Effects of Active Warm-up and Diurnal Increase in Temperature on Muscular Power

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ABSTRACT

RACINAIS, S., S. BLONC, and O. HUE. Effects of Active Warm-up and Diurnal Increase in Temperature on Muscular Power. *Med. Sci. Sports Exerc.*, Vol. 37, No. 12, 2134–2139, 2005. **Purpose:** To investigate the effects of both an active warm-up (AWU) and the diurnal increase in body temperature on muscular power. **Methods:** Eight male subjects performed maximal cycling sprints in the morning (7:00–9:00 a.m.) and afternoon (5:00–7:00 p.m.) either after an AWU or in a control condition. The AWU consisted of 12 min of pedaling at 50% of $\dot{V}O_{2max}$ interspersed with three brief accelerations of 5 s. **Results:** Rectal temperature, maximal force developed during the cycling sprint, and muscular power were higher in the afternoon than in the morning ($P < 0.05$). Rectal temperature, calculated muscular temperature, and muscular power were higher after AWU than in control condition ($P < 0.05$). **Conclusions:** The beneficial effect of an AWU can be combined with that of the diurnal increase in central temperature to improve muscular power. **Key Words:** CIRCADIAN RHYTHM, TIME OF DAY, ANAEROBIC EXERCISE, CYCLING SPRINT

The effect of time of day on short-term muscular performance in a neutral environment has been well documented. Maximal sprint performance shows a significant diurnal increase both when tests are conducted over an entire 24-h day (26) and when they are conducted during the daytime only (4,21). Muscular power is generally increased by the end of the afternoon, at the peak of the circadian temperature curve (9,26). Some studies have suggested that the simultaneous increases in central body temperature (from oral or rectal data) and muscular power are causally related because the diurnal increase in central temperature may have a beneficial passive warm-up (PWU) effect (4,18,20).

In parallel with the diurnal variation in central temperature, a variation in environmental temperature can also influence muscular power by a PWU effect. Indeed, Falk et al. (12) and Linnane et al. (15) demonstrated that muscular power (cycling sprint test) was greater in a warm environment than in a neutral environment. However, it was recently shown that the PWU effect of a warm environment increases muscular power in the morning, when the rectal temperature is at its lowest, but not in the afternoon, when it is at its highest (21). This suggests that the PWU effect of an increased central temperature and that of a warm environment cannot be combined to improve muscular power (21), possibly because of their similar effect on neuromuscular efficiency (22). These results point to a "ceiling," above which an increase in central temperature fails to improve muscular performance in a warm environment (22). This "ceiling" is in accordance with the recent results of Backx et al. (2) and Drust et al. (11), who observed no beneficial effect of a PWU (warm environment) on muscular power.

An active warm-up (AWU), however, differs from a PWU in that it engenders beneficial effects that do not depend on temperature (6) and that may thus be independent of the circadian variation in central temperature. Interestingly, an AWU was shown to increase muscular power more than a PWU (19). We thus hypothesized that an AWU would enhance muscular power beyond the beneficial effect of the diurnal increase in central temperature.

The purpose of this study was to determine whether the increases in cycling sprint performance previously observed with either an AWU (25) or the diurnal increase in central temperature (4,21,26) are cumulative.

METHODS

Subjects. Eight male physical education students gave written consent to participate in this study after receiving a

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thorough explanation of the protocol. The study was approved by the appropriate ethics committee. The mean age, height, body mass, and maximal oxygen consumption ($\dot{V}O_{2max}$) of the subjects were 27 ± 8 yr, 1.76 ± 0.06 m, 68.3 ± 10 kg, and 43.1 ± 8.9 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively. All the subjects were moderately active (physical activity: 7 ± 3 $h \cdot wk^{-1}$). Only men were studied in order to avoid interaction with the menstrual cycle in female subjects. Moreover, all the subjects were classified as "neither type" (score range from 42 to 55) from their responses to the self-assessment questionnaire of Horne and Östberg (14), which determines morningness–eveningness.

