Manuscript title: Effects of acute static stretching on exercise efficiency during high-intensity cycling exercise

Running Title: Static stretching and cycling exercise

Akinori WAKI [1], Lu CHEN [1, 2], Kei HATANO [1], Takahiro YUNOKI [1, 3]

[1] Graduate School of Education, Hokkaido University, Sapporo, Japan; [2] Department of Microbiology, Wu Lien-Teh Institute, Harbin Medical University, Harbin, China;
[3] Department of Health and Physical education, Faculty of Education, Hokkaido University, Sapporo, Japan

*Corresponding author: Takahiro Yunoki, Department of Health and Physical education, Faculty of Education, Hokkaido University, Kita-11, Nishi-7, Kita-ku, 060-0811, Sapporo Japan
E-mail: yunoki@edu.hokudai.ac.jp

ABSTRACT

BACKGROUND: Static stretching has been shown to reduce exercise efficiency and performance of aerobic exercises as well as decreasing the ability to generate maximum muscle force in momentary movements such as jumping. As a mechanism for the reduced efficiency, the possibility that changes in muscle fiber recruitment occur to compensate for the decrease in maximum voluntary contraction (MVC) has been suggested. We examined whether the stretching-induced decrease in exercise efficiency is accompanied by a decrease in MVC and changes in electromyographic (EMG) activities of exercising muscles.

METHODS: Eight healthy subjects performed 6 min of cycling exercise at 70% of maximal oxygen uptake in the conditions with and without pre-exercise static stretching (stretching condition (SC) and control condition (CC)). MVC was measured before stretching maneuvers (or the resting period in CC) and after the end of exercise. In the 6-min exercise test, respiratory parameters and EMG activities of knee extensors were measured.

RESULTS: Oxygen uptake at 3 min and 6 min during the cycling exercise were higher in the SC than in the CC ($P<0.05$). There was no difference in MVC at the end of 6 min exercise between the two conditions. Similarly, there were no differences in EMG activities during the 6-min exercise between the two conditions.

CONCLUSIONS: The results suggest that pre-exercise static stretching reduces exercise efficiency independent of its negative effect on MVC exertional capacity.

KEY WORDS: Exercise; Oxygen consumption; Muscle contraction

Introduction

Static stretching is widely used as part of a pre-exercise warm-up routine with the aim of improving exercise performance [1] and preventing injuries [2]. However, it has been shown that pre-exercise static stretching can reduce skeletal muscle maximum force generation capacity (e.g., maximal voluntary contraction, MVC) [3-5] and performance of anaerobic exercise that requires MVC [6-8]. In addition, pre-exercise static stretching has been shown to induce a decrease in exercise efficiency (an increase in oxygen uptake ($\dot{V}O_2$)) during aerobic exercise [9, 10]. This suggests that pre-exercise static stretching can negatively affect not only anaerobic exercise performance but also aerobic exercise performance.

Esposito et al. [9] reported that $\dot{V}O_2$ during high-intensity constant-load cycling exercise (85% of maximal oxygen uptake ($\dot{V}O_{2max}$)) was greater in a condition with pre-exercise static stretching than in a control condition without pre-exercise static stretching. A similar phenomenon has been observed during incremental-load cycling exercise above the ventilatory threshold [10]. In those previous studies, MVC of knee extensors measured before the start of exercise was lower in the stretching condition than in the control condition, indicating the possibility that pre-exercise static stretching increased the relative force on the pedal and crank during cycling exercise. Therefore, Limonta et al. [10] proposed the hypothesis that pre-exercise static stretching increases recruitment of inefficient type II fibers to compensate for the decreasing force output, resulting in the decrease in exercise efficiency during high-intensity cycling exercise. However, in those studies [9, 10], it was not determined whether the pre-exercise static stretching actually affects muscle fiber recruitment during the main exercise. In addition, it is unclear whether the effect of pre-exercise static stretching on MVC continues even during exercise. The decrease in MVC after static stretching has been reported to recover within 10 min [5]. Therefore, the possibility that the stretching-induced reduction of exercise efficiency is unrelated to MVC cannot be ruled out.

