SNAPSHOT EVALUATION OF FATIGUE USING HEART RATE VARIABILITY AND SUPERIMPOSED M WAVES OF MYOELECTRIC SIGNALS DURING SKIING EXERCISE

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Abstract—We simultaneously measured the heart rate (HR) and myoelectric (ME) signals during skiing exercise for a whole day. To realize snapshot evaluation of fatigue for this long-term exercise, biosignal processing should be designed to estimate the target factors from biosignals and to deal with biosignals measured at a restricted condition.

We accumulated power spectrum of the HR time-series within the target frequency bands determined by the results of wavelet analysis. On the other hand, the evoked potential approach was used for evaluating muscle fatigue via ME signals. The accumulated power spectrum of the HR time-series changed periodically during skiing and ski lift riding. Furthermore, a muscle fatigue index and the features of the HR time-series became prominent towards the final trial of the day. As a result, we could investigate fatigue at required time based on the relationship between the time-varying behavior of HR time-series and the muscular fatigue index, during long-term skiing exercise.

I. INTRODUCTION

The appropriate physical exercise is helpful to release mental stress, to maintain a healthy body, and to recover impaired physical function in rehabilitation medicine. In the appropriate physical exercise, the relationship between intensive motivation and fatigue should be balanced to avoid overwork. The feeling of fatigue is a reaction of the central nervous system caused by a variety of fatigue related factors. Muscular fatigue, one of the fatigue related factors, originates at peripheral muscles and transmits the information to the central nervous system via the cardiovascular system. Note that, in muscular fatigue, central fatigue as well as peripheral fatigue is also studied at the level of the motor command [1]. In this paper, we study biosignal processing developed for snapshot evaluation of the relationship between the feeling of fatigue and the muscular fatigue during long-term exercise.

In order to represent the feeling of fatigue at the central nervous system, we used the spectrum analysis of the heart rate variability (HRV). The HRV is dynamically controlled under the autonomic nervous system and the frequency components are considered as the indices of the sympatho-vagal balance. Sayars [2] classified the power spectrum of HR time-series into three frequency bands. From early 1980's, the frequency components of the HRV have been investigated energetically. The ratio between a low frequency component and a high frequency component was proposed as the noninvasive measure of the sympatho-vagal interactions [3]. Recently, time-varying analysis has been introduced to analyze several time-varying frequency components of the HRV [4] - [8]. The HR is substantially nonstationary and is modulated by many factors with different time-varying scales. As a result, the decreases of the parasympathetic tone are generally observed during exercise, but the behavior of the sympathetic tone has not been clarified. During long-term exercise, therefore, it is further difficult to identify the behavior of the anatomic nervous activities with the progression of fatigue.

On the other hand, muscle activity influences the reflex response of the cardiac sympathetic activity such as the mechanoreflex during exercise and then metaboreflex with the progression of muscular fatigue [9]. The impairment of muscle activity causes the increase of metabolic byproducts in the blood flow. Then, the central nervous system can sense the growth of metabolic byproducts and then increase the HRV. Muscular fatigue has been studied by surface myoelectric (ME) signals from late 1960's. Although we are now able to apply time-varying technique for analyzing dynamic ME signals during exercise, it is very hard to recognize the central fatigue from surface ME signals. Measuring the impulse trains, that are related to the central fatigue, is not practical. Moreover, muscular fatigue progresses gradually for long-term exercise, and is difficult to estimate by voluntary ME signals.

We selected skiing exercise as a long-term exercise. The autonomic nervous control would change periodically during skiing and ski lift riding, and the whole time-varying behavior could be affected by the progression of fatigue.

The wavelet analysis was used as preliminary evaluation of the HRV, because dynamic HRV contains several type of components with different time-varying scales. The wavelet analysis of the HRV can reveal the previously reported significant time-varying behavior of the high frequency component affected by the parasympathetic nervous activity and the low frequency peak regarding both sympathetic and parasympathetic nervous activities, at the same time. After focusing on the target frequency bands for snapshot evaluation, we compared the time-varying behavior of the HRV power spectra between skiing and ski lift riding during a whole day. On the other hand, the electrically elicited evoked potential of ME signals during a short sustained contraction was used as snapshot evaluation of muscular fatigue during a long-term exercise. We estimated the correlation of frequency components between evoked potentials and the preceding background activities.