Experimental procedure. In the first session, their $\dot{V}O_{2max}$ was measured and they were familiarized with the test procedures. The four following test sessions were held in random order. Two of them were conducted in the morning (7:00–9:00 a.m.) and two in the afternoon (5:00–7:00 p.m.) with either an active warm-up (AWU) or in control condition (CC). The laboratory conditions were recorded with an electronic thermometer–hygrometer (Novo 16755, Novo, France, precision 0.1°C) and were 21.5 ± 0.7°C and 65.5 ± 3% for temperature and humidity, respectively. The subjects were instructed to avoid any kind of strenuous activity for 24 h before each test, to sleep normally, and to wear the same sportswear and shoes for every test.

First session. Subjects were seated at rest and were asked to complete the morningness-eveningness questionnaire (14). If a subject i) was in good health, ii) did not have a marked chronotype, and iii) agreed to follow all instructions concerning sleep, alimentation, and activity, he was included in the study. Once included, all subjects performed an incremental test on an electromagnetic cycle ergometer. The test began by with a 3-min warm-up at 70 W followed by a continuous incremental test with 1-min steps. The intensity increment was 30 W and the test was performed until exhaustion. During the test, expired gases were recorded by a breath-by-breath analyzer (Vmax 229 D series, Sensormedics Corp., Yorba Linda, CA) in order to determine the $\dot{V}O_{2max}$ of each subject. The attainment of $\dot{V}O_{2max}$ was based on the attainment of a $\dot{V}O_{2max}$ plateau, a respiratory exchange ratio higher than 1.1, and the subject's exhaustion (impossibility to continue despite verbal encouragement). This test was followed by rest and hydration *ad libitum*. When ready, the subjects familiarized themselves with the experimental procedure that would be followed in the next four sessions.

Test sessions. The four test sessions took place in random order on different days within the limit of 1 wk. Each test session began with 1 h of rest in the seated position. Rectal temperature (T_{rect}) and cutaneous temperature above m. quadriceps femoris (T_{skin}) were then measured with a rectal probe (YSI 402, Yellow Springs Instruments, OH, insertion depth 15 cm) and a cutaneous probe (YSI 409B, Yellow Springs Instruments), respectively. The muscle temperature (T_{musc}) was estimated from the skin temperature as follows: $T_{musc} = 1.02 \times T_{skin} + 0.89$ [correlation with muscle temperature $r^2 = 0.98$, (8)]. The subjects were then seated on the electromagnetic cycle ergometer and the warm-up procedure began.

In order to reduce the risk of injury and to ensure similarity with previous studies (18,20,21), the CC condition began with 3 min of pedaling at 70 rpm at 50% of the $\dot{V}O_{2max}$. The WU condition consisted in 12 min of pedaling at 50% of $\dot{V}O_{2max}$, with brief 5-s accelerations at 4, 7, and 10 min. During the warm-ups, oxygen consumption was continuously monitored and the braking load was adjusted to maintain a relative intensity corresponding to 50% of each subject's $\dot{V}O_{2max}$. The same electromagnetic cycle ergometer and gas analyzer were used for the incremental test and the four test sessions. After warming up, the subjects rested for 5 min before starting the first sprint. Maximal cycling sprints were performed 5, 10, and 15 min after the end of the warm-ups on a friction-loaded cycle ergometer (Monark 824E, Stockholm, Sweden) specially adapted for sprint exercise. Temperatures were recorded every 3 min during the warm-ups and at 4, 9, 14, and 19 min of the cycling tests. The timing of the entire protocol (especially recovery time, measurement, and sprint start) was controlled by software developed in our laboratory with a LabVIEW interface (LabVIEW, National Instruments, TX).

Cycling sprint and calculation. The test consisted of a maximal sprint lasting approximately 7 s against a friction resistive load set at 60 $g \cdot kg^{-1}$ body mass applied on the periphery of the flywheel. The subjects were instructed to accelerate as fast as possible while remaining in the seated position and were strongly and similarly encouraged during all test sessions. The cycle was equipped with toe clips to prevent the subject's feet from slipping. All sprints were accompanied by a countdown and were performed from the same foot-start position.

The total force developed by the subject was calculated from both the force developed against the friction load (constant) and the force developed against inertia to accelerate the flywheel (calculated following the method of Martin et al. (17)). The velocity was recorded every 8° of pedal revolution by a photoelectric cell and a disk with alternating blind and clear portions. The power output was calculated by multiplying the velocity by the total force per pedal revolution. The data were collected by an acquisition card (DAQ-Pad 6020E, National Instruments) and analyzed by software developed in our laboratory with a LabVIEW interface (LabVIEW, National Instruments).