Therefore, in this study, in order to determine whether changes in MVC and recruitment of muscle fibers are involved in the stretching-induced reduction of exercise efficiency, we measured MVC of the exercising muscle before and immediately after 6-min high-intensity cycling exercise in the conditions with and without pre-exercise static stretching. Furthermore, if pre-exercise static stretching changes muscle fiber recruitment, it might be reflected in electromyogram (EMG) activities during exercise. Thus, in addition to MVC, EMG activities of knee extensors during the 6-min exercise were also measured. We hypothesized that pre-exercise static stretching induces a decrease in exercise efficiency during exercise along with a decrease in MVC and changes in EMG activities.

Materials and methods

Eight male healthy subjects participated in the study. Their mean (SD) age, height, weight, and $\dot{V}O_{2max}$ were 21±0.6 years, 170±2.1 cm, 63±2.4 kg, and 3003±87.2 ml/min respectively. Prior to participation in the study, each subject was fully informed of the experimental procedures and potential risks involved, and then they provided informed consent. The subjects were instructed to abstain from strenuous physical activity, drinking alcohol, and taking caffeine for 24 h prior to each test and experiment. This study was approved by the Human Research Ethics Committee of the Faculty of Education, Hokkaido University. Each subject participated in two experiments — a preliminary experiment and a main experiment (Figure 1) — at least two days apart.

Preliminary experiment

On the first day, a preliminary experiment was performed to confirm the effect of static stretching protocol implemented in the present study on MVC and flexibility. MVC by isometric knee extension (5 sec) was measured three times at 1-min intervals. One minute after the MVC measurement, the heel-to-buttock distance (HBD) was measured to assess the flexibility of the knee extensors. Measurements of MVC and HBD were performed before and after static stretching (Figure 1).

Thirty minutes after the MVC and HBD measurements, each subject performed an incremental-load exercise test in order to determine the load intensity of the cycling exercise in the main experiment. The incremental rate was set to 20 W/min, and the exercise load was increased until the subject could not maintain the required pedaling frequency (60 rpm). The exercise load when $\dot{V}O_2$ measured every 10 sec showed the maximum value ($\dot{V}O_{2max}$) was defined as the maximum work rate (W_{max}). A recumbent bicycle ergometer (Strength Ergo 240; Mitsubishi Electric Corp., Japan) capable of leg pedaling without using upper limbs was used in the preliminary and main experiments.

Main experiment (6-min cycling exercise test)

The main experiment was carried out approximately one week after the preliminary experiment. In the main experiment, after measuring MVC and HBD by the same procedure as that in the preliminary experiment, static stretching (stretching condition (SC)) or maintaining a resting state (control condition (CC)) was carried out (Figure 1). The duration for which static stretching was performed and the duration for which a resting state was maintained were the same (27 min 20 s). Four min (moving: 1 min, resting: 3 min) after the end of the static stretching or resting state, each subject performed constant-load cycling exercise at the intensity of 70% W_{max} (60 rpm) for 6 min. In this experiment, respiratory variables and EMG activities of the knee extensors were measured from 3 min before the start of exercise until the end of exercise. Immediately after the end of the exercise, MVC and HBD were measured again. Each subject visited to the laboratory twice, at least two days apart, and performed the cycling exercise test in each condition. Four of the eight subjects performed the SC first and the other four subjects performed the CC first.

Stretching protocol

Based on previous studies [9, 10], muscles in both lower limbs (knee flexors, ankle plantar flexors, hip extensors, knee extensors, hip flexors) were passively stretched for 45 sec each, for a total of three sets. The order in which each muscle was stretched was fixed. Each muscle was slowly stretched at the joint angle just before the pain threshold without recoil. The interval between stretches of each muscle was 10 s, and the total duration of the stretching protocol was 27 min and 20 sec.

Maximum voluntary contraction (MVC)

The subjects were instructed to keep a seated position at a knee angle of 90° on a custom-built chair with a backrest board and to perform isometric knee extension with the right leg with full force for 5 seconds. This trial was repeated 3 times at 1-min intervals, and the average of the three maximum muscle forces was defined as MVC. The force signal measured by a load cell (LC1205 - K500; A&D Company, Japan) was transmitted via a digital indicator (AD-4532A; A&D Company, Japan) and converted into a digital signal at a sampling rate of 2 kHz using an analog-digital converter (MacLab/8s, AD Instruments, Australia).

