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Spectral Analysis of Heart Rate Variability during Treadmill Exercise at Various Speeds and Grades

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=ABSTRACT=

This study was aimed to elucidate the changes in heart rate variability during treadmill exercise at various speeds and grades by spectral analysis.

Thirty-three untrained male college students aged 20~26 yr were employed to exercise on a treadmill using 4 speeds (4.02, 5.47, 6.76 and 8.05 km/h) and 6 grades (0, 4, 8, 12, 16 and 20%). A fixed speed was selected for each session with the grade increased every 3 min. The electrocardiogram, respiration and the stepping activity were continuously recorded through an A/D converter system on the computer disk. Power spectra of heart rate variability (HRV) were obtained by use of a fast Fourier transform algorithm. The frequency domain was divided into 3 bands: VLF (0~0.04 Hz), LF (0.04~0.15 Hz) and HF (0.15~1.00 Hz).

Heart rate was 74.4±2.1 beats/min at rest and showed a steady increase during treadmill exercise with increasing speed and grade up to 196.7±5.0 beats/min. Total power of HRV was 35.0±6.7 $(beats/min)^2$ at rest and progressively decreased during exercise down to 1.9±0.3 $(beats/min)^2$. The %VLF power of HRV was 34.5±3.7 % at rest and showed no significant change during exercise except for a decrease observed at the highest intensity of exercise. The %LF power was 44.1±3.0 % at rest and showed a progressive decrease, down to 4.5±1.0 % during those stages of exercise where heart rate was over 135 beats/min. The %HF power was 21.4±2.9 % at rest and showed a progressive increase up to 87.1±6.7 % during higher intensity exercise where heart rate was over 165 beats/min. Peak frequency of HF band was 0.200±0.018 Hz at rest and was shifted to higher frequencies up to 0.909±0.048 Hz at heart rates greater than 135 beats/min. Respiratory frequency was 18.0±1.5 breaths/min at rest and significantly increased during exercise up to 53.0±3.7 breaths/min. Stride frequency during treadmill exercise showed an increasing tendency with increasing speed from 55.6±0.9 steps/min at 4.02 km/h to 81.2±0.6 at 8.05 km/h.

It was concluded that total power of HRV decreased progressively with increasing exercise intensity due to the withdrawal of parasympathetic activity. At higher exercise intensity, %LF power decreased and %HF power increased with its peak frequency shifted to higher values in a progressive mode with increasing speed and grade, reflecting a readjustment in the cardiovascular system and the increased respiration and its rate, respectively.

Key Words: Fourier transform, Parasympathetic activity, Power spectrum, Stride frequency

INTRODUCTION

The spontaneous fluctuation of heart rate around the mean value, i.e. heart rate variability, has been known as a valuable tool to investigate the cardiovascular control system, especially the sympathetic and parasympathetic function (van Ravenswaaij-Arts et al, 1993). Heart rate variability measurements are easy to perform, are noninvasive, and have good reproducibility if used under standardized conditions (Grossman et al, 1991; Kleiger et al, 1991).

Power spectral analysis has been known as the most quantitative and reliable method in analyzing heart rate variability. The power spectra of instantaneous heart rate yield three major components in the following ranges: 0~0.04 Hz, 0.04~0.15 Hz, 0.15~1.00 Hz, defined as the very low frequency (VLF), low frequency (LF) and high frequency (HF) ranges, respectively (Akselrod et al, 1981; Perini et al, 1990). The HF fluctuation, also known as respiratory sinus arrythmia, is parasympathetically mediated and centered at respiratory frequency (Davidson et al, 1976; Akselrod et al, 1985). The LF fluctuation, also known as 10-second rhythm, results from self-oscillation in the baroreflex loop and is under both sympathetic and parasympathetic influence (Akselrod et al, 1985; Madwed et al, 1989). The VLF fluctuation is thought to arise from thermoregulatory peripheral blood flow adjustments and to be influenced by humoral and central factors of cardiovascular control (Kitney, 1975; Lindqvist et al, 1989; Saul, 1990).

