Complete recovery time after exhaustion in high-intensity work

Hsin-Chieh Wu*, Wen-Hsin Hsu □, Toly Chen □

*Department of Industrial Engineering and Management, Chaoyang University of Technology,
No.168, Jifong East Road, Wufong Township, Taichung County, 41349, Taiwan, ROC

□ Department of Occupational Safety and Health & Institute of Environmental Medicine,
China Medical University, Taichung, 404, Taiwan, ROC

□ Department of Industrial Engineering and System Management, Feng Chia University,
Taichung, 407, Taiwan, ROC

* Corresponding author
E-mail: hcwul@mail.cyut.edu.tw. Tel.: 886-4-2332-3000 ext.4537. Fax: 886-4-2374-2327.
Abstract

This study was aimed to investigate complete recovery time (CRT) after exhaustion in high-intensity work. Twenty-four subjects were divided into two groups based on the cardiorespiratory capability index, which was measured in the maximum capacity test. Each subject then performed two cycling tests (60% and 70% maximum working capacity). The subject continued cycling until exhaustion in each test, and then sat for recovering until he/she perceived no fatigue anymore or until the oxygen uptake (VO₂) and heart rate (HR) returned to their baselines, whichever was longer. The results indicated that HR required longest time to recover, and consequently HR data were adopted to set for the CRT. The CRT was significantly correlated with the cardiorespiratory capability index and the relative workload indices: RVO₂ and RHR. The RVO₂ was the average elevation in VO₂ during work from the resting level as a percentage of maximum VO₂ reserve. The RHR’s definition was similar to that of RVO₂. Based on the obtained CRT-prediction model, the CRT for a high-cardiorespiratory-capability person was 20.8, 22.1, 23.4, and 24.7 min at 50%, 60%, 70%, and 80% RHR levels, respectively. These suggested CRT values should be added 10 min for a low-cardiorespiratory-capability person.
1. Introduction

High-intensity work can be specified as any physical activity that mobilizes contraction of large muscle groups and requires oxygen uptake (VO$_2$) of at least 50% of the maximum oxygen uptake (VO$_{2\text{max}}$). The anaerobic energy-yielding metabolic process plays an increasing role in high-intensity work, because the lactate threshold occurring between 40% and 60% of the VO$_{2\text{max}}$ for most untrained individuals (Belmen and Gaesser 1991). In other words, the VO$_2$ and heart rate (HR) will increase continuously instead of reaching a steady state when someone is engaged in a high-intensity work task. The continuous increase in heart rate brings potential hazards and adherent problems associated with high-intensity activities (Pollock, et al. 1998).

Some researchers stated that work duration and intensity should be limited to prevent workers from injuries in high-intensity work (Kroemer and Grandjean 1997, Wu and Wang 2001). Besides, intermittent work with frequent and brief rest periods was proven to be more effective relief from fatigue than taking a long break after prolonged work time (Pulat 1992, Konz 1998). But to limit work intensity or to regulate fixed work duration may be hard to follow up for some high-intensity work jobs, such as fire fighting, road repairing, disaster salvaging, sports competition, etc. People who are engaged in these jobs always have great motivation and liability to continue working until exhaustion. They usually take a break after exhaustion and then return to work as they subjectively feel they have recovered. But, the subjective recovery time may be not equivalent to the physiological recovery time.
Kroemer et al. (1997) implied that if the energetic work demands exceed about half the person’s VO$_{2\text{max}}$, the length of time during which a person performs this work depends on the subject’s motivation and the will to overcome the feeling of ‘fatigue’. This fatigue can be counteracted by the insertion of rest periods. But if the rest period is too short to let energy consumption return to resting level, fatigue will accumulate as the subject return to work. Aminoff, et al. (1999) indicated that fatigue is related to sustaining high physiological strain, i.e. high level of VO$_2$ and HR. This study was therefore focused on how much time was the complete recovery time (CRT) after exhaustion in high-intensity work. The CRT was defined as the rest period that makes an individual perceive no fatigue anymore or let VO$_2$ and HR return to their resting levels (baselines), whichever was longer.