Heel-to-buttock distance (HBD)

To assess the flexibility of knee extensors, a test for measurement of heel-to-buttock distance (HBD) was performed. The shortest distance from the heel to the buttock while the subject flexed the knee joint maximally in a prone position was measured as an index of the flexibility of the knee extensors. In order to avoid a stretching effect of multiple measurements, only one measurement was taken.

Electromyogram (EMG)

A surface EMG was recorded via a bipolar EMG sensor electrode (interelectrode distance of 20 mm; SX 230; Biometrics Ltd., UK) positioned over the muscle belly of the vastus lateralis（VL）and rectus femoris (RF) of the right leg during MVC measurement and cycling exercise in the main experiment. The ground electrode was placed over the styloid process of the right wrist. The EMG signal was amplified using an amplifier imbedded in the EMG sensor (bandwidth of 20-450 Hz; common mode rejection ratio > 96 dB; input impedance > $10^{13}\Omega$; gain = 1000) and converted into a digital signal at a sampling rate of 2 kHz using the analog-digital converter described above. Then EMG data were processed offline using analysis software (LabChart 7, ADInstruments, Australia). Raw data were filtered using a band-pass filter with cutoff frequencies of 10 and 180 Hz for later analysis. The filtered data were used to assess integrated EMG (iEMG) and mean power frequency（MPF）. The iEMG and MPF during 6 min of cycling were calculated every 1 pedal revolution over 30 s from 2 min 30 s to 3 min (as 3-min values) and from 5 min 30 s to 6 min (as 6-min values) after the start of cycling exercise, respectively, and the data obtained for each 30 revolutions were averaged. By checking the crank angle recorded during cycling, iEMG and MPF were calculated during the knee extension phase (right side) during each pedal rotation. The iEMG during cycling was standardized by the iEMG obtained during MVC exertion.

Gas exchange variables and ventilation

In the main experiment, oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and inspired ventilation ($\dot{V}I$) were measured by the breath-by-breath method using a respiratory gas analyzer (AE-310S, MINATO, Japan). The flow meter and gas analyzers were calibrated prior to each test with a standard 2-l syringe and precision reference gas (O_2: 15.38%, CO_2: 5.132%). The breath-by-breath data were averaged over 30 s before the start of cycling (as the resting value) and over 30 s from 2 min 30 s to 3 min (as 3-min values) and from 5 min 30 s to 6 min (as 6-min values) after the start of cycling exercise.

Statistical analysis

The SPSS (v20) statistical package was used for data analysis. Normality of the data was checked using the Shapiro-Wilk test. In the present study, parametric tests were used for statistical analysis of all data except RF iEMG (6-min values), which did not show normality. In the preliminary experiment, a paired t-test was used to compare MVC or HBD before and after stretching. In the main experiment, differences in variables (MVC, HBD, respiratory parameters, EMG parameters) between the two conditions (SC and CC) with time were evaluated by two-way repeated-measures ANOVA. When ANOVA revealed a significant interaction or a main effect, the paired t-test was used to examine the effect of time or condition. For RF iEMG, the Wilcoxon signed-rank test was used. The magnitude of the changes in variables was expressed as the standardized effect size (ES, Cohen's d). All data are reported as the mean ± standard deviation. Statistical significance was set at $P < 0.05$.

Data availability

The data associated with the paper are not publicly available but are available from the corresponding author upon reasonable request.

Results

Flexibility of knee extensors

In the preliminary experiment, HBD after stretching (8.7±2.9 cm) was significantly lower than that before stretching (11.1±2.8 cm; P = 0.003, ES=0.846), indicating an increase in the flexibility of knee extensors induced by the stretching. In the main experiment, there was a significant interaction (P=0.007) between condition effect (P=0.532) and time effect (P=0.560). As shown in Table 1, HBD immediately after the end of the 6-min exercise showed a significantly lower value in the SC than in the CC (P=0.045, ES=0.265).

