Dynamics of the heart rate response to sinusoidal work in humans: influence of physical activity and age

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ABSTRACT

The purpose of the present study was to define the influence of age and exercise training on the heart rate (HR) dynamic response (i.e. kinetics) to sinusoidal work. A total of 63 healthy subjects (31 men and 32 women; age range 19–69 years) underwent a three-step incremental work test, during which peak oxygen uptake (VĖO₂peak) was estimated by the YMCA method. Sinusoidal work varying between 20% and 60% of HRreserve was employed for periods of 1, 3, 6, 9 and 12 min. HR was monitored in a beat-by-beat manner with a cardiotachometer. The kinetics of the HR response were analysed by frequency analysis and estimated by a first-order transfer function with time constant (τ) and time delay (TD). Physical training status was estimated as stepping frequency, as measured with a pedometer during the daytime, and averaged over seven consecutive days. The mean response time of HR kinetics (HRMRT: τ pulse TD) tended to increase gradually with age (0.36 s/year−1), and linear regression analysis revealed that the correlation between HRMRT and age was significant (rfl = 0.31, P < 0.05), although not as highly significant as that between HRMRT and physical activity (rfl = 0.48, P < 0.0001). HRMRT was not related to the S.D. of HR variation (an indicator of parasympathetic mediation) at rest. In addition, VĖO₂peak showed a significantly greater correlation with age (r = −0.60, P < 0.0001) than with physical activity (r = −0.14, not significant). In conclusion, these findings suggest that HR dynamics, which may depend on sympathetic nervous activity, are more sensitive to physical activity than to age, but that VĖO₂peak, as estimated by the age-associated decline in maximum HR, is unrelated to physical training status.

INTRODUCTION

Cardiovascular and gas exchange readjustments at rest and during exercise become slower with advancing age [1–5]. Cunningham et al. [4] compared heart rate (HR) kinetics in response to sinusoidal work in younger and older women, and found that HR kinetics were relatively sluggish in the latter. In contrast, Babcock et al. [2] observed no delay in HR kinetics in response to step work with increasing age, even though the kinetics of gas exchange variables were significantly slower with aging. These results raise the question of whether aging significantly influences HR kinetics in response to exercise stress. We suspect that the conflicting results for HR kinetics may reflect differences in the exercise protocols used (e.g. sinusoidal or step work protocols) or in the fitness of subjects. In humans, changes in HR kinetics during sinusoidal work have been attributed to the

Key words: age, heart rate, kinetics, physical activity, sinusoidal work.

Abbreviations: CVRR, coefficient of variation of the R–R interval; HR, heart rate; HRmax, maximum heart rate; HRMRT, mean response time of HR kinetics; MRT, mean response time; TD, time delay; τ, time constant; VĖO₂peak, peak oxygen uptake.

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simultaneous and integrated effects of withdrawal of vagal tone, stimulation of sympathetic tone and an increase in circulating catecholamines [6].

By contrast, exercise training can lead to marked improvements in ventilatory and gas exchange kinetics in both the elderly [7] and younger individuals [8,9]. However, exercise training does not improve HR kinetics in the elderly [7]. In our most recent trial study, the HR response was found to increase soon after the start of exercise training in 50-year-old subjects [10]. Because HR kinetics are also influenced by physical training status, they may increase during exercise due to a change in the balance of sympathetic and parasympathetic neural outflow caused by exercise training. We therefore hypothesized that faster HR kinetics during exercise would be due largely to physical training status. Surprisingly, these questions, i.e. whether HR kinetics, in which sympathetic neural adjustment may play a key role, are associated with either training status or age, have yet to be answered.