II. Methods

A. Time-Varying Behavior of HRV

An instantaneous HR time-series, in beat per minutes, was transformed into the HRV by uniformly resampling the third-order spline interpolated original nonuniform R-R interval time-series. In general, the frequency range around 0.04 Hz [7] or around 0.1 Hz [5], the low frequency region, has been widely accepted to show the increased sympathetic and parasympathetic tones. The high frequency region (0.15-0.5 Hz), on the other hand, relates to the respiratory activity and a sign of parasympathetic activity. Thus, it requires around several minutes of the HR time-series to apply the conventional spectrum analysis. However, the HR changes even in several minutes, and the field measurement sometimes limits the data acquisition time that is practically required for the conventional spectrum analysis.

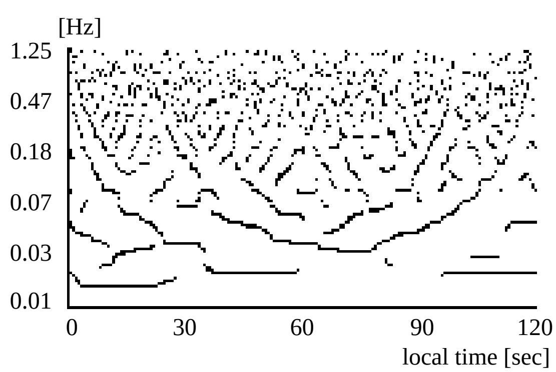

Fig. 1. Time-courses of target HRV frequency components.

We applied the wavelet analysis for each two minutes of HR time-series during skiing and lift riding in order to classify the time-varying behavior of the sympatho-vagal interactions within each phase. Assuming $W(f, t)$ is the wavelet transform of the HRV, we are able to trace several local peaks at dominant or target frequency ranges, by screening the power on the frequency axis at each time t (**Fig. 1**). Thus, the time-courses of the target HRV frequency components are obtained by tracking these local peaks. The discontinuity times are also determined, if the series of $|W(f, t)|$ as a function of f is constant towards high frequency ranges and $|W(f, t)|$ has a local peak around t. As a result, the wavelet analysis reveals the target frequency ranges in the HRV for snapshot evaluation during each phase of exercise. As a practical index to represent the different sympatho-vagal balance between skiing and lift riding, we accumulated the power spectrum of the HRV for individual target frequency ranges in each interval.

B. Relationship between Superimposed M Waves and Preceding Background Activity

ME parameters conventionally used to evaluate muscular fatigue are the root mean square value, the average rectified value (ARV), the mean power frequency (MPF), and the median frequency of ME signals, and the conduction velocity of motor unit action potentials.

During skiing exercise, muscular fatigue was difficult to evaluate because it is a long-term repetitive exercise including short-term voluntary skiing and comparatively long-term lift riding. We have used electrical stimulation of the muscle and measured superimposed M (SM) waves, as an evoked potential, accompanied by the preceding background activity during a sustained contraction [10]. The M waves have been used to distinguish “central fatigue” from peripheral fatigue in muscular fatigue process [1]. We focus on the changes in the SM waves effected by the preceding fatiguing contractions within less than one minute measurement. The MPF was calculated during the preceding background activity, while the instantaneous frequency (IF) was estimated from the synchronously averaged SM waveform. Regarding the IFs, we first of all obtain the synchronously averaged waveform in a frame and then estimated the IFs of the averaged SM waveform by the Hilbert transform, in each frame. As a muscle fatigue index, we calculated the correlation coefficients between MPF and IFs at specific local times of the SM wave (**Fig. 2**).