MVC

In the preliminary experiment, MVC after stretching (494±156 N) was significantly lower than that before stretching (529±168 N; P<0.037, ES=0.217). In the main experiment, as shown in Table 1, no significant interaction (P=0.614) or condition effect (P=0.678) was found, but there was a significant time effect (P=0.011).

EMG parameters

Figure 2 shows the changes in MPF and iEMG measured in the main experiment. There was no significant main effect or interaction for both EMG parameters.

Respiratory parameters

Figure 3 shows the changes in respiratory parameters during 6-min exercise in the two conditions of the main experiment. As shown in Figure 4, Two-way ANOVA (condition: CC and SC; time: rest, 3 min, and 6 min) showed significant main effects (condition: P=0.002, time: P<0.001) and interaction (P=0.031) for $\dot{V}O_2$. Although there was no significant difference in $\dot{V}O_2$ at rest between the two conditions, $\dot{V}O_2$ values in the SC were significantly higher at 3 min (2342±209 ml/min) and 6 min (2603±229 ml/min) during exercise than those (2241±242 ml/min and 2468±235 ml /min) in the CC (3 min: P=0.002, ES=0.446; 6 min: P=0.015, ES=0.580). Regarding $\dot{V}CO_2$ and $\dot{V}I$, ANOVA showed no significant interaction, but there were significant main effects of time and condition. There was no significant difference in $\dot{V}CO_2$ at rest between the two conditions, but $\dot{V}CO_2$ values in the SC were significantly higher at 3 min (2807±239 ml/min) and 6 min (2902±258 ml/min) during exercise than those (2635±378 ml/min and 2690±334 ml/min) in the CC (3 min: P=0.018, ES=0.543; 6 min: P=0.015, ES=0.711). While there was no significant difference in $\dot{V}I$ at rest between the two conditions, $\dot{V}I$ in the SC was significantly higher at 3 min (69.8±8.5 l/min) during exercise than that (64.0±8.5 l/min) in the CC (P =0.020, ES=0.685). $\dot{V}I$ at 6 min during exercise tended to be higher in the SC (76.8±14.0 l/min) than in the CC (70.0±6.5 l/min) (P = 0.077, ES=0.695).

Discussion

The main results of the present study were as follows: (1) there was no significant difference in MVC measured immediately after the end of the 6-min exercise between the SC and CC and (2) $\dot{V}O_2$ values at 3 and 6 min during the 6-min exercise were significantly higher in the SC than in the CC. These results indicate that pre-exercise static stretching increased $\dot{V}O_2$ during a high-intensity cycling exercise independent of the ability to exert MVC. These findings do not support our hypothesis that stretching-induced impairment of exercise efficiency is due to a decrease in MVC.

Flexibility of knee extensors

From the significant decrease in HBD observed in the preliminary experiment, it was confirmed that the stretching maneuvers implemented in the present study significantly improved the flexibility of knee extensors. Therefore, even in the main experiment, the stretching would have improved the flexibility of knee extensors before the start of the exercise. Since HBD at the end of the 6-min exercise showed a significantly lower value in the SC than in the CC (Table 1), the effect of pre-exercise stretching on muscle flexibility is considered to have persisted throughout the exercise.

Static stretching has been suggested to impair the stretching-shortening-cycle (SSC) function of the muscle tendon complex by reducing muscle stiffness [4, 11, 12]. SSC is a system that utilizes elastic energy stored at the moment of muscle extension during subsequent muscle shortening [13]. Therefore, increased muscle flexibility or decreased muscle stiffness with pre-exercise static stretching can lower exercise efficiency [12] by reducing SSC function. Indeed, the difference in HBD between the two conditions observed at the end of the 6-min exercise suggests that a decrease in exercise efficiency (increase in $\dot{V}O_2$) may have been caused by a decrease in SSC function. However, the observed difference in HBD was small (Table 1, ES=0.265). In addition, involvement of SSC function in cycling exercise is considered to be limited because cycling exercise, unlike running exercise [12], mainly involves concentric contractions [14]. Therefore, the results of the present study suggest that pre-exercise static stretching may lead to a decrease in exercise efficiency independent of a decrease in SSC function.