Based on the metabolic energy expenditure model, Mürrell (1965) provided the following formula to determine a rest-time requirement for any given work activity:

$$R = T \times \frac{(W - S)}{(W - BM)}$$,  

(1)

where $R$ is the total amount of rest required in minutes, $T$ is the total work time in minutes, $W$ is the average energy consumption of work in kcal·min$^{-1}$, $S$ is the endurance limit of energy expenditure (5 kcal·min$^{-1}$ for males, 4 kcal·min$^{-1}$ for females), and $BM$ is basal metabolism (1.7 kcal·min$^{-1}$ for males, 1.4 kcal·min$^{-1}$ for females). Based on the findings of similar physiological methods, Rohmert (1973b) also suggested a formula to predict the rest allowance (RA) for heavy dynamic muscular work as the following:
where RA is the required rest time in a percentage of the work time, T is the work time in minutes, \( N_{\text{eff}} \) is the average working heart rate (the heart rate above the resting level), and \( N_{\text{endurance limit}} \) is the endurance limit of working heart rate (about 30 beats \( \text{min}^{-1} \) above the resting level).

Both of Mürrell’s (1965) and Rohmert’s (1973b) formulas are based on the assumption that no work-related rest allowance is necessary for a job that demands a physiological cost less than the endurance limit. This endurance limit may need to be modified for the Taiwanese. Another problem is that these formulas based on the data of the Western may be not suitable for the Taiwanese, because of the great differences in ethnic group, body composition, and diet habit between the Western and the Taiwanese. In addition, these two formulas are aimed at predicting the rest requirement, whose definition is different from that of complete recovery time (CRT) in this study. We supposed that the CRT should be always longer than the rest requirement based on the assumption of endurance limit.

The profiles of VO\(_2\) and HR recoveries were found to be exponentially decreasing during the recovering process and could be adopted as two indices of physiological recovery level (Nanthavanij 1992, Short and Sedlock 1997, Takahashi and Miyamoto 1998). For this reason, this study conducted a physiological experiment to collect Taiwanese adults’ VO\(_2\) and HR responses during both work time and recovery processes at two different work intensities.
Besides, the subjective recovery time was also collected in the experiment. The characteristics of these three indices were then compared. Based on the comparison results, the best index for determining the CRT can be found out. The main purpose of this study was to determine CRT after exhaustion in high-intensity work. Factors that might affect the CRT were also investigated.

2. Methods

2.1. Subjects

Twenty-four untrained healthy young volunteers (with a mean age of 23), 12 males and 12 females, were recruited for this study. The age range was specified to be between 20 and 30, because high-intensity work is more suitable for young adults. The testing procedures and risks were fully explained to all the subjects, and then they were asked to provide written consent for participation. For testing whether the cardiorespiratory capability effect would be significant on the recovery time, the subjects were divided into two groups according to their values of cardiorespiratory capability index, $R_{(HR=125-150)}$. Group A was high-cardiorespiratory-capability group with personal $R_{(HR=125-150)} < 0.9$, whereas Group B was low-cardiorespiratory-capability group with personal $R_{(HR=125-150)} \geq 0.9$. The division was based on the finding of Wu and Wang (2001) that people who have higher $R_{(HR=125-150)}$ implies that they have lower cardiorespiratory capability. The $R_{(HR=125-150)}$ was the average respiratory quotient during the
HR range of 125~150 beats \text{ min}^{-1} \text{ in the maximum capacity test (Wu and Wang 2001). The protocol of the maximum capacity test is explained later (section 2.3).}

Table 1 indicated that 10 subjects (six males, four females) belonged to Group A, and the other 14 subjects (six males, eight females) belonged to Group B. It was reasonable that the mean $R_{HR=125-150}$ of Group A (0.83) was significantly lower than that of Group B (1.01). Besides, male subjects had significantly greater body height, mass, VO$_{2\text{max}}$, and W$_{max}$ than female subjects.

[Insert table 1 about here]

2.2 Equipments

A pulmonary function testing system, K4 system, (Cosmed Srl, Italy), was used to measure VO$_2$, HR, and the respiratory quotient in the experiment. The K4 system has been validated as an accurate device for VO$_2$ measurement during exercise (Hausswirth et al. 1997). It contains a portable unit, a receiving unit, and a battery charger unit. A facemask is used to connect a person to the portable unit. A cardiac belt transmits impulses to the portable unit, and the exhaled gas is sampled and mixed into a dynamic micro chamber. Before using the K4 system, it is necessary to calibrate the O$_2$ and CO$_2$ analyzers. The chamber also has to be cleaned before each test. All of the measured data were transmitted in real time via radio to the receiver unit for processing and display.
An electrical bicycle ergometer, Ergometrics er800s, (Ergoline, Germany), was used for the incremental and constant cycling tests. The pedalling frequency ranges from 30 to 130 (revolutions-min\(^{-1}\)). The work rate range was from 25 to 999 watts. A calibrated digital display was used to monitor the pedalling frequency. Seat height, handlebar height and handlebar position were adjustable to accommodate to subjects’ heights from 120 to 210 cm.

