oxygen uptake during human walking at incremental and decremental treadmill speeds (abstract). In : ISOTT2008 Abstract Book. The 36th Annual Meeting of International Society on Oxygen Transport to Tissue. Japan : Oxygen Dynamics Society;2008. p.32.
- 9) Takahashi T, Miyamoto Y. Influence of light physical activity on cardiac responses during recovery from exercise in humans. Eur J Appl Physiol 1998;77:305-11.
- 10) Takahashi T, Niizeki K, Miyamoto Y. Respiratory responses to passive and active recovery from exercise. Jpn J Physiol 1997;47:59-65.
- 11) Durnin JVGA, Namyslowski L. Individual variations in the energy expenditure of standardized activities. J Physiol 1958;143:573-8.
- 12) Takano N. Effects of pedal rate on respiratory responses to incremental bicycle work. J Physiol 1988;396:389-97.
- 13) Milner M, Quanbury AO. Facets of control in human walking. Nature 1970;227:734-5.
- 14) Hirokawa S, Matsumura K. Gait analysis using a measuring walkway for temporal and distance factors. Med Biol Eng Comp 1987;25:577-82.
- 15) Takahashi T, Okada A, Saitoh T, Hayano J, Miyamoto Y. Difference in human cardiovascular response between upright and supine recovery from upright cycle exercise. Eur J Appl Physiol 2000;81:233-9.

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REFERENCES

- 1) Pollock ML, Wilmore JH. Exercise in Health and Disease. Philadelphia : W. B. Saunders Company ; 1990.
- 2) Takahashi T, Okada A, Hayano J, Takeshima N. Responses of heart rate and vagal tone to treadmill walking on land and in water in healthy older adults. JAPA 2003;11:18-26.
- 3) Zarrugh MY, Radcliffe CW. Predicting metabolic cost of level walking. Eur J Appl Physiol 1978;38:215-23.
- 4) Takahashi T, Okada A, Tamura T, Miyamoto Y. Cardiorespiratory responses to walking and running at an incremental speed of treadmill. Adv Exp Med Biol 2001;499:363-8.
- 5) Bastien GJ, Willems PA, Schepens B, Heglund NC. Effect of load and speed on the energetic cost of human walking. Eur J Appl Physiol 2005;94:76-83.
- 6) Niizeki K, Takahashi T, Miyamoto Y. A model analysis of asymmetrical response of pulmonary $\dot{V}O_2$ during incremental and decremental ramp exercise. J Appl Physiol 1995;79:1816-27.
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- 8) Takahashi T, Yanagida H, Niizeki K, Wang S, Matsuo T, Watanabe S, et al. Oxygen uptake during human walking at incremental and decremental treadmill speeds (abstract). In : ISOTT2008 Abstract Book. The 36th Annual Meeting of International Society on Oxygen Transport to Tissue. Japan : Oxygen Dynamics Society;2008. p.32.
- 9) Takahashi T, Miyamoto Y. Influence of light physical activity on cardiac responses during recovery from exercise in humans. Eur J Appl Physiol 1998;77:305-11.
- 10) Takahashi T, Niizeki K, Miyamoto Y. Respiratory responses to passive and active recovery from exercise. Jpn J Physiol 1997;47:59-65.
- 11) Durnin JVG, Namyslowski L. Individual variations in the energy expenditure of standardized activities. J Physiol 1958;143:573-8.
- 12) Takano N. Effects of pedal rate on respiratory responses to incremental bicycle work. J Physiol 1988;396:389-97.
- 13) Milner M, Quanbury AO. Facets of control in human walking. Nature 1970;227:734-5.
- 14) Hirokawa S, Matsumura K. Gait analysis using a measuring walkway for temporal and distance factors. Med Biol Eng Comp 1987;25:577-82.
- 15) Takahashi T, Okada A, Saitoh T, Hayano J, Miyamoto Y. Difference in human cardiovascular response between upright and supine recovery from upright cycle exercise. Eur J Appl Physiol 2000;81:233-9.

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