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Relationships between Muscle Activity and Autonomic Regulation during Cycling with a Torque-Assisted Bicycle

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Abstract—**For customizing the assistance scheme of a torque-assisted bicycle, we estimated physical activity during cycling with ECG and surface EMG for the circuit including a steep uphill section near the middle and compared it with the vehicle data. Using the respiratory-sinus-arrhythmia-related power ratio in the fluctuation of the R-R interval, pr_{RSA}, and a muscular fatigue index, we classified physical activity into four groups for each trial. Results showed that the assist enlarged pr_{RSA}, but did not sufficiently support muscular fatigue.**

Index Terms—**torque-assisted bicycle, time-frequency analysis, cycling exercise, autonomic regulation, muscular fatigue**

I. INTRODUCTION

Torque-assisted bicycles (TABs), or electric power assist cycles, support rider-generated torque with electric power from the beginning of cycling up to a predetermined speed [1]. However, current TABs are limited because they are not designed for handling physical activity. Although a practical objective is to facilitate voluntary movement and support muscle force that has degenerated due to aging or muscular fatigue, excessive assistance could happen to reduce physical work capacity. Thus, our goal is to design customized assistance based on varying individual physical activity and vehicle data from the TABs.

Physiological studies have shown that the autonomic nervous system regulates physical activity levels based on cardiorespiratory interaction [2]–[5] during exercise. To evaluate autonomic regulation, heart-rate variability (HRV), *i.e.*, the fluctuation in the R-R interval derived from electrocardiograms (ECGs), has been widely used. During cycling, researchers have reported the overall behavior of HRV during exercise and rest [2], [5] and in relation to the respiratory cycle and muscle contractions [3], [4] under different workload intensities. We have studied the changes in autonomic regulation and neuromuscular activity that occur during cycling in relation to vehicle data from the TAB. We recorded ECGs and surface electromyograms (SEMGs) as biosignals and measured the speed, cadence, and torque as vehicle data during repeated cycling trials. The circuit included a steep uphill section near the middle. Thus, the effort required resulted in significant physical changes during and after the climbing. Classifying physical activity by the indices of muscular fatigue and autonomic regulation, we analyzed the relationship between muscle activity at each contraction during climbing and autonomic regulation before and after climbing.

II. METHODOLOGY

A. Experimental Procedure

The participants in the field experiments were 13 healthy volunteers (eight men and five women, 20 ± 0.8 yrs) who were informed of the risks involved and signed a consent form in advance. An experimental set consisted of six consecutive trials and each participant completed once or twice on separate days. After eliminating trials with noise or accidental sample loss, we had data for a total of 103 trials for further analysis, of which 80 had been done with motor torque assist. The circuit was approximately 840 m long and included a steep uphill section near the middle. We divided the circuit into three phases based on the inclination; the maximum gradient was 5.7°. Each participant was asked to keep the pedaling rate as close to 60 rpm as possible by listening to a tone pace maker. Each trial comprised about 2.5 minutes of cycling followed by 2 minutes of rest.

B. Measurement

We recorded ECGs by attaching three disposable disk electrodes with a sensitivity of 46 dB (1.06–1000 Hz) to each participant's chest. Besides, we obtained bipolar SEMGs from the right and left vastus lateralis muscles using two active four-bar electrodes attached to the participant's skin parallel to the muscle fibers. Each bar was 1 mm in diameter and 1 cm long, and the distance between each bar for a bipolar configuration was 1 cm. Thus, three SEMG channels could be measured. We selected a specific channel in advance that was not affected by the innervation zone during cycling. The gain of the amplifier was 60 dB, and the raw signals were bandpass filtered at 5.6–1000 Hz. Both the ECGs and SEMGs were sampled at 5000 Hz and recorded directly onto the hard disk of a sub-notebook computer (Libretto, Toshiba) through a PCMCIA-type analog-to-digital converter (DAQCard-700, National Instruments) with 12-bit resolution.

We measured the speed, cadence, and torque of the TAB (YAMAHA, PX20 with 20-inch wheels and an optional four-speed automatic transmission (SHIMANO, AIS4038)). With the trigger pulses from a sensor mounted on the front wheel, we obtained the speed, $spd(m)$ at m-th pulse. The cadence $cdc(n)$, crank revolutions per minute, was calculated using the time of the pulse at the crank. The crank torque was a voltage acquired with a torque meter mounted on the crank, with a sampling rate the same as that

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for the ECG and SEMG recordings. The voltage was further averaged in a half-cycle interval from n-th crank pulse, then the averaged voltage was converted into the estimated torque at n, $trq(n)$. The torque-assistance ratio, the ratio of rider-generated torque to additional electric-motor-produced torque, is 1:1 when the speed is less than a pre-determined level [1]. As a result, the additional electric-motor-produced torque during climbing was the same as the rider-generated torque. We adjusted the pre-determined levels so that the ratio remained at 1:1 from the beginning of cycling to reaching the hilltop.