Heart rate variability has been found to decrease as a function of exercise intensity and characteristic changes in power spectra of instantaneous heart rate occur during exercise at different intensities (Arai et al, 1989; Perini et al, 1990; Yamamoto et al, 1991). With increasing exercise intensity, a tendency in LF peak to disappear has been shown both during incremental tasks (Bernardi et al, 1990) and at constant loads (Perini et al, 1990). HF peak, in contrast, has been shown to persist and shift towards higher frequencies due to the increased ventilation (Arai et al, 1989; Bernardi et al, 1990).

Treadmill exercise with varied speeds and grades is utilized for testing and training purposes. Oxygen consumption at specific speed-grade combination can be predicted by use of regression equations (American College of Sports Medicine, 1980; Choe et al, 1995). However, heart rate variability during treadmill exercise with varied speed and grade has not been studied.

The present study was undertaken to elucidate the changes in heart rate variability during treadmill exercise at various speeds and grades by spectral analysis.

METHODS

Subjects

Thirty-three untrained male college students aged 20~26 yr participated in this study (Table 1). None of the subjects had a history of cardiovascular disease and all were considered healthy. All subjects were briefed about the experimental procedures and were familiarized with the protocol, prior to the experiments.

Exercise

After completing the resting measurements in a sitting position, each subject performed two sessions of exercise on a treadmill (Model 24-49B, Quinton).

Table 1. Physical characteristics of subjects

Age (yr)	Height (cm)	Weight (kg)	HRmax (beats/min)
21.8±1.5	173.5±4.7	65.0±7.5	200.2±3.1

Values are means±S.D. (*n*=33).
HRmax = maximum heart rate predicted from: 217-0.77 ×Age (Park et al, 1993).

The first exercise was done at a speed of either 4.02 or 5.47 km/h, and the second exercise at 6.76 or 8.05 km/h. These 4 speeds were chosen from stages II-V of the Bruce protocol (Bruce et al, 1973), and randomly assigned to each subject. Each exercise consisted of 5 stages of 3-min duration. The treadmill grade was increased stage by stage: 0, 8, 12, 16 and 20% in the first exercise, and 0, 4, 8, 12 and 16% in the second exercise.

Data acquisition

The electrocardiogram (ECG) and respiration were recorded throughout the experiment by using a pair of surface electrodes placed at both sides of the chest wall at the level of the cardiac apex along with a ground electrode placed on the right lower abdomen. The electrodes were connected to the impedance pneumograph and cardiac couplers, which were plugged into the physiograph (MK-IV-P, Narco Biosystems), to record the respiratory activity and ECG, respectively. The analog signal outputs from the physiograph were fed into two channels of a data acquisition system (Model 1401 Plus, Cambridge Electronic Design Limited, CED), which A/D converted the ECG and the pneumogram at 250 and 100 Hz, respectively. The digital data outputs were transmitted into a personal computer which displayed the signals while storing them on the disk. During the exercise, the stepping activity was also recorded on the third channel by pressing a key on the keyboard every time the left foot hit the treadmill belt.

Data analysis and statistics

A script language program was written using a software command set (Spike2 version 4, CED) for