MVC and EMG activities

In the preliminary experiment, MVC significantly decreased after the stretching maneuvers. Therefore, as confirmed in previous studies [9, 10], even in the main experiment, it can be assumed that the stretching caused a decrease in MVC before the start of the exercise. Nevertheless, there was no significant difference in MVC measured immediately after the end of the 6-min exercise between the SC and CC. In the main experiment, a significant time effect (P=0.011) was observed, suggesting that although MVC decreased immediately after stretching in the SC, the ability to exert MVC decreased to the same extent in both conditions due to exercise-induced fatigue, at least by 6 min after the start of exercise. Thus, even though the decrease in MVC was comparable in both conditions, there was a significant difference in $\dot{V}O_2$ during exercise, suggesting that the stretching-induced decrease in exercise efficiency occurs independently of MVC.

As described in the Introduction, a previous study suggested that pre-exercise static stretching increases the recruitment of type II fibers to compensate for the decrease in MVC, resulting in a decrease in exercise efficiency during high-intensity cycling exercise [9]. Since type II fibers have a higher frequency of EMG power than that of type I fibers [15], we had expected that increased recruitment of type II fibers by pre-exercise static stretching would increase the MPF during cycling exercise in the SC. However, there was no difference in EMG activities between the two conditions (Figure 2). This may be related to the fact that there was no difference in MVC during exercise in both conditions.

With regard to EMG activities, it has been reported that there is a correlation between the incremental component of $\dot{V}O_2$ and the increase in iEMG [16] or MPF [17] during constant-load exercise. This suggests that an increase in the recruitment of muscle fibers may be involved in the decrease in exercise efficiency; however, in the present study, no difference in EMG activities was observed between the two conditions. Therefore, it is thought that the decrease in exercise efficiency due to pre-exercise static stretching can occur without changes in the recruitment pattern of muscle fibers.

Gas exchange variables and ventilation

$\dot{V}I$ values during the 6-min exercise tended to be higher in the SC than in the CC (Figure 3, 4). These results are consistent with the results of a previous study [18] showing that pre-exercise static stretching increased ventilation during prolonged cycling exercise. Static stretching has been reported to decrease the excitability of the spinal motor neuron pool that innervates the stretched muscle [4, 19]. In exercise under such conditions, if central motor command is increased to compensate for the decrease in spinal cord excitability, this may cause an increase in ventilation (the so-called central command theory of exercise hyperpnea). Furthermore, since the ventilatory response during cycling exercise has been reported to increase after exercise with eccentric contractions [20], an increase in afferent inputs from the stretched muscles to the respiratory center [21] might have increased $\dot{V}I$ during exercise in the SC. In any case, it is possible that pre-exercise static stretching increases ventilatory response during exercise, and increased ventilation results in increased O_2 consumption due to increased work of the respiratory muscles, resulting in decreased exercise efficiency. Hence, when calculating oxygen consumption of respiratory muscles using the estimation equation reported previously [22], the values at 3 min and 6 min during the 6-min exercise were 11.8 and 16.8 ml/min, respectively. These only account for 11.7% and 12.5% of the difference in $\dot{V}O_2$ between the two conditions (3 min: 101 ml/min, 6 min: 135 ml/min). Therefore, it is considered that the increase in respiratory muscle oxygen consumption associated with the increase in ventilation only explains a part (approximately 10%) of the decrease in exercise efficiency.

It has been shown in animal excised muscles that static stretching increases the non-insulin-dependent glucose uptake into muscle [23]. Furthermore, in type 2 diabetic patients, blood glucose levels have been reported to be decreased by 4 sets of static stretching of 30 sec [24]. In the present study, $\dot{V}CO_2$ during the 6-min exercise was higher in the SC than in the CC (Figure 4). Therefore, in the SC, pre-exercise stretching might have activated glucose metabolism during exercise, leading to an excessive increase in metabolic rate. Further research is needed to verify this mechanism.