In most cases, maximal HR (HR\textsubscript{max}) at peak exercise can be very conveniently estimated as \(HR_{\text{max}} = 210 - 0.8 \cdot \text{age} \ [11,12]\). The decrease in \(HR_{\text{max}}\) may be the result of the withdrawal of sympathetic activity associated with advancing age. We hypothesized that, if the age-related changes in the functioning of the O\textsubscript{2} transport system (i.e. \(HR_{\text{max}}\)) are dependent on peak oxygen uptake (\(VO_{\text{peak}}\)), then both the indirect estimation of \(VO_{\text{peak}}\) by \(HR_{\text{max}}\) estimation and the previously used direct measurement of \(VO_{\text{peak}}\) must be useful parameters. However, because \(VO_{\text{peak}}\) is known to be associated with physical training status, we considered both the HR response during the performance of submaximal exercise and \(HR_{\text{max}}\) when estimating \(VO_{\text{peak}}\).

The aim of the present study was to investigate: (1) the relative contribution of changes in physical activity to the age-related delay in HR kinetics during a sinusoidal work protocol; and (2) the validity of estimating \(VO_{\text{peak}}\) using the HR response for investigating the age-related decline in \(VO_{\text{peak}}\) in a large number of subjects ranging in age from 19 to 69 years old (\(n = 63\)).

METHODS

Subjects

The subjects of this study were 63 healthy men and women volunteers aged between 19 and 69 years old, none of whom was on medication known to affect cardiovascular function. A medical history and a 12-lead resting ECG were obtained for all subjects (Table 1). The subjects were fully informed of any risks and discomforts associated with these experiments before giving their written, informed consent to participate in the study, which was approved by the ethics committee of the Institutional Review Board of the Prefectural University of Kumamoto. We did not take into consideration the usual level of physical activity of the subjects, some of whom had an exercise training background.

Measurement of physical activity

A digital pedometer (HJ-3; Omuron, Tokyo, Japan) was attached to the waist of each subject throughout each day of the study period. Subjects recorded their stepping frequency during all of their activities, which included sports activities, such as walking, running, jogging or racquet sports, for seven consecutive days, and the average number of steps recorded was used as the index of physical activity. Use of a pedometer has been shown previously to accurately reflect total physical activity, although not necessarily energy expenditure [13].

Two exercise protocols during incremental work and sinusoidal work

The subjects underwent a submaximal incremental work test consisting of three 3-min exercise stages. Exercise intensity was fixed at 60, 120 and 150 W for men aged 20–50 years, and at 30, 60 and 90 W for all women and for men > 50 years old. The ECG, taken from a V5 lead, was monitored continuously on an oscilloscope. HR, derived in a beat-by-beat manner with a cardiograph (AT-601 G; Nihon Kohden, Tokyo, Japan), was obtained during the final 60 s of each stage. The incremental work test was terminated successfully when at least two work periods were completed with an HR of between 110 and 150 beats·min\(^{-1}\). \(HR_{\text{max}}\) was determined by the formula 210 – 0.8·age, to ensure the safety of elderly subjects [11,14]. The regression line was obtained from the relationship between the three different work rates and the three HR data points during each of the three stages of the incremental work test. The estimated maximum work rate (in W) was calculated from this regression line at the subject’s age-predicted \(HR_{\text{max}}\) as described above. The corresponding estimated \(VO_{\text{peak}}\) during the YMCA cycle ergometer test was calculated from the maximum work rate (\(WR_{\text{max}}\)) by using the following equation [15] (where kpm is the mechanical work unit during one rotation of cycling):

\[
VO_{\text{peak}} \text{ (ml·min}^{-1} = \left[WR_{\text{max}} \text{ (W)} \cdot 6 \text{ kpm·W}^{-1}\right] \cdot 2 \text{ ml·kpm}^{-1} + 300 \quad (1)
\]

This test is a modification of the Åstrand–Ryhming test protocol based on the Åstrand–Ryhming nomogram (see eqn 2 below). In addition, two relative work rates, i.e. 20% and 60% of \(HR_{\text{reserve}}\) (see below), were also calculated from incremental work by using the following equation:

\[
\% \text{ of } HR_{\text{reserve}} = \frac{(HR_{\text{exercise}} - HR_{\text{rest}})/(HR_{\text{max}} - HR_{\text{rest}})}{100} \quad (2)
\]