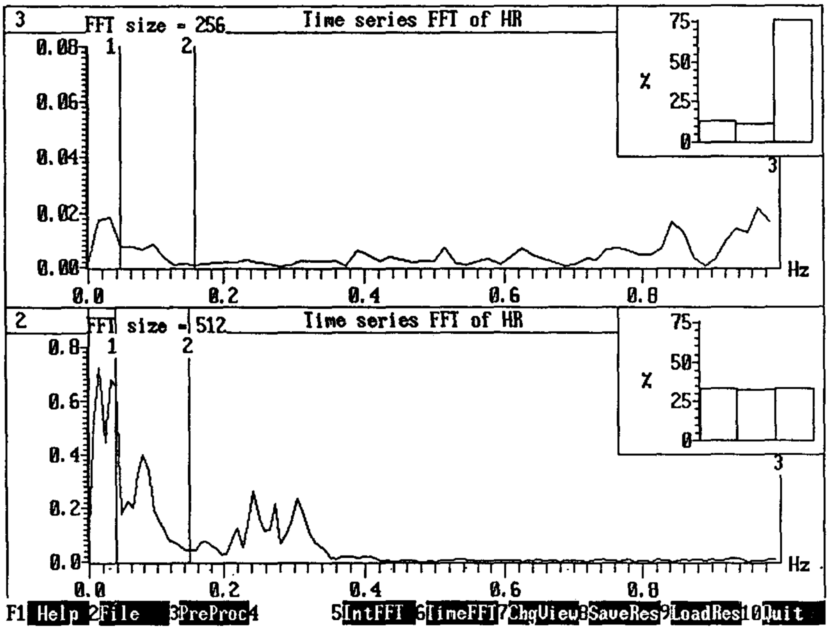

Fig. 1. A copy of computer screen showing power spectra of heart rate variability obtained by fast Fourier transform (FFT) analysis at rest (lower panel) and during treadmill exercise at 6.76 km/h, 16% (upper panel) in a representational subject. Y axes of both panels are drawn in units of Hz^2 per bin, but in different scales. The 3 numbered vertical bars dissect the spectra into 3 bands: VLF, LF and HF, the powers of which are plotted as percent of total power in insets. Bottom line shows main functions of the script program, SPECT.TXT, assigned to the function keys.

the power spectral analysis of the digital data. From the ECG, peaks of QRS complex were detected and from these event points a time series of instantaneous heart rate was constructed at equal intervals of 0.25 s. A third-order polynomial regression was determined and subtracted from the heart rate values to remove the general trends. Power spectra of heart rate variability were obtained by use of a fast Fourier transform algorithm (Fig. 1). Epoch size of 64 or 128 s to include 256 or 512 data points was chosen to give a frequency resolution of 15.6 or 7.8 mHz, respectively. The frequency domain was divided into 3 bands: VLF (0~0.04 Hz), LF (0.04~0.15 Hz) and HF (0.15~1.00 Hz). The power for each band was obtained and converted to percent of total power which was the sum of 3 bands. The peak frequency of each band was determined as the frequency showing the maximum power spectral density within the band. From the pneumogram data, a time series was collected at intervals of 0.2 s and underwent a similar process of power spectral analysis, from which only the peak frequency was determined and presented as the respiratory frequency. From the stride event data, the mean stride frequency for each stage of exercise was determined.

The results were presented as means±S.E. The differences between speeds and grades were examined by an analysis of variance for repeated measures. A *P*<0.05 level of significance was used.

RESULTS

Heart rate was 74.4±2.1 beats/min at rest and significantly increased during treadmill exercise (Fig. 2). It showed a steady increase with increasing speed and grade. The heart rate during exercise ranged from 116.1±6.8 beats/min at 4.02 km/h, 0% and 196.7±5.0 beats/min at 8.05 km/h, 16%.

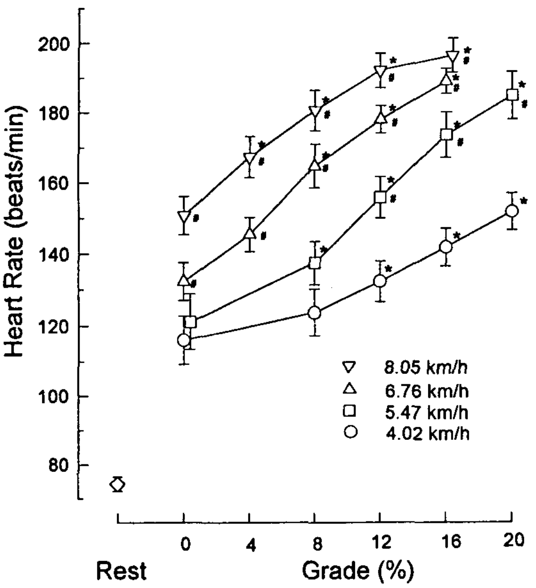

*Fig. 2. Heart rate during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. All values during exercise are significantly (P < 0.05) higher than the resting value. *P<0.05 vs. grade 0%. #P<0.05 vs. speed 4.02 km/h.*