2.3 Maximum capacity test

Before the maximum capacity test, the subject was checked for good physical condition and provided with an adequate warm up procedure. The subject was then asked to perform the incremental cycling test on a bicycle ergometer. The work rate for males was designed with an increase of 10 watts per minute after an initial work rate of 120 watts. The work rate for females was designed with an increase of 5 watts per minute after an initial work rate of 80 watts. The pedalling frequency was maintained at 60 rpm. In order to avoid change in posture during cycling, the adjustment to the bicycle ergometer to standard position was done for each maximum capacity test. We set the angle between the extended axis of the upper body and the thigh for 10° with the pedal is at its lowest position. In general, a subject can sustain this incremental cycling test for 6 to 12 minutes. The K4 system was set to continuously collect VO\(_2\) and HR data at 30-second intervals throughout the test. The \(R_{\text{HR}=125-150}\) was collected during the HR range of 125~150 beats \(\text{min}^{-1}\) in this maximum capacity test. In addition, the
VO$_{2\text{max}}$ was also obtained in this test. The approach of a subject’s VO$_{2\text{max}}$ was confirmed when at least two of the three following test criteria were satisfied (Heil, et al. 1995): (1) there is no further increase in oxygen uptake despite a further increase in the work rate, (2) the respiratory quotient is over 1.10, and (3) HR$_{\text{max}}$ falls within ±15 beats of age-predicted maximal HR (220–age). When VO$_{2\text{max}}$ was approached, the corresponding work rate was defined as his/her maximum working capacity (W$_{\text{max}}$). The results of this test are listed in table 1.

2.4. Experimental task and procedure

Two constant cycling tests were designed to simulate two levels of high-intensity work (60% and 70% of personal W$_{\text{max}}$). After every subject’s W$_{\text{max}}$ was determined, each subject was assigned the constant cycling tests at 60% and 70% of his/her W$_{\text{max}}$ on two separate days. Since the minimum adjustable unit of work rate on the bicycle ergometer was 5 watts we could not always set the work intensity for exactly 60% and 70% of personal W$_{\text{max}}$. But these two cycling tests could be considered as requiring about 60% and 70% of personal VO$_{2\text{max}}$ reserve.

Before performing the test, the subject adjusted the saddle of the bicycle ergometer to the proper standard position. The suggested angle between the extended axis of the upper body and the thigh was about 10° with the pedal is at its lowest position. This was to ensure that every subject rode on the bicycle ergometer with the same posture. The K4 system was then carried by the subject and was set to continuously collect VO$_2$ and HR at 30-second intervals.
throughout the test.

At the first 20 minutes of each test, the subject was seated on the bicycle ergometer for achieving his/her steady state resting level. VO$_2$ and HR were continuously measured during this time, but only data obtained during the last five minutes were averaged and used as the baselines (VO$_{2\text{rest}}$ and HR$_{\text{rest}}$). The subject was then asked to exercise continuously with the pedalling frequency of 60 revolutions·min$^{-1}$. When the subject felt exhausted and stopped to rest, the time to exhaustion ($T_e$) was recorded. The subject was then seated in a chair and remained there until he/she perceived no fatigue anymore or until the VO$_2$ and HR returned to their baselines, whichever was longer. When all of the three kinds of recovery time were obtained, the test was terminated.

To ensure that the testing environment was appropriately controlled, the laboratory was kept as quiet as possible during all the recovering measurements. The testing room was air conditioned during the experiment with ambient temperature in comfortable range ($24\sim26^\circ\text{C}$). Subjects were asked to wear similar clothing (slacks, T-shirt) for all of the tests.