Conclusions

$\dot{V}O_2$ during the 6-min high-intensity cycling exercise was significantly higher in the SC than in the CC. In contrast, there was no difference in MVC immediately after the exercise between the two conditions. Similarly, there were no differences in EMG activities during the exercise between the two conditions. These results suggest that pre-exercise static stretching reduces exercise efficiency during a high-intensity cycling exercise independent of its negative effect on MVC exertional capacity.

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Conflicts of interest. —The authors declare that they have no conflict of interest.

Authors' contributions. —AW and TY conceived and designed the research. AW, LC, KH, and TY conducted the research. AW and TY analyzed the data and wrote the manuscript. All authors read and approved the manuscript.

Table 1. Changes in HBD and MVC in the main experiment.

	Pre	Post
HBD (cm)		
control condition (CC)	10.2 ±3.4	10.6±3.7
stretching condition (SC)	10.6±3.7	9.7±3.4 #
MVC (N)		
control condition (CC)	481±144	428±105 *
stretching condition (SC)	496 ±129	430±129 *

Data are mean±SD.

HBD: heel-to-buttock distance; MVC: maximal voluntary contraction; pre: before stretching (or the resting period in CC); post: immediately after the end of 6-min exercise.

Significant difference vs. CC ($P<0.05$); * Significant difference vs. pre ($P<0.05$)

TITLES OF FIGURES

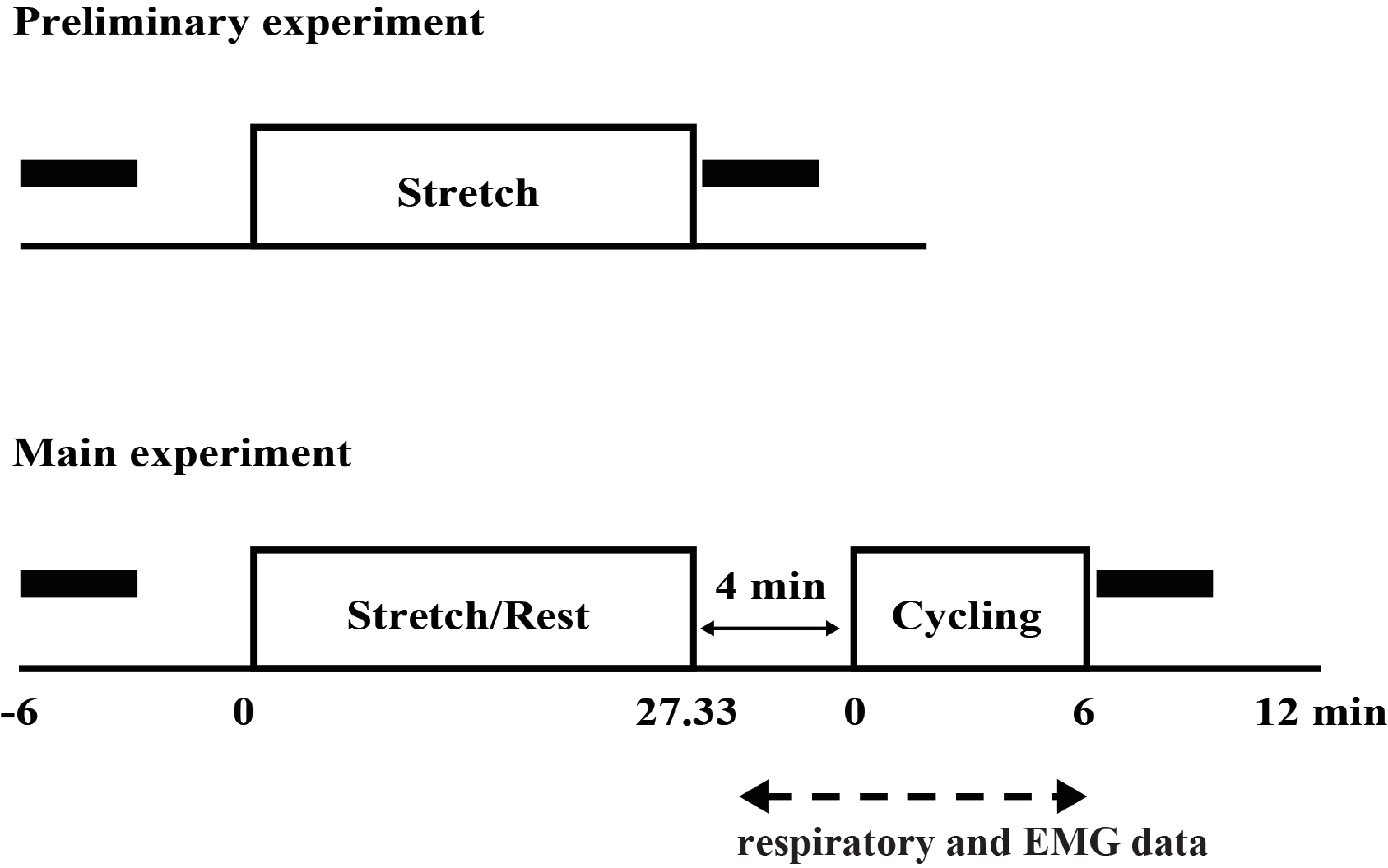
Figure 1.— Overview of the experimental protocol. The black horizontal bars indicate measurement timing of maximal voluntary contraction (MVC) and heel-to-buttock distance (HBD). HBD was measured 1 min after the MVC measurement. These measurements were performed approximately 6 min before and immediately after the stretch in the preliminary experiment, and approximately 6 min before the stretch (or rest) and immediately after the end of cycling exercise in the main experiment. Stretch represents static stretching. Rest represents resting in the supine position. Both periods were the same (27 min 20 sec). In the main experiment, each subject participated in both conditions (Stretch: stretching condition [SC] / Rest: control condition [CC]). Cycling exercise was performed for 6 min at 70% intensity of maximal oxygen uptake. In the main experiment, electromyographic activities of knee extensors and respiratory parameters were measured during the exercise.