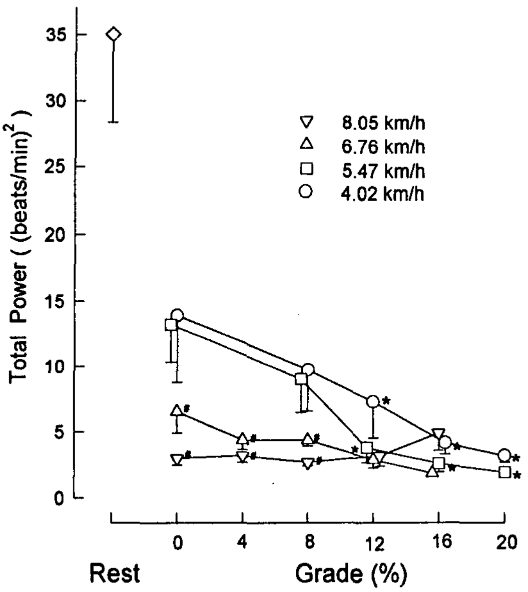

*Fig. 3. Total power of heart rate variability during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. All values during exercise are significantly (P<0.05) lower than the resting value. *P<0.05 vs. grade 0%. #P<0.05 vs. speed 4.02 km/h.*

Total power of heart rate variability (HRV) was 35.0±6.7 $(beats/min)^2$ at rest and significantly decreased during exercise (Fig. 3). At the speeds of 4.02 and 5.47 km/h, total power showed progressive decreases with increasing grade, from 13.9±5.2 at 0% to 3.2±0.5 at 20% and from 13.2±2.9 at 0% to 1.9±0.3 $(beats/min)^2$ at 20%, respectively. At 6.76 and 8.05 km/h, the mean values ranged 1.9~6.5 $(beats/min)^2$, which was significantly lower than values at 4.02 km/h, 0~8%, but did not change significantly with grade.

%VLF power of HRV was 34.5±3.7 % at rest and showed no significant change during exercise except for 8.05 km/h, 12% and 16% at which heart rate was over 190 beats/min and %VLF power was lowered to 13.0±4.9 % and 8.4±5.8 %, respectively. %LF power was 44.1±3.0 % at rest and significantly decreased at those stages of exercise where heart rate was over 135 beats/min (Fig. 4). It showed decreasing tendencies with increasing speed and grade, and the lowest %LF power was 4.5 ±1.0 % observed at 8.05 km/h, 16%. The %HF power was 21.4±2.9% at rest and significantly increased at those stages of exercise where heart rate was over 165 beats/min (Fig. 5). It showed increasing tendencies with increasing speed and grade except for 4.02 km/h at which speed there was no significant difference among grades. The highest %HF power was 87.1±6.7% observed at 8.05 km/h, 16%.

Peak frequency of VLF band showed no significant differences and averaged to 24.3±0.1 mHz. Peak frequency of LF band showed no significant differences and averaged to 59.1±0.2 mHz. Peak frequency of HF band was 0.200±0.018 Hz at rest and showed a significant increase at 4.02 km/h, 16~20%; 5.47~6.76 km/h, 8~20%; and at 8.05 km/h, all grades (Fig. 6). It showed increasing