In eqn (2), \(HR_{\text{exercise}}\) indicates the HR response during sinusoidal work, and \(HR_{\text{rest}}\) indicates the HR response at
Table 1  Physical characteristics and physical activity of the subjects
Data shown are means ± S.E.M.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sex</th>
<th>19–29 years old</th>
<th>30–39 years old</th>
<th>40–49 years old</th>
<th>50–59 years old</th>
<th>60–69 years old</th>
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</thead>
<tbody>
<tr>
<td>No. of subjects</td>
<td>Male</td>
<td>11</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>22</td>
<td>8</td>
<td>9</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Age (years)</td>
<td>Male</td>
<td>22.5 ± 4.1</td>
<td>35.0 ± 1.7</td>
<td>40.8 ± 0.5</td>
<td>54.7 ± 2.2</td>
<td>64.7 ± 3.7</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>20.8 ± 3.6</td>
<td>35.0 ± 2.6</td>
<td>47.4 ± 2.0</td>
<td>52.9 ± 2.9</td>
<td>61.3 ± 2.3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>Male</td>
<td>172.8 ± 7.2</td>
<td>173.0 ± 1.0</td>
<td>172.2 ± 5.8</td>
<td>167.2 ± 6.8</td>
<td>160.2 ± 3.4</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>157.6 ± 5.1</td>
<td>162.3 ± 4.7</td>
<td>157.6 ± 5.9</td>
<td>153.9 ± 5.4</td>
<td>152.2 ± 3.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>Male</td>
<td>65.0 ± 8.0</td>
<td>65.8 ± 7.7</td>
<td>67.7 ± 13.0</td>
<td>63.8 ± 5.6</td>
<td>58.2 ± 5.1</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>49.0 ± 6.4</td>
<td>57.2 ± 5.1</td>
<td>57.3 ± 3.4</td>
<td>54.2 ± 7.7</td>
<td>57.3 ± 7.3</td>
</tr>
<tr>
<td>Physical activity</td>
<td>Male</td>
<td>11110 ± 2765</td>
<td>7530 ± 2380</td>
<td>8759 ± 2001</td>
<td>7072 ± 3913</td>
<td>9312 ± 1907</td>
</tr>
<tr>
<td>(steps day⁻¹)</td>
<td>Female</td>
<td>8526 ± 2915</td>
<td>10761 ± 925</td>
<td>13207 ± 4037</td>
<td>9639 ± 4012</td>
<td>11415 ± 5452</td>
</tr>
</tbody>
</table>

Figure 1  Frequency distribution of number of walking steps per day (A), and relationship between physical activity and age in 63 subjects (B)

In (B), $y = 9841 - 4.1 \cdot \text{age (years)}$ ($r = 0.02$; not significant).

rest. With regard to sinusoidal work, a work rate varying sinusoidally from 20% to 60% of HR reserve, for periods of 1, 3, 6, 9 and 12 min, with several repeat cycles was employed in the present study. The subjects pedalled at a constant rate (approx. 60 rev./min) throughout each test. Similarly, the ECG taken from the V5 lead was monitored continuously on an oscilloscope, and HR, derived beat-by-beat by the cardiotachometer (AT-601G), was displayed digitally and transmitted into a microcomputer (PC9801RA; NEC, Tokyo, Japan) where it underwent analogue-to-digital conversion, with a sampling rate of 500 Hz, for on-line use of an analogue-to-digital converter (AJD-98; Canopus, Kobe, Japan) throughout the measurement period.

