Self-Biofeedback Control of Heart Rate during Exercise

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Abstract: To improve cardiac adjustment to exercise, we developed a new self-biofeedback heart rate (HR) controller. Using this device, we analyzed time courses of HR, running speed (RS), stride length (ST) and pitch of gait (PI) in response to various preset HR levels in 7 normal human subjects. When HR was preset at 80 bpm, HR increased rapidly in response to exercise and exceeded the preset level at 12.1 s with overshoot. At the preset HRs of 100, 120, 140 and 160 bpm, the HRs increased to each preset level at 39.2, 64.5, 58.5 and 83.0 s after the onset of exercise, respectively, and the HRs were adjusted with a range of $\pm 4\%$. For all preset HRs, RS, ST and PI increased more rapidly than the

HR and reached the maximum values within 30 s. During exercise, RS, ST and PI remained constant within 1.5–5.5 min. HR, RS, ST and PI increased in proportion to the preset HR. The increases in PI against HR ($\Delta PI/\Delta HR$) decreased with the higher HR level, and at HRs of 160–170 bpm, HR and PI showed identical rhythm. The increases in RS were produced by 18–59% increases in PI and by 12–44% increases in ST. We concluded that, using our newly developed self-biofeedback HR control system, we could control HR to a given preset value by a change in RS due to PI and ST. [Japanese Journal of Physiology, 49, 275–281, 1999]

Key words: biofeedback, heart-rate controller, running speed, stride, pitch.

Heart rate (HR) response is thought to be an important index of cardiac function during exercise [1, 2]. A program for cardiac training and rehabilitation was determined by HR response to a given workload, using either a treadmill or bicycle ergometer. In these conventional methods, exercise load was fixed and the HR varied. On the other hand, portable HR monitors were developed and applied in laboratory and field settings [3, 4]. These methods are usually both load and HR varying. When the HR varying methods were used, the possibility that an excess increase in the HR with exercise become dangerous for subjects could not be neglected. Therefore, those methods are difficult to apply for self cardiac training and/or rehabilitation in the daily lives of patients. It is necessary to develop a safe cardiac training and/or rehabilitation system.

If we develop a new device in which subjects can

easily be aware of whether their own HR exceeds a preset level during exercise, the subjects could externally control their own HR to the preset value by changing running and/or walking speed. Such self-biofeedback control of HR during exercise is expected to have an advantage to avoid any risk for exercise-related cardiac events due to excessive increase in HR over a preset value, particularly in patients with extensive myocardial damage and significantly impaired cardiac performance.

To our knowledge, there were no studies regarding changes in HR, running speed, stride and pitch and the relationship between each parameter to various preset HRs during exercise. In this study, using a new self-biofeedback HR control system, time courses and magnitudes of running speed, stride and pitch in response to various preset HRs were analyzed in healthy human subjects.

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Fig. 1. A block diagram of the newly developed HR controller is shown. A R-wave detection circuit, which consists of a cardiogram amplifier (ECG amplifier), a comparator, and a monostable multivibrator (1) shape the R wave into pulses with a duration of 0.1 s. The shaped R wave is fed into a digital HR meter. When the HR for 10 s exceeds a

preset value (set by the 8-bit thumb wheel switch), a monostable multivibrator (2) generates the warning signal (3 KHz sound) for 5 s. The shaped R wave and warning signals are indicated by each LED and transmitted to a data recorder by the FM transmitter.

METHODS

HR controller and biofeedback control of HR. A new HR controller 6.0 (width) $\times$ 10.3 (height) $\times$ 2.7 (depth) cm in size and 130 g in weight, including lithium battery, was developed. Power consumption is about 14 mA with photo- and sound alarm signals and 0.5 mA without the signals. Figure 1 shows a block diagram of the newly developed HR control system.