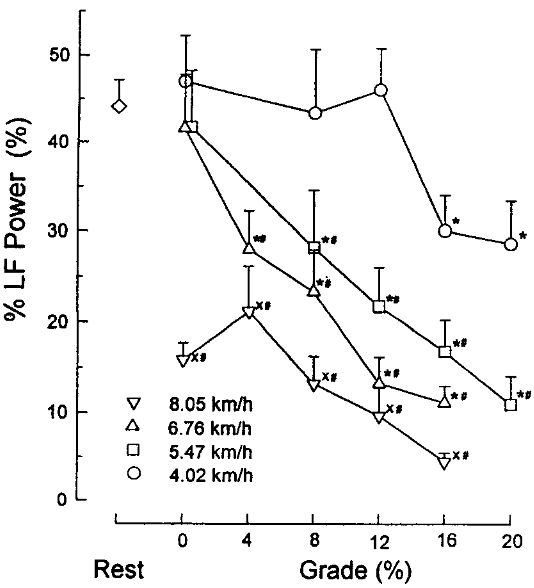

Fig. 4. Percent low frequency (0.04-0.15 Hz) power of heart rate variability during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. **P<0.05 vs. rest and vs. grade 0%.* ×*P<0.05 vs. rest.* #*P<0.05 vs. speed 4.02 km/h.*

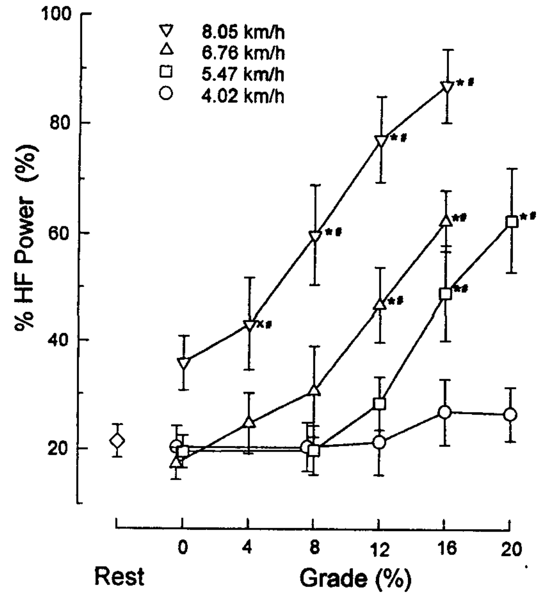

Fig. 5. Percent high frequency (0.15-1.00 Hz) power of heart rate variability during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. **P<0.05 vs. rest and vs. grade 0%.* ×*P<0.05 vs. rest.* #*P<0.05 vs. speed 4.02 km/h.*

tendencies with increasing speed and grade, and the highest HF peak frequency was 0.909±0.048 Hz observed at 8.05 km/h, 16%.

Respiratory frequency was 18.0±1.5 breaths/min at rest and significantly increased during exercise ranging from 27.8±5.3 at 4.02 km/h, 0% to 53.0±3.7 breaths/min at 8.05 km/h, 16% (Fig. 7). At 6.76 km/h, all grades and at 8.05 km/h, 16%, it was significantly higher than that at 4.02 km/h. Respiratory frequency showed no significant change among grades except for 8.05 km/h, 16% where it was significantly higher than at 0%.

Stride frequency during treadmill exercise showed an increasing tendency with increasing speed but no significant change among grades (Fig. 8). It was averaged to 55.6±0.9 steps/min at 4.02 km/h, 60.4±0.8 at 5.47 km/h, 65.4±0.7 at 6.76 km/h, and 81.2±0.6 at 8.05 km/h.

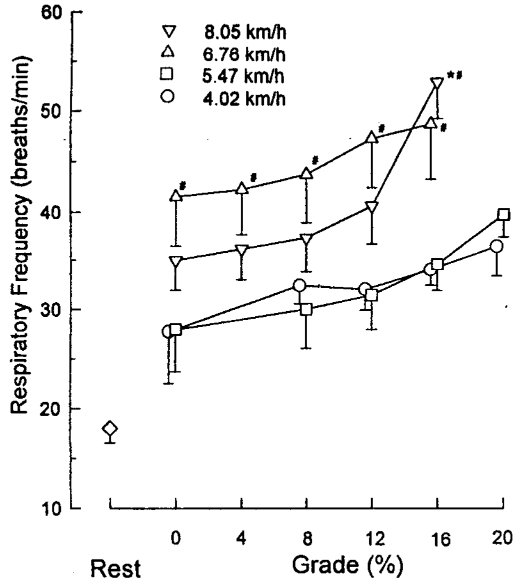

*Fig. 7. Respiratory frequency during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. All values during exercise are significantly (P<0.05) higher than the resting value. *P<0.05 vs. grade 0%. #P<0.05 vs. speed 4.02 km/h.*