C. Biosignal Processing

We used cubic spline interpolation and a resampling algorithm to obtain uniformly sampled R-R interval time-series. To extract the time-varying frequency components in HRV, we used the continuous wavelet transform (CWT) with the Gabor function and controlled the time-frequency resolution. We estimated the CWT of HRV from 0.01 to 1.25 Hz for 600 small frequency ranges with a logarithmic scaling factor. Conventional indices for studying the overall behavior of autonomic regulation are the powers of the low-frequency (LF) and high-frequency (HF) components and of the LF/HF component of HRV [2]. We employed the respiratory sinus arrhythmia (RSA) [2]–[5] related power ranging from 0.3 to 0.6 Hz in HRV for representing the behavior of autonomic regulation in relation to climbing efforts.

Regarding muscle activity, we used the short-term Fourier transform (STFT) for analyzing the SEMGs to identify the behavior of frequency components with short duration. The STFT is well suited for practically analyzing muscular activity at around 200 contractions for a trial with low computational cost. We estimated the typical muscular activity indices, the averaged rectified value (ARV) as an amplitude variable, and the mean power frequency (MPF) as a spectral variable. We divided a contraction, setting the threshold by the highest crank torque, into the first half and the second half, because changes of muscle activity were expected even in a single pedal stroke during climbing. The ARV and MPF ranging from 5 to 500 Hz were estimated with a sliding 50-msec interval every 25-msec in each pedal stroke interval of 400-msec.

Since the timings of the trigger pulses at the wheel and the crank were non-uniform due to pedaling-rate variations, the sampling times of $spd(m)$, $cdc(n)$, $trq(n)$, ARV, and MPF were further adjusted to match those of the R-R interval by using a resampling technique for interpolated functions. We used 4 Hz as the resampling frequency to study the overall behaviors. After estimating original indices, we further arranged suitable parameters and locations for assessment of changes in physical activity. To represent the degree of RSA in HRV, we calculated the time-varying RSA-related power ratio, pr_{RSA}, at each resampling time:

$$pr_{\mathrm{RSA}} = (\text{total power at } 0.3\text{–}0.6 \text{ Hz}) \,/\, (\text{total power at } 0.01\text{–}1.25 \text{ Hz})\ .$$

Since the measured speed varied among trials, even for the same participant, we then converted the time-series of biological indices and vehicle data with respect to the distance from the start point to average individual samples for each period [6]. Accordingly, pr_{RSA} was practically averaged before and after climbing and for the rest period. Then we compared muscular-activity-related indices with pr_{RSA}. Regarding muscle activity, we obtained the correlation coefficients between ARV and MPF ($\gamma_{\mathrm{ARV\text{-}MPF}}$), and between ARV and the torque ($\gamma_{\mathrm{ARV\text{-}}trq}$) at every stroke. After surveying the results, we selected a pair of consecutive 5 strokes from the beginning of climbing and just before the hilltop and then averaged muscular-activity-related indices. Note that there was a plateau, several meters after the beginning of climbing.

D. Grouping

Using pr_{RSA} and $\gamma_{\mathrm{ARV\text{-}MPF}}$, we classified 103 trials into four groups. Firstly, we set the threshold as 20% of averaged pr_{RSA} before climbing, estimating the median (21.3%) from 103 trials. With a high percentage in pr_{RSA} (HRSA) before climbing, there is a large fluctuation in the R-R interval before and after climbing, especially during rest periods. There is a little fluctuation in the R-R interval before and after climbing with a low percentage in pr_{RSA} (LRSA) before climbing.

Secondly, we used averaged $\gamma_{\mathrm{ARV\text{-}MPF}}$ for 5 strokes just before the hilltop because in the positive $\gamma_{\mathrm{ARV\text{-}MPF}}$ region samples showed the largest shift in pr_{RSA} in relation to climbing efforts. At the first half in a peal stroke, positive and negative $\gamma_{\mathrm{ARV\text{-}MPF}}$ means increasing muscle activity and muscle fatigue, respectively. At the second half, positive and negative $\gamma_{\mathrm{ARV\text{-}MPF}}$ means decreasing and disappearing muscle activity, respectively. We hereafter represent positive $\gamma_{\mathrm{ARV\text{-}MPF}}$ as I/D (Increasing or Decreasing muscle activity) and denote negative $\gamma_{\mathrm{ARV\text{-}MPF}}$ as F/D (Fatigue or Disappearing muscle activity).