The HR controller generates photo- and sound signals synchronized with the R wave of an electrocardiogram during exercise. Before exercise, we determine the desirable HR, ranging 50–250 bpm, and set it on the controller. During exercise, the controller can produce photo- and sound alarm signals whenever the HR exceeds the preset value. Subjects can adjust their own HR by changing running speed to the preset value. The alarm signal is generated for 5 s whenever the number of R waves for a given consecutive 10 s exceed those of the preset HR.

Experimental procedure and protocol. Healthy male subjects whose ages ranged from 25–46 years ($n=7$, average 36 years) participated in this

study. All subjects provided written informed consent. In this study, five different HRs of 80, 100, 120, 140 and 160 bpm were selected as preset values. For each preset HR value, each exercise was performed for 6 min. Baseline HR was measured over 3–5 min in sitting position. Thereafter, subjects stood up and started the first exercise for 6 min under the preset HR, 80 bpm.

Before the second, third, fourth and fifth exercises trials, subjects took a rest in the sitting position until their HR decreased to the baseline value. Resting intervals ranged from 3–20 min.

Measurements of HR, speed, stride and pitch. All the data, comprising (1) signals synchronized with the R waves of ECG from the HR controller and instantaneous HR, (2) electromyogram (EMG) from the unilateral quadriceps muscle for detecting each step, (3) alarm signals when HR exceeded the preset value and (4) signals of 30 m running distance were simultaneously recorded on a data recorder (TEAC SR-50).

All the recorded data were drawn on paper from the recorder at an appropriate speed. Mean HRs over 6 different elapsed times (i.e., 0.5, 1.5, 2.5, 3.5, 4.5 and

Fig. 2. An example of change in HR before, at the onset of (solid arrows) and during exercise at the preset HRs of 80, 120 and 160 bpm in a healthy male subject. The upper three panels show time courses of HR response to each preset value. Lower panels show a high-speed

recording of the initial phase of the exercise in the upper middle panel with signals of the HR controller, HR response and electromyogram (EMG) from the unilateral quadriceps muscle. Arrowheads indicate alarm signals.

5.5 min) were obtained by counting the R waves of ECG in intervals of 0–1.0, 1.0–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0 and 5.0–6.0 min, respectively, during exercise. In the same manner, mean running speed (m/s), mean stride (m/step) and mean pitch (steps/min) were also obtained over 6 different elapsed times.

Statistics. The statistical significances for the differences of (1) measured HRs, running speed, stride and pitch among the six different elapsed times of each preset HR, (2) the increases in pitch against HR (i.e., $\Delta\text{pitch}/\Delta\text{HR}$ to each preset HRs in the six elapsed times) and (3) incidences of alarm signals among the five groups with preset HRs of 80–160 bpm in each elapsed time were tested for analysis of variance and Student's range Q test [5]. The statistical significances between changes in stride and those in pitch to each preset HR were tested for Student's t -test for paired comparison. A p value of <0.05 was used as the criterion for significance. All results are expressed as means $\pm$ standard error (SE).

RESULTS

Change in HR

Figure 2 shows an example of change in HR before, at the onset and during exercise at preset HRs of 80, 120 and 160 bpm. The upper three panels show time courses of HR response to each preset value and alarm signal (arrowheads).

At the preset HR of 80 bpm, the HR quickly overshoot the preset value at 21 s after onset, when the first alarm signal was produced. Then, the incidence of alarm signals was increased in the initial phase rather

than the later phase of exercise. At the preset HR of 120 bpm, HR increased rapidly from 92 bpm at the onset of exercise to 123 bpm within about 40 s, and then the first alarm signal was generated. Thereafter, the subject could keep the preset HR by changing his running speed during exercise. At the preset HR of 160 bpm, HR gradually increased to the preset value and the first alarm signal was produced at 102 s after onset.

Time courses of changes in HR, running speed, stride and pitch

Figure 3 summarizes the time courses of HRs before, at the onset and after the 6 different elapsed times during exercise and those in running speed, stride and pitch at the five preset HRs, 80–160 bpm. At the preset HR of 80 bpm, the HR increased rapidly within 0.5 min with an overshoot of 10.8% from the preset level, and then gradually decreased to the preset level during exercise. At the preset HRs of 100, 120, 140 and 160 bpm, the values increased smoothly to each preset level over 0.5 min after the onset of exercise and thereafter remained constant within $\pm 4\%$ from each preset level during exercise.