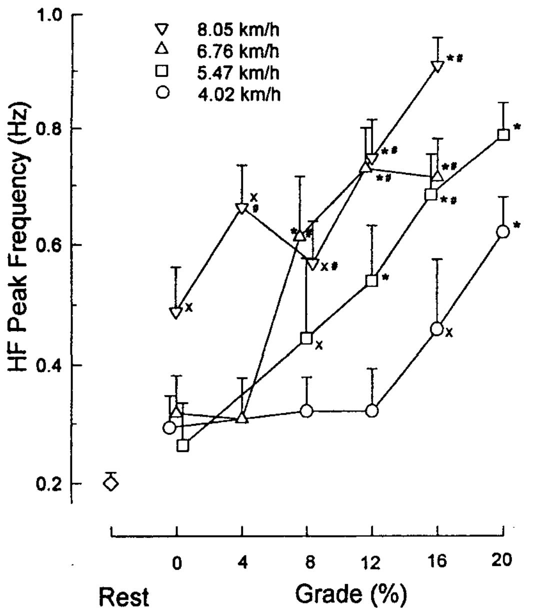

*Fig. 6. Peak frequency within high frequency band of heart rate variability during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. *P<0.05 vs. rest and vs. grade 0%. xP<0.05 vs. rest. #P<0.05 vs. speed 4.02 km/h.*

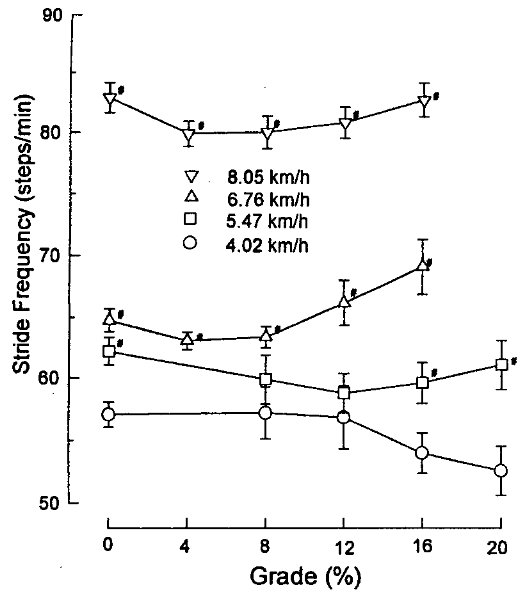

Fig. 8. Stride frequency during treadmill exercise at 4 speeds and 6 grades. Vertical bars represent standard errors. No significant differences vs. grade 0%. #P<0.05 vs. next lower speed.

DISCUSSION

Heart rate is known to increase linearly with increasing oxygen consumption ($\dot{V}O_2$) during exercise and can be used as a good physiological index of exercise intensity. In the present study, the heart rate during exercise ranged from 116.1 to 196.7 beats/min. As the predicted maximum heart rate (HRmax) of the subjects averaged 200.2 beats/min (Table 1), the range can be expressed as 58.0% to 98.3% of HRmax. Using a regression equation ($\%\dot{V}O_2max = 1.462 \cdot \%HRmax - 46.13$) which was reported by Kim et al (1993) and applicable to the present subject group, the %HRmax range can be converted into the range of 38.7% to 97.5% of $\dot{V}O_2$max. It represents moderate to high intensity exercise.