Data analysis
The R–R intervals during sinusoidal work were calculated beat-by-beat by the computer, and 1 s interval HR data were measured from the calculated R–R intervals and stored as a text file. The repeated HR responses to sinusoidal work were overlapped in correspondence with the cycle period, and the mean HR data at each respective cycle were obtained. The fundamental harmonic component of HR kinetics in response to sinusoidal work was obtained by frequency analysis, as described in detail previously [16]. It has been shown previously that a first-order transfer function model with time delay (TD) can approximate HR kinetics. In the present study, the time constant ($\tau$), TD and mean response time (MRT) of the HR response (HR_MRT) were calculated by the least-squares method [16]. MRT was defined as $\tau$ pulse TD. We chose this model because HR_MRT is mostly equivalent to other transfer function models, such as the second-order model, or the first-order model without TD [16].

Additionally, in 25 of the subjects, the coefficient of variation of the R–R interval (CVRR) at rest was determined as an indicator of parasympathetic activity [17].

Statistical analysis
All values are presented as means ± S.E.M. The data with regard to age and physical activity were also subjected to linear and multiple regression analysis, and the significance of differences was determined by one-way ANOVA and the Newman–Keuls test. The level of significance was set at $P < 0.05$. 

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RESULTS

The subjects ranged in age from 19 to 69 years, and there were no differences in height or body weight among the different age groups (Table 1). A histogram of the frequency distribution of the averaged number of physical steps per day is shown in Figure 1(A). In 32 of the 63 subjects (~50%), the number of physical steps per day ranged from 8000 to 12000. No decreases in physical activity, as measured with the pedometer, were observed with age (Figure 1B).

Figure 2 shows the superimposed HR responses obtained from a representative subject over periods of 3, 6 and 12 min. A larger amplitude and a smaller phase shift in HR kinetics became evident with a prolonged period of sinusoidal work. Within each period there were no significant differences in amplitude or phase shift of HR kinetics among the age groups (Table 2). The average minimum, maximum and magnitude [i.e. 

Table 2 HR response of amplitude and phase shift to sinusoidal work in each period

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>12 min</th>
<th>9 min</th>
<th>6 min</th>
<th>3 min</th>
<th>1 min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amp. (%)</td>
<td>PS (°)</td>
<td>Amp. (%)</td>
<td>PS (°)</td>
<td>Amp. (%)</td>
</tr>
<tr>
<td>19–29</td>
<td>37.5 ± 5.0</td>
<td>34.5 ± 7.2</td>
<td>37.0 ± 6.7</td>
<td>39.8 ± 6.4</td>
<td>39.7 ± 6.0</td>
</tr>
<tr>
<td>30–39</td>
<td>36.4 ± 6.0</td>
<td>42.9 ± 2.1</td>
<td>34.3 ± 8.2</td>
<td>49.5 ± 7.2</td>
<td>31.9 ± 3.6</td>
</tr>
<tr>
<td>40–49</td>
<td>31.2 ± 4.1</td>
<td>38.3 ± 2.9</td>
<td>30.6 ± 6.5</td>
<td>42.0 ± 8.6</td>
<td>26.1 ± 5.7</td>
</tr>
<tr>
<td>50–59</td>
<td>35.2 ± 12.6</td>
<td>42.1 ± 9.2</td>
<td>34.9 ± 10.3</td>
<td>50.0 ± 13.7</td>
<td>29.8 ± 9.7</td>
</tr>
<tr>
<td>60–69</td>
<td>36.3 ± 8.7</td>
<td>37.5 ± 7.0</td>
<td>35.4 ± 5.9</td>
<td>43.8 ± 7.8</td>
<td>33.2 ± 5.5</td>
</tr>
</tbody>
</table>

Figure 3 HR_MRT in response to sinusoidal work as a function of age and physical activity

Significant correlations were found between HR_MRT and age (A) \( r = 0.363 \) (\( p < 0.05 \)) and between HR_MRT and physical activity (B) \( r = -0.48 \) (\( p < 0.001 \)).
Heart rate kinetics with age and physical activity

The slope of the age-related decline in $V_O^{\text{peak}}$ was $-0.39 \text{ ml kg}^{-1} \text{ min}^{-1} \cdot \text{year}^{-1}$. However, no close relationship was observed between $V_O^{\text{peak}}$ and physical activity (Figure 4B).