2.5. Measurements and Statistical analyses

The measured dependent variables included time to exhaustion ($T_e$), relative oxygen uptake ($\text{RVO}_2$), relative heart rate ($\text{RHR}$), subjective recovery time ($T_{sr}$), VO$_2$ recovery time ($T_{or}$), and HR recovery time ($T_{hr}$). $T_e$ was the endurance working time from the start of the cycling
exercise to the moment that the subject felt exhausted and stopped to rest. RVO₂ was defined as:

\[
RVO₂ = \frac{(VO₂_{work} - VO₂_{rest})}{(VO₂_{max} - VO₂_{rest})} \times 100\%,
\]

where VO₂_{work} was calculated by averaging the VO₂ measures during Tₑ, VO₂_{rest} was the average VO₂ during the last five minutes of the 20-min seated pre-exercise rest period, and VO₂_{max} was obtained in the maximum capacity test. Similarly, RHR was defined as:

\[
RHR = \frac{(HR_{work} - HR_{rest})}{(HR_{max} - HR_{rest})} \times 100\%,
\]

where HR_{work} was obtained by averaging the heart rate measures during Tₑ, HR_{rest} was the average heart rate during the last five minutes of the 20-min seated preexercise rest period, and HR_{max} was estimated by 220 minus the subject’s age.

T_{sr} was the time from exhaustion to the moment that the subject perceived no fatigue anymore. T_{or} was the time required for VO₂ to return to its baseline (VO₂_{rest}) after exhaustion. T_{hr} was the time required for HR to return to its baseline (HR_{rest}) after exhaustion. The longest recovery time for all the three kinds of recovery time would be considered as the complete recovery time (CRT).

The SPSS₁₀.₀ software package was used to analyze the data. All variables measured during the cycling tests were described as mean values with their standard deviations (SD). Analyses of variance (ANOVAs) were performed to evaluate the gender, group (i.e., cardiorespiratory capability), work intensity, and the interaction effects for each of the measured
variables. Student’s t-test was applied to test the difference between each pair of the mean values for the three kinds of recovery time. Statistical significance was accepted for all tests at $p < 0.05$. The Pearson product-moment correlations were calculated to obtain the correlation coefficients between each pair of the dependent variables and the characteristics of the subjects. In order to predict the CRT after exhaustion by some given work load and cardiorespiratory capability index, forward regression analyses were also conducted. Linear, non-linear, and piecewise linear regression models were compared and then the best-fitted model would be found.

3. Results

After comparing the collected VO$_2$ and HR profiles between cycling at 60% and 70% W$_{\text{max}}$, some similar phenomena were observed:

(1) VO$_2$ and HR increased rapidly during the first two or three minutes of the cycling exercise and then continued to increase gradually until the individual stopped voluntarily due to exhaustion.

(2) VO$_2$ and HR declined sharply during the first three or four minutes of the recovery process and then decreased slowly until approaching their baselines.

(3) HR tended to take more time to return to its baseline than VO$_2$.

(4) The lengths of the recovery times after exhaustion for cycling at 60% and 70% W$_{\text{max}}$ were
approximately the same.

The greatest discrepancy between cycling at 60% and 70% W_{max} was the time to exhaustion. The time to exhaustion for the cycling exercise at 60% W_{max} (about 27 minutes) was obviously longer than that at 70% W_{max} (only about 14 minutes). Besides, the VO_2 and HR response levels during cycling at 60% W_{max} were a little lower than those at 70% W_{max}.

The gender effect was not significant on all of the dependent variables, so the measured results were pooled and then the averages of groups A and B were calculated and shown in table 2. The cardiorespiratory capability effect was significant on the time to exhaustion and on all of the three kinds of recovery time. The mean T_e of Group A (30.0 min at 60% W_{max}, 15.4 min at 70% W_{max}) was significantly longer than that of Group B (24.8 min at 60% W_{max}, 12.7 min at 70% W_{max}). Besides, the mean T_{sr}, T_{or}, and T_{hr} of Group A were all significantly less (about 1~5 min less) than those of Group B.

For the work intensity effect, the mean T_e at 60% W_{max} was significantly greater (about twofold) than that at 70% W_{max}. The relative workload levels (i.e. RVO_2 and RHR) at 60% W_{max} were significantly lower (about 10% less) than those at 70% W_{max}.

Since the work intensity effect was not significant on any of the three kinds of recovery time, the measurement results in the 60% and 70% W_{max} tests were pooled, and then the averages of groups A and B were calculated, as shown in figure 1. It was obvious that the mean HR recovery time was the greatest (25.3 min for Group A and 30.7 min for Group B), followed
by the VO$_2$ recovery time (15.0 min for Group A and 18.1 min for Group B) and the subjective recovery time (6.4 min for Group A and 7.6 min for Group B). The differences among these three kinds of recovery times between groups A and B were statistically significant (p < 0.05).