Consequently, we categorized each trial into four groups by the median of pr_{RSA} and the sign of $\gamma_{\mathrm{ARV\text{-}MPF}}$, in the scatter graph between pr_{RSA} before climbing and $\gamma_{\mathrm{ARV\text{-}MPF}}$ during consecutive 5 strokes just before the hilltop. The abbreviations of four gropes were HRSA-I/D, HRSA-F/D, LRSA-I/D, and LRSA-F/D. Note that physical activity was heaviest just before the hilltop.

III. RESULTS

Fifty-four of 80 assist-on trials (67.5%) were HRSA trials, whereas 16 of 23 assist-off trials (69.6%) were LRSA ones (**Table 1**). Even the assist-on trials, 52 trials showed negative $\gamma_{\mathrm{ARV\text{-}MPF}}$ regardless of pr_{RSA}. Besides, around a half of negative $\gamma_{\mathrm{ARV\text{-}MPF}}$ trials appeared at first and second trials. Eight of the 20 experimental sets consisted of two or three assist-off trials followed by assist-on trials. Three participants recovered from LRSA to HRSA, while the other participants eventually shifted to LRSA, even though temporary recovery was observed immediately after the first assist-on trial.

TABLE 1
NUMBER OF TRIALS FOR EACH GROUP

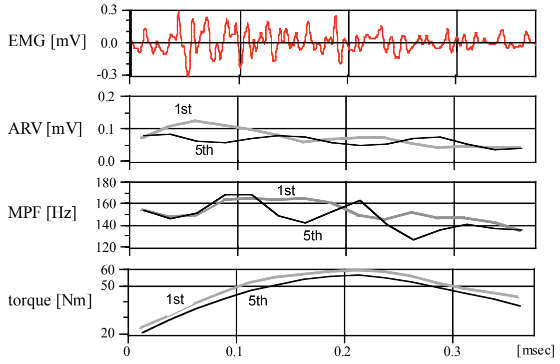
assist on	1st trial	2nd trial	3rd trial	4th trial	5th trial	6th trial	total
HRSA–I/D	1	1	4	7	3	3	19
HRSA–F/D	9	10	2	5	7	2	35
LRSA–I/D	0	0	1	2	3	3	9
LRSA–F/D	0	1	5	4	4	3	17
subtotal	10	12	12	18	17	11	80

assist off	1st trial	2nd trial	3rd trial	4th trial	5th trial	6th trial	total
HRSA–I/D	1	0	1	0	0	0	2
HRSA–F/D	2	0	3	0	0	0	5
LRSA–I/D	2	4	2	1	0	0	9
LRSA–F/D	3	3	0	0	1	0	7
subtotal	8	7	6	1	1	0	23

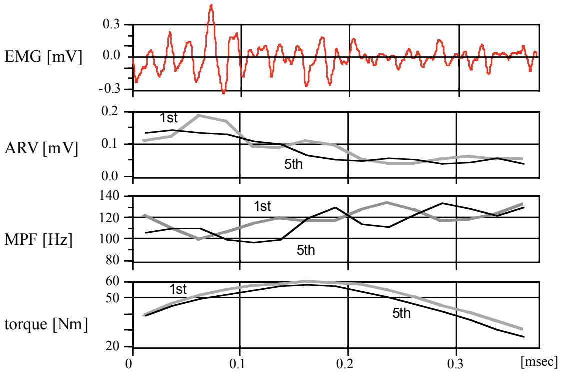
Figure 1 shows the examples of EMG signal at the first stroke and ARV and MPF at the first and fifth strokes for consecutive 5 strokes just before the hilltop, for (a) positive and (b) negative $\gamma_{ARV\text{-}MPF}$ trials. The results indicated that ARV and MPF demonstrated the similar behavior for positive $\gamma_{ARV\text{-}MPF}$ trials, whereas ARV and MPF demonstrated reverse behavior for negative $\gamma_{ARV\text{-}MPF}$ trials. Namely, MPF decreased from the beginning of a contraction against increasing ARV for negative $\gamma_{ARV\text{-}MPF}$ trials. Note that the torque did not show the difference between positive and negative $\gamma_{ARV\text{-}MPF}$ trials.