Multiple-regression analysis was utilized to investigate the contributions of physical activity and age according to the equations shown below. The parameters of this statistical analysis are expressed as the values of the standardized partial regression coefficients:

$$
\text{HR}_{MRT} = 95.5 - 0.47 \cdot \text{(physical activity)} + 0.29 \cdot \text{age} \\
V_O^{\text{peak}} = 53.1 + 0.13 \cdot \text{(physical activity)} - 0.60 \cdot \text{age}
$$

There was a significantly higher standardized partial correlation for physical activity and $\text{HR}_{MRT}$ than for age and $\text{HR}_{MRT}$, while $V_O^{\text{peak}}$ was more strongly correlated with age than with physical activity.

We calculated CVRR at rest in 25 randomly selected subjects; there was no significant correlation between CVRR and $\text{HR}_{MRT}$ (Figure 5).

**DISCUSSION**

To our knowledge, this is the first study to characterize HR kinetics during moderate exercise in a large sample of subjects and to determine age-related and physical-activity-related changes in HR function using a mathematical model. The most striking finding of the present study was that $\text{HR}_{MRT}$ was more strongly associated with levels of physical activity than with age. Moreover, $\text{HR}_{MRT}$ in response to sinusoidal work was not closely related to CVRR. This supports our hypothesis that, in the present study, physical activity was more closely related to the cardiac chronotropic response than to the inotropic response, indicating that the dynamic control of HR during exercise occurred via the sympathetic

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**Figure 4** $V_O^{\text{peak}}$ as a function of age and physical activity

$V_O^{\text{peak}}$ was estimated using the YMCA method. The slope of the age-related decline in $V_O^{\text{peak}}$ was $-0.39 \text{ ml kg}^{-1} \text{ min}^{-1} \cdot \text{year}^{-1}$, was similar to the slope reported in many previous studies (A), whereas a close relationship between $V_O^{\text{peak}}$ and physical activity was not observed (B) ($r = 0.36$, $p < 0.0001$) (Figure 4A).

A first-order model with TD could approximately describe $\text{HR}_{MRT}$. $\text{HR}_{MRT}$ increased gradually with age (slope 0.36 s $\cdot$ year$^{-1}$; y-axis intercept 63.1 s), and linear regression analysis yielded a significant correlation between $\text{HR}_{MRT}$ and age ($r = 0.303$, $P < 0.05$) (Figure 3A). The increases in $\text{HR}_{MRT}$ tended to be somewhat lower among subjects who were older than 50 years, demonstrating that HR kinetics were not substantially slower among elderly subjects. Consequently, there was no statistically significant difference in $\text{HR}_{MRT}$ between the younger (20–39 years old) and elderly (50–69 years old) groups. Instead, $\text{HR}_{MRT}$ was correlated more closely with physical activity ($r = -0.48$, $P < 0.0001$) than with age (Figure 3B). In addition, $\text{HR}_{MRT}$ tended to reach a plateau just before 65 s; this time point coincided with the physical stepping frequency of the subjects reaching more than 10000 steps $\cdot$ day$^{-1}$.

The age-related $V_O^{\text{peak}}$ estimated by the YMCA method [15] declined significantly with age (Figure 4A);
outflow. We also found a greater standardized partial correlation between \( \dot{V}_{O_2\text{peak}} \) and age (after controlling for physical activity) (Figure 3) than between \( \dot{V}_{O_2\text{peak}} \) and physical activity, even after controlling for age.

**Slower HR kinetics with advancing age**

HR kinetics were found to change little with age in a stepped work study [3], whereas Cunningham et al. [4] demonstrated that HR kinetics in elderly women were slower during a sinusoidal work protocol. The differences between the findings in relation to HR kinetics in these studies may have been due to the different types of work undertaken, differences in relative fitness, or small variations in the subjects. Chilibeck et al. [18] observed that the \( \tau \) values of the HR during both cycling and walking were markedly different between elderly and younger individuals. Taken together, the available evidence suggests that slower HR kinetics during the on- and off-transient phase of exercise are characterized by a comparatively greater HR-MRT with advancing age.