As mentioned above, the time required for heart rate to return to its baseline was significantly longer than both of the VO$_2$ recovery time and the subjective recovery time. Based on the definition of CRT mentioned in the introduction section, HR recovery time was thus considered as the CRT in this study. Table 3 exhibits that CRT was significantly and positively correlated with R$_{(HR=125-150)}$ (r = 0.42), RVO$_2$ (r = 0.45), and RHR (r = 0.40). The RVO$_2$ was positively correlated with RHR (r = 0.50, p < 0.05). The R$_{(HR=125-150)}$, RVO$_2$ and RHR were subsequently used as the predictors to find the fitted regression function for estimating CRT. The results of regression analyses were summarized in table 4. It indicated that the piecewise linear regression models, functions (g) and (h), yielded the highest r$^2$ value (0.74) as compared with those of the other regression models (0.27~0.34).

Table 5 exhibits the CRT after exhaustion for some given workloads, which were derived from the fitted regression functions (g) and (h). For a high-cardiorespiratory-capability person with R$_{(HR=125-150)}$ = 0.8, the suggested CRT is 22.5, 23.0, 23.6, and 24.1 minutes at 50%, 60%,
70%, and 80% RVO₂ levels, respectively. Similarly, the suggested CRT is 20.8, 22.1, 23.4, and 24.7 minutes at 50%, 60%, 70%, and 80% RHR levels, respectively. When it comes to a low-cardiorespiratory-capability person with $R_{(HR=125-150)} = 1.0$, the CRT should be suggested greater (about 10 min more) than that for a high-cardiorespiratory-capability person.

[Insert table 4 about here]

[Insert table 5 about here]

4. Discussion

4.1. Subjective and physiological recovery times

According to the results, the mean subjective recovery time was quite short (6.4 min for Group A and 7.6 min for Group B) as compared with those of the physiological recovery time. Based on the collected heart rate data, when the subjects felt that they have recovered, the mean HR was 111 beats per minute, which was about 27 beats $\text{min}^{-1}$ above average resting HR level. As comparing this finding with the endurance HR proposed by European researchers (30 beats $\text{min}^{-1}$ above resting HR), it showed merely a little difference in the endurance HR between the Taiwanese and European workers. It meant that the subjective recovery time may be the best predictor for the rest requirement based on the assumption that no work-related rest allowance is necessary for a job that demands a physiological cost less than the HR endurance limit.
Besides, this study proved that people were not able to perceive clearly when the VO$_2$ or HR will recover completely to the resting level. Furthermore, the subjective recovery time (or called required rest time by personal perceived fatigue) was significantly shorter than physiological recovery time. When the subject felt exhausted in a high-intensity work job, his/her cardio strain needed more time to recover (about 28 min), as compared with that of the respiratory strain (about 17 min). This finding was consistent with that of Short and Sedlock’s study (1997). Their study indicated that HR recovery is slower than VO$_2$ recovery after a 30-min cycling exercise at 70% of personal peak VO$_2$. But on the contrary, Kroemer et al. (1997) found that HR fell back more quickly to the baseline than VO$_2$ in the moderate dynamic muscular work. This is due to the differences in work intensity. In Kroemer et al.’s experiment, a subject achieved a steady state of about 120 heart beats . min$^{-1}$ for 5 minutes and then stopped to rest. Its degree of cardio strain was obviously less than that in the exhaustion state (about 180 heart beats . min$^{-1}$) observed in this study. Consequently, it was proven that HR recovery time was significantly longer than VO$_2$ recovery time after exhaustion in high-intensity work. But if the work load was moderate or light, HR recovery time might be not longer than VO$_2$ recovery time.

Although it may still be doubted that the one that recovers most slowly is the most important one, or one that ensures that it is safer to return to work. It is possible that other factors may be more important, such as cellular changes in muscle or hormonal changes. We
could merely say that HR recovers most slowly and therefore might be a more conservative standard to determine the ‘complete recovery time’ in high-intensity work. Besides, heart rate data in the field can be collected much easier and with fewer costs than oxygen uptake measurements, so it is more desirable to apply heart rate to predict the CRT than oxygen uptake. Fortunately, two CRT prediction functions based on RVO2 and RHR respectively were obtained in this study (refer to functions (g) and (h) in table 4). Their prediction powers were quite high ($r^2 = 0.74$).

4.2. Cardiorespiratory capability effect

As shown in table 2, the mean time to exhaustion of Group A was significantly greater than that of Group B. It meant that people who had lower $R_{(HR=125-150)}$ (less than 0.9) implied that they had higher cardiorespiratory capability, and could continue working for a longer period. This result supports Wu and Wang’s (2001) finding that individual differences, such as $R_{(HR=125-150)}$, do have significant influences on the endurance performance and the maximum acceptable work time.