Figure 2.— Electromyographic (EMG) activities at 3 min and 6 min during the 6-min cycling exercise in the control (white columns) and stretching (black columns) conditions of the main experiment. Data presented are mean±SD. VL: vastus lateralis, RF: rectus femoris, MPF: mean power frequency, iEMG: integrated EMG.

Figure 3.— Changes in oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and ventilation ($\dot{V}I$) during the 6-min cycling exercise in the control (white circles) and stretching (black circles) conditions of the main experiment. Data presented are mean±SD.

Figure 4.— Oxygen uptake ($\dot{V}O_2$), carbon dioxide output ($\dot{V}CO_2$), and ventilation ($\dot{V}I$) at rest and at 3 min and 6 min during the 6-min cycling exercise in the control (white columns) and stretching (black columns) conditions of the main experiment. Data presented are

mean±SD. * Significant difference vs. control condition ($P<0.05$).


Preliminary experiment
Stretch
Main experiment
Stretch/Rest
4 min
Cycling
-6
0
27.33
0
6
12 min
respiratory and EMG data

VL-MPF (Hz)
80
75
70
65
60
3 min
6 min
VL-iEMG (x 100%)
1.2
1
0.8
0.6
0.4
0.2
0
3 min
6 min
RF-MPF (Hz)
80
75
70
65
60
3 min
6 min
RF-iEMG (x 100%)
1.2
1
0.8
0.6
0.4
0.2
0
3 min
6 min

V̇O2 (ml/min)
3000
2500
2000
1500
1000
500
0
-60
0
60
120
180
240
300
360
V̇CO2 (ml/min)
3500
3000
2500
2000
1500
1000
500
0
-60
0
60
120
180
240
300
360
V̇I (l/min)
100
80
60
40
20
0
-60
0
60
120
180
240
300
360
Time (sec)


3000
2500
2000
1500
1000
500
0
V̇O2 (ml/min)
*
*
rest
3 min
6 min
3500
3000
2500
2000
1500
1000
500
0
V̇CO2 (ml/min)
*
*
rest
3 min
6 min
100
80
60
40
20
0
V̇I (l/min)
*
rest
3 min
6 min