However, the greater value of HR-MRT in response to sinusoidal work in the present study is incompatible with previous observations of the response to other work patterns [8,9]. Sone et al. [6] observed that HR remained constant despite a decrease in the difference in the R–R interval in the ECG around the lower HR, suggesting that the enhanced sympathetic activity did not result in a particularly faster decrease during the decremental phase of the sinusoidal work. Further, in a HR dynamics study using fractal frequency analysis, Yamamoto et al. [19] found that cardiac vagal tone was dramatically reduced, beginning at > 110 beats \( \cdot \) min\(^{-1} \), in the HR response to incremental work; indeed, the average values of HR under the five different sinusoidal works ranged from 109 to 130 beats \( \cdot \) min\(^{-1} \). Thus, in the present study, the relatively higher value of HR must have been associated with the slowed HR kinetics. Thus, although HR kinetics are governed by the autonomic nervous system in which the sympathetic and parasympathetic mechanisms interact, parasympathetic nervous activity may have already been withdrawn, judging chiefly from the higher mean value of HR in the present study. Nor did we find any significant correlation between CVRR and HR-MRT (Figure 5), indicating that vagal activity does not play a predominant role in the HR dynamic system during moderate sinusoidal work; rather, this system seems to be mediated by the age-related reduction in sympathetic activation.

With regard to humoral influences on the HR response, the reduced maximal capacity to release noradrenaline and adrenaline upon provocation in elderly men may also be related to slower sympathetic outflow into the heart. Furthermore, the sensitivity of the target organ, i.e. the heart, to catecholamines also declines with age, as suggested by the smaller increases in HR and blood pressure for a given increase in noradrenaline concentration during exercise [20]. By contrast, neither systemic nor regional vascular sympathetic nervous system activation was impaired during isometric exercise in elderly humans [21]. Similarly, intrinsic HR, a non-autonomic mechanism, has been reported to have decreased by approx. 5 beats \( \cdot \) min\(^{-1} \) in the population over the last decade [22], indicating that age suppresses original heart function. Judging from the available evidence, age-related sluggish HR kinetics may be regulated mostly by the age-related withdrawal of sympathetic outflow with \( \beta \)-adrenergic-receptor responsiveness [23] and the lower intrinsic HR [22].

**HR kinetics are related to physical activity**

This study demonstrates for the first time that HR kinetics reflect small differences in physical activity state more than age. In particular, among subjects who took approx. 10000 steps per day, the autonomic regulation of HR during submaximal exercise seemed to be dramatically improved, and HR-MRT approached a plateau at nearly 65 s. Moreover, HR-MRT was unaffected by a further increase in physical activity to > 10000 steps per day, allowing us to recommend a level of physical activity of 10000 steps per day to improve central circulation via autonomic nervous regulation of the heart.

Since the minimum HR values at the trough of sinusoidal work during the longer work periods (i.e. 9 and 12 min) were below 100 beats \( \cdot \) min\(^{-1} \), we should consider the physical influence on bradycardia. The bradycardia that is often observed in the chronic endurance-trained state is mediated by decreases in cardiac sympathetic tone [24] and by non-autonomic mechanisms in relation to the lower intrinsic HR [25]. The plasma adrenaline concentration and \( \beta \)-receptor density in rat myocardial tissue were decreased by exercise training [26] and by a fall in sympathetic activation [27]. However, it has also been reported that exercise training has no effect on the mechanism of up-regulation of the \( \beta \)-adrenergic receptor system in lymphocytes [28]. Even though exercise training induces decreased sympathetic activation [29], no difference in baroreceptor sensitivity in response to exercise training was found by power spectral analysis [30,31]. Thus the training-induced action of baroreceptors remains unknown.