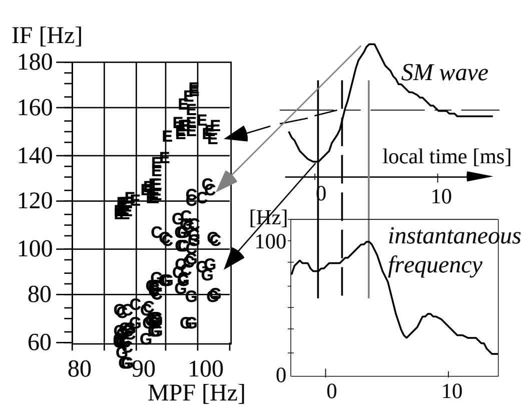

Fig. 2. MPF-IF distribution

Comparing the correlation coefficients among the specific local times, the specific time that showed the highest correlation coefficients was selected. The first peak of the SM wave was generally selected to represent the features of the correlation between MPF and IF. The previous study [10] reported that there were two different classes, Ω_1 and Ω_2, in the MPF-IF distribution. The class Ω_1 showed a high positive correlation between MPF and IFs; on the other hand, the MPF and IFs were uncorrelated or showed different correlation coefficients in Ω_2.

III. EXPERIMENT

We simultaneously monitored the HRV and ME signals during skiing and the HRV during lift riding. Two male subjects participated in our experiment on separate days after they were informed of the experimental procedures and risks associated with the muscle fatiguing efforts. About thirteen trials per day were performed for around seven hours including the one hour lunch break. A trail of skiing exercise consisted of about 3 minutes of skiing and 10 minutes of lift riding and the preparation for measurement. The SM waves during a 40 s contraction were acquired at the beginning of exercise, just before and after the lunch break, and at the end of exercise. We measured the SM waves while the subject contracted the tibialis anterior muscle with maximum effort. The stimulation level was adjusted to obtain the highest SM wave within pain tolerance (a supramaximal stimulation). The period of the stimulation pulse was 1 s. The stimulation pulses were used as the external trigger signals of the SM wave. Refer to [10], for a detailed description of experimental conditions.

The gains of the amplifier were 46 dB (a highcut frequency was f_c was 1 kHz and a time constant τ was 0.5 s) for ECG recording, and 74 dB (f_c was 1 kHz and τ was 0.005 s) for surface ME signals. EEG and ME signals were sampled at 5 kHz and recorded directly into the hard disk of a notebook computer through the analog-to-digital convertor with the resolution of 12 bits.

Two minutes of HRV was analyzed for the frequency ranged from 0.01 Hz to 1.25 Hz. The Gabor function was selected as a mother wavelet. FFT algorithm was used for calculating the accumulated power spectrum based on the results of the wavelet analysis. That is, after inspecting the time-varying behavior of HRV, we determined the range for the low frequency components from 0.05 Hz to 0.15 Hz and the range for the high frequency components from 0.2 Hz to 0.8 Hz. The MPF-IF distribution included around 39 combinations of the MPF and the IFs in each measurement. We estimated the correlation coefficient of the MPF-IF distribution, $\rho_{MPF\text{-}IF}$ [10]. Moreover, the changing ratios of the MPF and ARV of preceding background activity were estimated for references of conventional indices.

IV. RESULTS

A. Time-Varying Behavior of HRV

Figure 3 shows the time-course of the accumulated power spectra for high and low frequency components of the HRV during consecutive five trials of a day. Note that more information could be obtained from the representation like Fig. 1, but a few frequency bands can be physiologically interpreted. In each trial, the accumulated power spectra increased during a lift riding phase and decreased during a skiing phase. The local change possibly corresponds to the parasympathetic nervous activity. The periodic change became prominent towards the final trial of the day. The accumulated power spectra, however, did not show the expected sympathetic activity during skiing. Although it is a preliminary study, the discontinuity of frequency components (Fig. 1) might be related to the increase of the sympathetic tone.

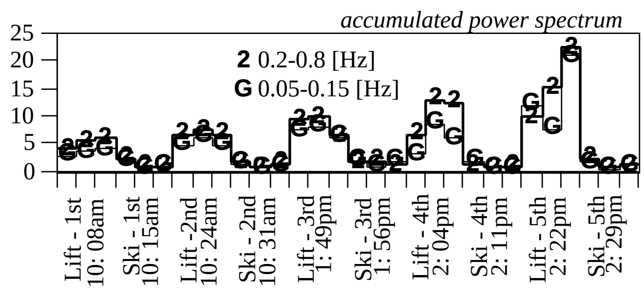

Fig. 3. Time-course of the accumulated power spectra.