For all preset HRs, running speed, stride and pitch increased more rapidly than HR and reached maximum values within 0.5 min. The maximum values of running speed at 0.5 min were 1.36 ± 0.12 , 1.64 ± 0.09 , 2.29 ± 0.15 , 2.76 ± 0.23 and 3.06 ± 0.26 m/s at preset HRs of 80, 100, 120, 140 and 160 bpm, respectively. Within 1.5–5.5 min, the running speed of each preset HR almost decreased to plateau values of 1.11 ± 0.07 , 1.49 ± 0.09 , 1.91 ± 0.12 , 2.30 ± 0.15 and 2.57 ± 0.16 m/s

Fig. 3. Changes in HR before, at the onset of (solid arrows) and the 6 different elapsed times during exercise, and those of running speed, stride and pitch at the five preset HRs of 80, 100, 120, 140 and 160 bpm. Mean values of each parameter in a given preset HR are shown in a corresponding circle. Vertical bars, $\pm$ SE.

respectively, at 2.5 min.

Stride also increased more rapidly than HR and reached maximum values within 0.5 min; 0.68 ± 0.03 , 0.74 ± 0.04 , 0.83 ± 0.04 , 0.96 ± 0.06 and 1.03 ± 0.06 m, respectively, at each preset HR. Within 1.5–5.5 min, the stride of each preset HR almost decreased to its plateau value of 0.64 ± 0.03 , 0.72 ± 0.04 , 0.76 ± 0.04 , 0.85 ± 0.04 and 0.92 ± 0.04 m/s, respectively, at 2.5 min.

As well as changes in running speed and stride, pitch also increased more rapidly than HR and reached maximum values within 0.5 min; 119 ± 9 , 134 ± 6 , 164 ± 4 , 170 ± 5 and 176 ± 6 steps/min, respec-

Fig. 4. The relationships between HR and running speed during the 6 elapsed times obtained at the 5 preset HRs of 80, 100, 120, 140 and 160 bpm. Running speed increased linearly with HR.

tively, at each preset HR. Within 1.5–5.5 min, the pitch of each preset HR almost decreased to its plateau value of 104 ± 3 , 124 ± 7 , 150 ± 4 , 162 ± 4 and 167 ± 6 steps/min, respectively, at 2.5 min.

Relationship between HR and running speed

Figure 4 shows the linear relationships between HR and running speed over the 6 elapsed times. They are expressed by the formula, running speed = $0.04\text{HR} - 2.09$, $r=1$, $p<0.001$ at 0.5 min; and running speed = $0.02\text{HR} - 0.45$, $r=0.99$, $p<0.001$ at 1.5–5.5 min. The increases in running speed against HR (i.e., Δ running speed/ Δ HR) were significantly larger at 0.5 min than at 1.5–5.5 min. These results indicated that running speed increased linearly to preset and actual HRs and that a faster running speed was necessary at the initial phase of exercise at 0.5 min than at the later phase.

Relationship between HR and pitch

Figure 5 shows the relationships between HR and pitch over the 6 elapsed times. Pitch was also increased with increase in HR over all of the elapsed times. At 1.5–5.5 min, the increases in pitch against HR (i.e., Δ pitch/ Δ HR) decreased more the higher the HR level. The slope of the HR-pitch curve at 0.5 min was greater than those at 1.5–5.5 min. The HR-pitch curves at 1.5–5.5 min tended to close to the identical line of HR and pitch (i.e., HR: pitch = 1:1). These results indicated that, to keep HR at a given high level, greater pitch is necessary at the initial phase of exercise than at the later phase.