**Age-related decline in \( \dot{V}_{O_2\text{peak}} \)**

The observed slope of the age-related decline in \( \dot{V}_{O_2\text{peak}} \) was \( -0.39 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{year}^{-1} \), and was compatible with the results from a series of cross-sectional studies performed by measuring \( \dot{V}_{O_2\text{peak}} \) directly, in which the mean slope was \( -0.41 \) (range \(-0.20\) to \(-0.52\)) \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{year}^{-1} \) in men and \(-0.30\) (\(-0.19\) to \(-0.45\)) \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \cdot \text{year}^{-1} \) in women [32]. Com-
comparison with $V_{O2\text{peak}}$ confirmed the validity of the indirect calculation of $V_{O2\text{peak}}$ values by the YMCA method. The age-related decline in $V_{O2\text{peak}}$ in elderly men is attributable primarily to the HR response rather than to peripheral $O_2$ utilization and a decrease in stroke volume [33]. Thus the reduction in $HR_{\text{max}}$ results in a decrease in maximal cardiac output that is translated into a proportionate decrease in the rate of convective $O_2$ delivery to tissues, with no differences in peripheral $O_2$ extraction during exercise between young and old individuals [34]. This finding seems to be related to a decrease in myocardial contractility in the elderly [35]. Thus the decline in $V_{O2\text{peak}}$ with increasing age is likely to be limited by $O_2$ transport from the heart to the tissues, and provides evidence that the YMCA method in the present study is a useful means of calculating $V_{O2\text{peak}}$ indirectly for a broad population.

$V_{O2\text{peak}}$ and physical activity

No close relationship was observed between physical activity and $V_{O2\text{peak}}$ in the present study. It has been shown that an increase in $V_{O2\text{peak}}$ is elicited by endurance exercise training in the elderly to the same relative extent as in young subjects [36], and that $V_{O2\text{peak}}$ in a trained group is significantly higher than that in a sedentary group for any age group. However, the rate of decline of $HR_{\text{max}}$, with age has been shown to be independent of aerobic exercise state [12], and thus maximal $O_2$ transport from the heart to muscle tissues would seem to be related to age [37]. This observation is compatible with the data from the analysis of Smith and Gilligan [38], as well as with the earlier findings of Astrand et al. [11]. Taken together, although $V_{O2\text{peak}}$ reflects both central vascular dynamics and peripheral $O_2$ utilization, the YMCA method used here might not reflect adequately the effects of exercise training on the peripheral metabolic machinery. This may be why we did not observe a close relationship between physical activity and $V_{O2\text{peak}}$ in the present study. Secondly, there is the question of exercise intensity. Whereas in the elderly an increase in $V_{O2\text{peak}}$ can occur even at an exercise intensity of 40% of $V_{O2\text{peak}}$ [39], in younger subjects an exercise intensity of 60–70% of $V_{O2\text{peak}}$ will be necessary to induce such a rise. In accordance with this observation, we must consider that an absolute value of $V_{O2\text{peak}}$ may be dependent on exercise intensity rather than amount of exercise. Therefore the age-related decrease in $V_{O2\text{peak}}$ does not seem to be limited by the amount of physical activity as measured with a pedometer.

Conclusion

In conclusion, the results of the present study show that HR dynamics during moderate-intensity sinusoidal work are related to both advancing age and physical activity, with physical activity making a larger contribution to HR dynamics than age. In addition, CVRR and HR$_{\text{MRT}}$ were not closely correlated. This observation is evidence that HR dynamics in response to moderate sinusoidal work are attributable to sympathetic neural control into the heart. These results clearly demonstrate that HR dynamics are very sensitive to broad differences in habitual physical state, and less sensitive to differences in age. Moreover, HR dynamics are superior as a means of estimating the ideal level of exercise training. In addition, although estimated $V_{O2\text{peak}}$ calculated by measuring the HR response to incremental work is highly valid for a broad population, the YMCA method has limitations when investigating the physiological implications of the age-related decline in $V_{O2\text{peak}}$.

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