In addition to the exhaustion time, the mean CRT (25.3 min) required by Group A was significantly less than that of Group B (30.7 min), as shown in figure 1. This result indicated that an individual who had higher cardiorespiratory capability would recover more quickly after exhaustion, although his/her endurance working time was longer. Therefore, the differences in
the cardiorespiratory capability must be taken into consideration in determining the CRT for different workers in the workplace. This is also the reason why table 5 suggests more CRT after exhaustion for a person with lower cardiorespiratory capability.

4.3. Work intensity effect

No matter Group A and Group B, the mean time to exhaustion at 70% \( W_{\text{max}} \) was significantly less (about half) than that at 60% \( W_{\text{max}} \) (table 2). Besides, the mean \( \text{RVO}_2 \) (or RHR) at 70% \( W_{\text{max}} \) was significantly greater (about 10% more) than that at 60% \( W_{\text{max}} \). It is reasonable that a higher level of work intensity provokes significant increases in the relative workload levels (i.e., \( \text{RVO}_2 \) and RHR responses), which is accompanied by a great fall in the time to exhaustion.

Although the mean HR recovery time at 60% \( W_{\text{max}} \) was a little less (one minute less) than that at 70% \( W_{\text{max}} \), the difference was not statistically significant. This is because in both the 60% and 70% \( W_{\text{max}} \) tests, the subject was asked to continue cycling until he/she felt exhausted. We found that the subject’s heart rate and oxygen uptake at the exhaustion moment in the 60% \( W_{\text{max}} \) test reached about the same levels as those in the 70% \( W_{\text{max}} \) test, and therefore the same level of strain requires the same time for recovery. These results are in accordance with those of Rohmert’s study (1973a), showing that it took the same time to recover after the same level of strain at the end of exercise. Both exercise intensity and duration are important determinants of the strain level (Rohmert 1973a, Rohmert 1973b, Wu and Wang 2002) and they
have great influences on the VO$_2$ and HR responses after excess exercise (Sedlock et al. 1989, Gore and Withers 1990, Short and Sedlock 1997). Consequently, the same exhaustion states found in these two cycling tests here indicated that although different levels of work intensity lead to different endurance working time, but the required recovery time will be approximately the same.

Although the difference in the CRT was not significant between the 60% and 70% $W_{\text{max}}$ tests, CRT was found to be significantly and positively correlated with both RVO$_2$ and RHR (see table 3). We could infer that if the worker’s RVO$_2$ and RHR during work time were higher, he/she would require a little more time to recover after exhaustion. This is also the reason why table 5 suggests a little more CRT after exhaustion when the RVO$_2$ and RHR are greater.

4.4. Limitation to the results of this study

The suggested CRT after exhaustion in this paper is mainly for healthy young Taiwanese adults with ages ranging from 20 to 30. More experiments are still required to prove whether these results are also suitable for different age groups (e.g. 30-40, 40-50, 50-60).

Since the current experimental data were collected through leg cycling tests, the suggested CRT prediction functions (g) and (h) in table 4 are likely to be most applicable to tasks involving mainly lower limb muscular efforts such as rapid and prolonged walking or climbing stairs. Further studies are necessary to investigate whether these findings can be
generalized to other work modes such as upper-body or whole-body muscular efforts.

Finally, it should be noted that the CRT suggested here was merely applicable to a high-intensity work task that requires at least 50% $RVO_2$ and the worker must continue working until exhaustion. If the work/rest schedule can be controlled arbitrarily by the worker, taking a brief break after a short work time is always better than taking a long break after exhaustion.

5. Conclusion

It would be not suitable to determine complete recovery time (CRT) merely by personal subjective cognition, because the findings of this study implied that subjective recovery time (about 7 min) was significantly shorter than physiological recovery time. The experimental results indicated that heart rate recovery time (about 28 min) was significantly greater than oxygen uptake recovery time (about 17 min). Since HR recovered most slowly after exhaustion in high-intensity work, it was considered as the CRT. Furthermore, the CRT was confirmed to be significantly correlated with the cardiorespiratory capability index ($R_{HR=125-150}$) and relative workload indices ($RVO_2$ and RHR) during work. Two functions for predicting the CRT with $RVO_2$ and RHR were obtained, respectively. Derived from the RHR-based prediction model, the CRT for a high-cardiorespiratory-capability person is 20.8, 22.1, 23.4, and 24.7 min at 50%, 60%, 70%, and 80% RHR levels, respectively. For a low-cardiorespiratory-capability person,
the CRT should be suggested greater (about 10 min more) than that for a
high-cardiorespiratory-capability person. These results are convenient and useful in
determining sufficient recovery time after exhaustion for a high-intensity work job including
mainly lower limb muscular efforts.