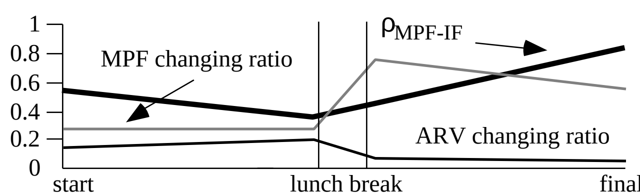

Fig. 4. Correlation coefficient, $\rho_{MPF\text{-}IF}$, and the changing ratios of the MPF and the ARV of preceding background activity.

B. Relationship between Superimposed M Waves and Preceding Background Activity

Figure 4 demonstrates the snapshot results of $\rho_{MPF\text{-}IF}$ and the changing ratios of the MPF and the ARV of preceding background activity at four separate times of the day. The result showed that $\rho_{MPF\text{-}IF}$ decreased just before the lunch break, but it increased towards the final trial. The behavior of $\rho_{MPF\text{-}IF}$ after lunch have not occurred in the basic experiments [10]. The changing ratio of the MPF increased after the lunch break, whereas that of the ARV decreased. These results possibly showed the gradually progressing muscular fatigue during long-term exercise.

We confirmed the results of this subject, comparing them with the characteristics of the MPF-IF distribution obtained in the basic experiments.

V. DISCUSSION

A. Snapshot Evaluation

Snapshot evaluation during a long-term exercise was useful to proceed the seamless measurement. To realize snapshot evaluation, biosignal processing should be designed to estimate target factors from biosignals and to deal with biosignals measured at a restricted condition.

The direct interpretation of the feeling of fatigue from the wavelet analysis of the HRV was difficult, because the time-frequency representation showed many frequency components with different time-varying scales (Fig. 1). Thus, we used the wavelet analysis so as to determine several target time-varying frequency components from the wide frequency band. Then, the accumulated power spectrum was used as a practical index to show the differences of the autonomic nervous activities between skiing and lift riding as snapshot evaluation.

Muscle activities in the field experiments was hard to be interpreted because of several limited conditions. The muscular fatigue does not appear in a constant manner during periodical skiing exercise. The SM wave approach was effective because the impulsive response of the muscle was obtained at the same input energy. The SM wave seems to contain both central fatigue related information and peripheral fatigue related information regarding muscular fatigue [1]. Combining this information by the MPF-IF distribution, we were able to represent the degree of muscular fatigue at a required time during skiing exercise. Further investigation will establish snapshot evaluation of muscular fatigue during long-term exercise.

B. HRV and Muscular Fatigue during Exercise

It has not been clarified how much the feeling of fatigue and/or the muscular fatigue would influence the HRV and the ME signals during long-term periodical skiing exercise. For example, during skiing exercise, the feeling of fatigue was sometimes ignored because of volitional activity, on the other hand, it was enlarged because of the mental stress. In our results, the fatigue related features in the HRV and in the SM waves became prominent towards the final trial of the day. Among many physiological factors, the increase of metabolic byproducts probably augmented the fatigue related features [9].

VI. CONCLUSION

The accumulated power spectra of the HRV frequency components determined by the wavelet transform increased during a ski lift riding phase and decreased during a skiing phase. The correlation coefficients obtained from the superimposed M (SM) waves decreased temporally, but it increased towards the final trial. The results showed that the features estimated from the HRV and from the SM waves enlarged towards the final trial of the day. Among many physiological factors, the increase of metabolic byproducts is probably a major factor. Practically, our snapshot methods will be useful to design the moderate physical exercise even for patients with impaired physical function as well as healthy persons, because our method does not restrict performance during measurement and the data acquisition time is short enough.

ACKNOWLEDGMENTS

The authors wish to thank the staff at Ikenotaira Ski Ground and the students of Niigata University. This research has been supported by the Nissan Science Foundation.

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