Relative changes in running speed, stride and pitch to exercise

Figure 6 shows the relative changes of overall data for 6 min in running speed, stride and pitch at the pre-

Fig. 5. The relationships between HR and pitch during the 6 elapsed times obtained at the 5 preset HRs of 80, 100, 120, 140 and 160 bpm. A dotted line indicates an identical line (i.e., HR: pitch=1:1). The relationship lines shift upward from the identical line.

Fig. 6. Relative changes of overall data for 6 min for running speed, stride and pitch at the preset HRs of 100, 120, 140 and 160 bpm against those at the preset HR of 80 bpm. Vertical bars, $\pm$ SE. * $p < 0.05$ compared with the corresponding stride values.

Table 1. Time(s) required for the initial alarm signals in each preset HR.

	Preset HR (bpm)				
	80	100	120	140	160
Time (s)	12.1 $\pm$ 4.8	39.2 $\pm$ 8.4*	64.5 $\pm$ 14.3*	58.5 $\pm$ 9.9*	83.0 $\pm$ 12.1*

Values are mean $\pm$ SE, given in s. Statistical significances were tested for analysis of variance and Student's range *Q* test among groups with five different preset HRs. * $p < 0.05$ compared with corresponding value at the preset HR of 80 bpm.

Fig. 7. Incidence of alarm signal in the five preset HRs at the 6 elapsed times during exercise. Vertical bars, $\pm$ SE. * $p < 0.05$ compared with each corresponding value at the preset HR of 80 bpm.

set HRs of 100, 120, 140 and 160 bpm against those at the preset HR of 80 bpm. The running speed was linearly and markedly increased by 30.7 ± 2.7 , 69.0 ± 1.2 , 95.1 ± 3.4 and $128.0 \pm 1.7\%$ at the preset HRs of 100, 120, 140 and 160 bpm, respectively. The increases in running speed were caused by increases in pitch of 18.0 ± 1.7 , 42.7 ± 1.4 , 51.1 ± 2.5 and $58.5 \pm 2.6\%$, respectively, and increases in stride of 11.9 ± 1.0 , 19.1 ± 1.3 , 29.8 ± 2.6 and $44.3 \pm 2.1\%$, respectively, at each

preset HR. The relative magnitudes of increases in pitch were significantly greater than those in stride for all of the preset HRs.

Incidence of alarm signals

Table 1 shows time required for the first alarm signal of each preset HR after the onset of exercise. Times significantly increased in proportion to preset HR. Incidences of alarm signal in the five preset HRs

at the 6 elapsed times during exercise are shown in Fig. 7. At 0.5 min, the decrease in incidence of alarm signal at higher preset HRs was statistically significant. At 1.5–5.5 min, incidences did not decrease significantly at the preset HRs of 120, 140 and 160 bpm over the five elapsed times.

DISCUSSION

To improve quality of life, it is important for not only normal subjects but also cardiac patients to carry out self cardiac training and/or rehabilitation in daily life safely. Until now, there were two kinds of exercise training method: (1) load constant and HR varying, and (2) both load and HR varying. The former is usually provided by a bicycle ergometer [6, 7] and a treadmill [8], and the latter is provided by portable HR monitors [3, 4]. In both HR varying methods, excess increase in HR with exercise might be dangerous for the subjects, particularly cardiac patients. Therefore, it is necessary to develop a new system which prevents the excess elevation of HR (i.e., HR constant and load varying). Such a method (e.g., heart rate-control ergometer [9]) was previously developed, however, it was difficult to apply for self cardiac training and/or rehabilitation in daily life. The present study demonstrates that, as shown in Fig. 3, using a newly developed HR controller, HR can be controlled in a range of about 10% of the preset HR of 80 bpm, and within $\pm 4\%$ of the preset HRs of 100–160 bpm during exercise. Accordingly, our method would be useful to improve cardiac adaptation and decrease the risk of cardiac overload in exercise during daily life.