Acknowledgements

The authors thank National Science Council of ROC for providing financial support under
Project No. NSC91-2213-E-324-030.

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Table 1. Characteristics of the subjects in groups A and B.

<table>
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<tr>
<th>Group A</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Mass* (kg)</th>
<th>$R_{(HR=125-150)}$*</th>
<th>$VO_{2\text{max}}$ (l. min$^{-1}$)</th>
<th>$W_{\text{max}}$ (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males (n=6)</td>
<td>23.0 (3.7)</td>
<td>172.3 (7.2)</td>
<td>72.8 (8.1)</td>
<td>0.82 (0.06)</td>
<td>3.633 (0.577)</td>
<td>204.2 (23.0)</td>
</tr>
<tr>
<td>Females (n=4)</td>
<td>22.8 (2.4)</td>
<td>158.3 (4.6)</td>
<td>49.0 (4.2)</td>
<td>0.85 (0.05)</td>
<td>1.951 (0.377)</td>
<td>119.5 (9.1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Group B</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Mass* (kg)</th>
<th>$R_{(HR=125-150)}$*</th>
<th>$VO_{2\text{max}}$ (l. min$^{-1}$)</th>
<th>$W_{\text{max}}$ (Watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males (n=6)</td>
<td>23.5 (3.7)</td>
<td>167.9 (5.4)</td>
<td>62.7 (4.8)</td>
<td>1.03 (0.09)</td>
<td>2.972 (0.428)</td>
<td>198.3 (16.1)</td>
</tr>
<tr>
<td>Females (n=8)</td>
<td>23.9 (1.8)</td>
<td>160.4 (3.1)</td>
<td>51.3 (4.0)</td>
<td>0.99 (0.07)</td>
<td>2.121 (0.369)</td>
<td>126.3 (9.9)</td>
</tr>
</tbody>
</table>

* Significant difference between groups, P < 0.05.
* Significant difference between males and females, P < 0.05.
$R_{(HR=125-150)}$ : Average respiratory quotient during the HR range of 125~150 beats . min$^{-1}$.
$VO_{2\text{max}}$ : Maximum oxygen uptake.
$W_{\text{max}}$ : Maximum working capacity.
Table 2. The results of the measured variables of groups A and B in two cycling tests.

<table>
<thead>
<tr>
<th></th>
<th>$T_e$ * (min)</th>
<th>$\text{RVO}_2$ (%)</th>
<th>$\text{RHR}$ (%)</th>
<th>$T_{sr}$ * (min)</th>
<th>$T_{or}$ * (min)</th>
<th>$T_{hr}$ * (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group A (n=10)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60% $W_{max}$</td>
<td>30.0 (11.4)</td>
<td>60.8 (7.6)</td>
<td>64.3 (4.0)</td>
<td>6.5 (1.9)</td>
<td>14.6 (4.5)</td>
<td>24.9 (6.0)</td>
</tr>
<tr>
<td>70% $W_{max}$</td>
<td>15.4 (3.8)</td>
<td>70.4 (6.2)</td>
<td>74.1 (4.8)</td>
<td>6.4 (1.6)</td>
<td>15.5 (6.1)</td>
<td>25.7 (6.0)</td>
</tr>
<tr>
<td><strong>Group B (n=14)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60% $W_{max}$</td>
<td>24.8 (6.4)</td>
<td>64.6 (9.8)</td>
<td>66.2 (4.3)</td>
<td>7.3 (2.3)</td>
<td>17.8 (3.8)</td>
<td>30.3 (6.8)</td>
</tr>
<tr>
<td>70% $W_{max}$</td>
<td>12.7 (4.4)</td>
<td>74.5 (9.8)</td>
<td>74.8 (5.1)</td>
<td>8.0 (2.8)</td>
<td>18.5 (3.7)</td>
<td>31.2 (6.3)</td>
</tr>
</tbody>
</table>

* Significant difference between groups, $P < 0.05$.
□ Significant difference between 60% $W_{max}$ and 70% $W_{max}$, $P < 0.05$. 
Table 3. Pearson product-moment correlation matrix (n=48).