Table 2 shows the conventional muscle fatigue index, MPF at the first half and the second half in a stroke, averaged for consecutive 5 strokes from the beginning of climbing (after-L-corner) and just before the hilltop (before-H-corner), for each category. The short-term MPF did not change at both sides of the slope for each trial. During a pedaling stroke, the MPF for the second half significantly decreased compared with that for the first half, except for the MPF in LRSA and positive $\gamma_{ARV\text{-}MPF}$. The MPF in LRSA was relatively lower than that in HRSA. The MPF with assist off seemed to be lower than that with assist on, but it was not significant. Furthermore, the MPF in negative $\gamma_{ARV\text{-}MPF}$ was significantly higher than that in positive $\gamma_{ARV\text{-}MPF}$. Significant difference ($p < 0.05$) was evaluated by the paired *t*-test for two halves during a pedaling stroke and for two locations and the Wilcoxon rank sum test for categorized states.

Table 3 shows vehicle data and indices of physical activity during climbing. Note that a high $\gamma_{ARV\text{-}trq}$ indicated a relatively tight connection between muscular activity and torque. The HRSA-F/D, the largest number of trials, showed negative $\gamma_{ARV\text{-}MPF}$ with a high pr_{RSA}: even in HRSA with assist-on trials negative $\gamma_{ARV\text{-}MPF}$ sometimes occurred. In this group, the speed was medium and the torque was the lowest. On the other hand, negative $\gamma_{ARV\text{-}MPF}$ and LRSA emerged for the LRSA-F/D. Besides, the speed was the lowest and the torque was medium. In the LRSA-I/D, the speed was close to that of the HRSA-F/D and the torque was larger than those of the HRSA-F/D and LRSA-F/D. However, the large torque did not tightly link to the strength of muscle activity from the beginning of climbing. The muscle activity sufficiently linked to the torque and negative $\gamma_{ARV\text{-}MPF}$ did not appear with enough autonomic regulation for the HRSA-I/D. Contrary to expectation for TABs, the torque-assist was supporting HRSA, but it was sometimes not enough for muscle activity.



(a) positive $\gamma_{ARV\text{-}MPF}$



(b) negative $\gamma_{ARV\text{-}MPF}$

Fig. 1. Typical stroke pattern

TABLE 2
CHANGE IN MPF OF A STROKE FOR EACH CATEGORY

	MPF-*fh*	MPF-*sh*	MPF-*fh*	MPF-*sh*
	assist on (80)		assist off (23)	
after-L-corner	146.7±28.9	141.8±23.3	144.1±14.8	138.7±15.3
before-H-corner	145.4±29.7	141.5±25.4	143.7±14.5	137.6±10.2
	HRSA (61)		LRSA (42)	
after-L-corner	149.8±27.8	144.2±20.6	140.6±23.4	136.7±22.7
before-H-corner	148.3±29.6	142.6±23.0	140.3±22.2	137.6±22.7
	positive $\gamma_{ARV\text{-}MPF}$ (39)		negative $\gamma_{ARV\text{-}MPF}$ (64)	
after-L-corner	136.0±21.6	134.5±20.9	152.2±27.2	145.1±21.4
before-H-corner	134.3±20.0	133.2±19.6	151.6±28.7	145.1±23.7

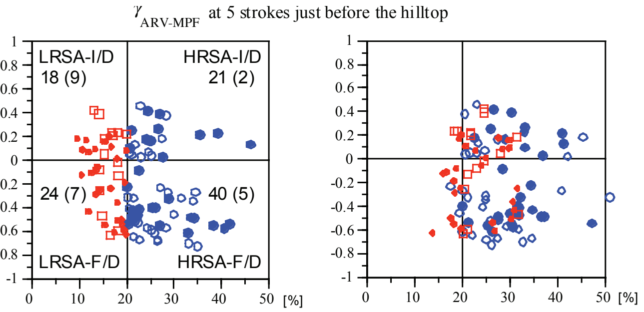
mean±sd [Hz]