Total power of heart rate variability (HRV) has been reported to decrease progressively with increasing exercise intensity (Arai et al, 1989; Perini et al, 1990; Yamamoto et al, 1991). Sun et al (1993) demonstrated that the decrease in power occurred in all defined frequency ranges between 0 and 1 Hz. In the present study, total power of HRV during exercise was significantly lower than that at rest. Withdrawal of the parasympathetic activity would account for the reduction in total power, because the parasympathetic system mediates fluctuations of heart rate in all three frequency ranges, *i.e.* VLF, LF and HF (Perini et al, 1993; Sun et al, 1993). The decrease was more or less proportionate to increasing speed and grade in the speed range of 4.02 to 6.76 km/h. At 8.05 km/h, total power was around 3 $(beats/min)^2$ at lower grades and showed no further decrease but rather an increasing tendency with increasing grade, which was attributable to the increase of HF power.

The VLF power represented a fairly constant part, around 35%, of total HRV throughout the experiment, except during the highest intensity of exercise. %LF power was around 44% at rest and was not changed until heart rate exceeded 135 beats/min which was equivalent to 52% of $\dot{V}O_2$max. At higher exercise intensities than this, %LF decreased progressively to as low as 4.5% with increasing speed and grade. Conversely, the %HF power was around 21% at rest and was not changed until heart rate exceeded 165 beats/min which was equivalent to 74% of $\dot{V}O_2$max. At higher exercise intensities than this, it was increased progressively to as high as 87% with increasing speed and grade. The HF peak was shifted to higher frequencies at heart rates greater than 135 beats/min. These changes in spectral components of HRV during exercise are roughly in accordance with Perini et al (1993) who demonstrated a decreased %LF (from 45% to 8.5%) and increased %HF (from 5.0% to 20%) with an upward shift of HF peak at high intensities of cycle exercise.

A tendency in LF power to disappear with increasing exercise intensity has been shown both during incremental tasks (Bernardi et al, 1990) and at constant loads above 30% of $\dot{V}O_2$max (Perini et al, 1990). The lack of change in %LF power at lower exercise intensities would suggest that HRV at LF band was unaffected until the cardiovascular response to exercise was determined mainly by the increase in cardiac output via the vagal withdrawal (Rowell & O'Leary, 1990). At higher intensities where increases in sympathetic activity have been shown to occur, the consequent readjustments in the cardiovascular system, including reset of baroreceptors, would seem to have influenced the LF rhythm (Perini et al, 1993). This same effect might account for the decrease in %VLF power observed at highest intensities in the present study.

The HF peak, which is a quantitative expression of respiratory arrhythmia (Pomeranz et al, 1985), has been found to be constantly present during exercise and to represent the major part of the total power at near maximal intensity due to the increased ventilation (Arai et al, 1989; Bernardi et al, 1990). And the central frequency of the HF peak was found to be linearly related to $\%\dot{V}O_2$max. This should reflect the increase in respiratory rate, as has been suggested by observations both at rest with controlled breathing (Pomeranz et al, 1985; Pagani et al, 1986) and during exercise (Arai et al, 1989; Bernardi et al, 1990).

In the present study, respiratory and stride frequencies were recorded to elucidate possible relationship with frequencies of HRV. Respiratory frequency was plotted in units of breaths/min in Fig. 7 on an equivalent scale as the HF peak frequency in units of Hz in Fig. 6. Mean resting respiratory frequency was 18.0 breaths/min (0.300 Hz) which was 1.5 times higher than resting HF peak frequency of 0.200 Hz. Respiratory frequency significantly increased during exercise ranging from 27.8 to 53.0 breaths/min (0.463 to 0.883 Hz), but showed little correlation with HF peak frequency. Stride frequency during treadmill exercise increased with increasing speed but showed no correlation with frequencies of HRV.

In summary, total power of HRV decreased progressively with increasing exercise intensity due to the withdrawal of parasympathetic activity. At higher exercise intensity, %LF power decreased and %HF power increased with its peak frequency shifted to higher values in a progressive mode with increasing speed and grade, reflecting a readjustment in the cardiovascular system and the increased respiration and its rate, respectively.

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