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] CRT</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[2] Age</td>
<td>0.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[3] Height</td>
<td>-0.05</td>
<td>-0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[4] Mass</td>
<td>-0.15</td>
<td>0.09</td>
<td>0.87*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[5] $R_{(HR=125-150)}$</td>
<td>0.42*</td>
<td>0.31*</td>
<td>-0.10</td>
<td>-0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[6] VO2max</td>
<td>-0.22</td>
<td>-0.37*</td>
<td>0.66*</td>
<td>0.73*</td>
<td>-0.31*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[7] Te</td>
<td>-0.05</td>
<td>0.10</td>
<td>0.02</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[8] RVO2</td>
<td>0.45*</td>
<td>0.14</td>
<td>-0.05</td>
<td>-0.07</td>
<td>0.25</td>
<td>-0.22</td>
<td>-0.21</td>
<td></td>
</tr>
<tr>
<td>[9] RHR</td>
<td>0.40*</td>
<td>0.24</td>
<td>0.02</td>
<td>0.02</td>
<td>0.23</td>
<td>-0.09</td>
<td>-0.51*</td>
<td>0.50*</td>
</tr>
</tbody>
</table>

* Significant at p < 0.05.
Table 4. The results of the regression analyses for predicting the CRT

<table>
<thead>
<tr>
<th>Regression model</th>
<th>Fitted function</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Linear</strong></td>
<td>(a) CRT = -6.3 + 19.4 × $R_{(HR=125-150)}$ + 24.5 × RVO$_2$</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>(b) CRT = -13.6 + 20.4 × $R_{(HR=125-150)}$ + 32.9 × RHR</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Exponential</strong></td>
<td>(c) CRT = 22.6 + $e^{(-3.7 + 2.0 × R_{(HR=125-150)} + 5.0 × RVO_2)}$</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>(d) CRT = 7.3 + $e^{(1.1 + 0.9 × R_{(HR=125-150)} + 1.6 × RVO_2)}$</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Linear and Exponential</strong></td>
<td>(e) CRT = 10.7 + 16.2 × $R_{(HR=125-150)}$ + 0.001 × $e^{(10.8 × RVO_2)}$</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>(f) CRT = 5.8 + 20.1 × $R_{(HR=125-150)}$ + 0.012 × $e^{(8.1 × RHR)}$</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Piecewise linear</strong></td>
<td>(g) CRT = {18.3+ 1.7× $R_{(HR=125-150)}$+ 5.6× RVO$<em>2$ for $R</em>{(HR=125-150)} \leq 0.9$} or {9.7+ 17.2× $R_{(HR=125-150)}$+ 11.1× RVO$<em>2$ for $R</em>{(HR=125-150)}&gt;0.9$}</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>(h) CRT = {13.3+ 1.4× $R_{(HR=125-150)}$+ 12.8× RHR for $R_{(HR=125-150)} \leq 0.9$} or {8.0+ 17.8× $R_{(HR=125-150)}$+ 12.8× RHR for $R_{(HR=125-150)}&gt;0.9$}</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Table 5.  Suggested CRT after exhaustion for some given workloads.

<table>
<thead>
<tr>
<th>Given workload RVO₂ (%)</th>
<th>CRT (min)⁴ for a high-cardiorespiratory-capability person</th>
<th>CRT (min)⁵ for a low-cardiorespiratory-capability person</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CRT (min)⁶ for a high-cardiorespiratory-capability person</td>
<td>CRT (min)⁷ for a low-cardiorespiratory-capability person</td>
</tr>
<tr>
<td>50</td>
<td>22.5</td>
<td>32.5</td>
</tr>
<tr>
<td>60</td>
<td>23.0</td>
<td>33.6</td>
</tr>
<tr>
<td>70</td>
<td>23.6</td>
<td>34.7</td>
</tr>
<tr>
<td>80</td>
<td>24.1</td>
<td>35.8</td>
</tr>
</tbody>
</table>

⁴ The values were derived from function (g) with R(HR=125-150) = 0.8 and RVO₂ = 50–80%.
⁵ The values were derived from function (g) with R(HR=125-150) = 1.0 and RVO₂ = 50–80%.
⁶ The values were derived from function (h) with R(HR=125-150) = 0.8 and RHR = 50–80%.
⁷ The values were derived from function (h) with R(HR=125-150) = 1.0 and RHR = 50–80%.
Figure 1. Three kinds of recovery time for groups A and B.