TABLE 3
VEHICLE DATA AND INDICES OF PHYSICAL ACTIVITY

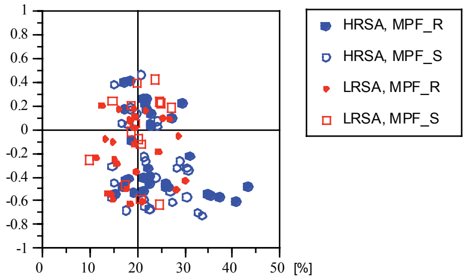
	HRSA_I/D	HRSA_F/D	LRSA_I/D	LRSA_F/D
speed [km/h]	18.3 ± 2.1	16.4 ± 2.4	16.2 ± 2.5	15.9 ± 2.2
torque [Nm]	31.0 ± 8.6	23.4 ± 7.1	29.2 ± 7.9	25.3 ± 6.1
γARV-MPF-LC	0.11 ± 0.23	-0.39 ± 0.22	0.39 ± 0.22	-0.31 ± 0.25
γARV-MPF-HC	0.19 ± 0.33	-0.47 ± 0.15	0.18 ± 0.11	-0.34 ± 0.21
γARV-trq-LC	0.70 ± 0.22	0.66 ± 0.31	0.55 ± 0.24	0.79 ± 0.10
γARV-trq-HC	0.66 ± 0.18	0.62 ± 0.33	0.66 ± 0.21	0.64 ± 0.22

Figure 2 shows a scatter graph of pr_{RSA} at each phase and $\gamma_{\mathrm{ARV\text{-}MPF}}$ just before the hilltop. The number of samples for each group was also displayed in (a) with the number of assist-off trials in parentheses. The percentage of assist-off trials was the highest in LRSA-I/D and the lowest in HRSA-I/D. Samples significantly varied in pr_{RSA} over three phases in a trial for the positive region of $\gamma_{\mathrm{ARV\text{-}MPF}}$. Other alternative indices such as $\gamma_{\mathrm{ARV}\text{-}trq}$ or the MPF difference at a stroke did not demonstrate this behavior in pr_{RSA}. In HRSA samples, pr_{RSA} decreased (b) just after climbing then recovered (c) during rest. In LRSA samples, pr_{RSA} increased unilaterally over these phases.

Note that there were two types of the variations in MPF samples at every stroke during climbing for consecutive trials: MPF samples remained (MPF_R) and sifted down (MPF_S) as a function of trial number. The variations in MPF samples did not correlate to $\gamma_{\mathrm{ARV\text{-}MPF}}$. The difference between $\gamma_{\mathrm{ARV\text{-}MPF}}$ and the variations in MPF samples was caused by the different intervals of interest. Thus, the time scale should be controlled for evaluating muscle fatigue.



(a) pr_{RSA} before climbing (c) pr_{RSA} during rest



(b) pr_{RSA} just after climbing

Fig. 2. Scatter graphs of pr_{RSA} at each phase and $\gamma_{\mathrm{ARV\text{-}MPF}}$ at 5 strokes just before the hilltop during climbing.

IV. DISCUSSION

During a series of repetitive exercise, the function of autonomic regulation is to support continuous exercise by controlling the cardiovascular system. Grouping by pr_{RSA} before climbing was reasonable for assessing physical activity in advance. Assistance created HRSA with an approximately 0.67 probability. Moreover, there were a few results of shifting from LRSA to HRSA following assist-on trials. Accordingly, torque-assist seems to enlarge the capacity of autonomic regulation, but did not sufficiently support muscle fatigue.

The pr_{RSA} before climbing decreased just after climbing for HRSA, especially in the positive $\gamma_{\mathrm{ARV\text{-}MPF}}$ region, whereas it still increased for LRSA (Fig. 2). These changes caused overlapping of the HRSA and LRSA samples in the scatter graphs. Therefore, the target zone of pr_{RSA} for customizing the assistance scheme is around 20%, that is, the threshold level for separating the two states. Thus, improving the property in HRSA-F/D would be effective for customizing the assistance scheme of TABs. In practice, for long-term repetitive cycling, a higher torque-assistance ratio would enlarge the capacity of autonomic regulation, and temporally changing the torque-assistance ratio for individuals is probably required for preventing muscular fatigue during climbing.

V. CONCLUSION

We studied variations in physical activity and vehicle performance during repeated cycling trials on a torque-assisted bicycle. Using the respiratory-sinus–arrhythmia-related power ratio, pr_{RSA}, measured before climbing, we categorized the physical activity into four groups for each trial with muscular-fatigue-related indices. Surveying several muscular-fatigue-related indices with different intervals of interest, we selected a scatter graph of pr_{RSA} at each phase and the correlation coefficient between amplitude and spectral variables of EMG signals just before the hilltop. The results showed that the torque-assist enlarged pr_{RSA}, but was not always effective for supporting muscle fatigue. Accordingly, monitoring the autonomic-regulation-related index and the muscular-activity-related indices for different timings and time scales in this scatter graph would be suitable for customizing a torque-assisted bicycle individually.

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