Analysis of response patterns. In unanesthetized dogs, change in cardiac response to treadmill exercise was reported to be different between onset and during exercise [10]. At the onset of exercise, three main adaptation patterns of cardiac response (i.e., overshoot, fluctuating and smooth) were found in response to steep treadmill input load and for the first trial in a given experiment day; an overshoot pattern occurred primarily with HR. Experience primarily influenced the patterns, timing and magnitudes of cardiac adaptation. In our study, at the transition phase of exercise, two adaptation patterns of HR response (i.e., overshoot and smooth) were found in response to 5 different preset HRs. The overshoot pattern was observed at the preset HR of 80 bpm, while the smooth pattern was found at preset HRs of 100–160 bpm. At the transition phase, patterns of increase in HR were different with those of running speed, stride and pitch for the five preset HRs. At the onset of exercise, the rapid increase in running speed due to pitch and stride

was followed by a gradual increase in HR because, for all preset HRs, subjects increased running speed very quickly to elevate the HR to the preset levels. As a consequence, as shown in Figs. 4 and 5, both the HR–running speed relationship and the HR–pitch relationship in response to exercise were different between onset and during exercise. In addition, the slope of relationships (i.e., the $\Delta\text{running speed}/\Delta\text{HR}$ and $\Delta\text{pitch}/\Delta\text{HR}$) became smaller at 1.5–5.5 min than at 0.5 min.

Analysis of rhythm. Interactions between HR and locomotor rhythm [11, 12], HR and ventilation rate and among cardiac, respiratory and locomotor rhythm [13] were previously reported. HR and step rates showed a 1 : 1 coupling at one or more speeds on a motorized treadmill; while coupling was present, the mean walking HR was about 125 beats/min and the mean running HR was 163 beats/min [11]. Cardiocomotor coupling was found at one or more treadmill speeds, however, it was independent of the absolute HR and locomotion speed values [13]. In this study, we found that 1 : 1 coupling between HR and pitch occurred at a HR of 160–170 beats/min. In another study, subjects walked and ran, at a cadence natural to them, on a motorized treadmill and/or bicycle ergometer. We used free locomotion on a flat floor to a given preset HR. Therefore, differences may be explained by the different methods of exercise (i.e., (1) load constant and HR varying, (2) load and HR varying, and (3) HR constant and load varying).

Analysis of steady-state. At the plateau level during exercise, HR linearly increased with running speed [10]. In our study, as shown in Fig. 4, at 1.5–5.5 min after exercise onset, running speed increased linearly with the HR. In addition, we found pitch and stride increased in proportion to the preset HRs (Fig. 6). The relative magnitudes of increase in pitch were 32–124% greater than that of stride. It is concluded that, at the plateau level, the response magnitudes of running speed, pitch and stride are quantitatively different to the preset HRs. The dominant variable for increasing running speed is pitch rather than stride within the preset HRs of 100–160 bpm.

Analysis of alarm. In this study, a new finding is that the time required for the first alarm signal increased in proportion to the preset HR. This finding suggests that the response time of HR changed dependent on the preset HR. It is interesting to note that the incidence of alarm signal and difference in actual HRs from the corresponding preset levels differed significantly between 0.5 min and 1.5–5.5 min after the onset of exercise (Figs. 3 and 7). At 0.5 min with a preset HR of 80 bpm, the rapid increase in HR with overshoot showed a shorter time for the first alarm signal,

at 12.1 s (Table 1), and a greater incidence of alarm signals of 3.3 times/min. These rapid and frequent alarm signals decreased the overshoot response to within a range of 10% over the preset value. At preset HRs of 100–160 bpm, the smooth increases in HR produced a longer time for the first alarm signal at 39.2–83.0 s. At the steady-state, the HR can be stabilized within $\pm 4\%$ of the preset HR by alarm signals of 20–30 s intervals. We conclude that, for self-biofeedback control, sound alarm signals generated whenever the HR exceeds the preset level are essentially important to avoid the risk of cardiac events due to an excess elevation of HR during exercise.

In conclusion, using a newly developed HR controller, we could control HR to a given preset value by a change in running speed due to pitch and stride. The new system is applicable to carry out self cardiac training and/or rehabilitation in daily life.

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