Maximal power (P_{max}), maximal force (F_{max}) and maximal velocity (V_{max}) were calculated from the pedal revolution with the highest power development, the highest force production and the fastest velocity, respectively. The F_{max} is generally obtained at the start of the sprint, when the subject develops a high force in order to initiate the rotation of the flywheel from a standstill position (very low velocity), whereas the V_{max} is generally obtained at the end of the sprint.

Statistical analysis. Each variable was tested for normality using the skewness and kurtosis tests with acceptable *Z* values not exceeding +1 or −1. Once the assumption of normality was confirmed, parametric tests could be per-

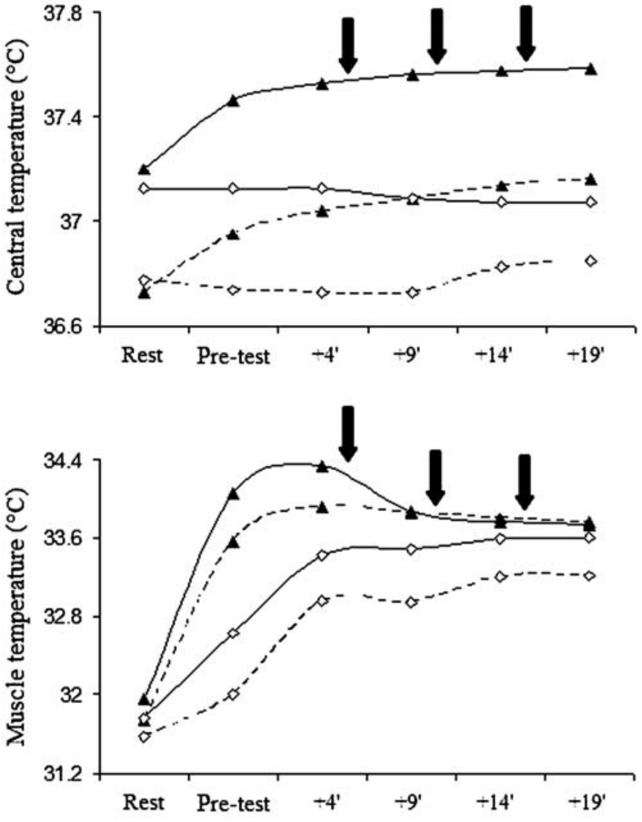

FIGURE 1—Mean values of central temperature (upper graph) and muscle temperature (bottom graph) at rest (Rest), at the end of the warm-ups (CC vs AWU) and during the test period (at 4, 9, 14, and 19 min). ***Downward arrow*****, cycling sprint test;** ***solid line*****, afternoon values;** ***dashed line*****, morning values;** ***closed triangle*****, AWU condition;** ***open diamond*****, CC.**

formed. The effects of time of day, an AWU, and recovery time were verified by a three-way ANOVA with repeated measures (ANOVA 2R*2R*3R, time of day * warm-up procedure * sprint repetition). This analysis revealed the global effect of time of day, the global effect of the warm-up procedure, and the effect of the interaction between time of day and the warm-up procedure. Data are displayed as mean ± SD and the statistical significance was set at $P < 0.05$.

RESULTS

The temperature values are displayed in Figure 1. The values of P_{max} and both F_{max} and V_{max} are shown in Figures 2 and 3, respectively. Table 1 summarizes the variations observed in percentage of variation.

Warm-up and temperature parameters.

Warm-up was performed with a mean intensity of 50.4 ± 5% of the subjects' $\dot{V}O_{2max}$. At this intensity, the mean power developed for the AWU was 122 ± 19 and 123 ± 18 W in the morning and afternoon, respectively.

The mean values of T_{rect} temperature at rest were significantly lower in the morning than in the afternoon (36.7 ± 0.2 vs 37.2 ± 0.2°C, $P < 0.01$]. Furthermore, T_{rect} increased from rest to the end of the warm-up in AWU ($P < 0.01$) but not in CC. Consequently, T_{rect} remained higher in the afternoon than in the morning throughout the experiment ($P < 0.01$) and was significantly higher during the cycling sprint in AWU than in CC ($P < 0.01$, Fig. 1).

TABLE 1. Percentage of variation in T_{musc}, T_{rect}, P_{max}, V_{max}, and F_{max} with both time of day and the performance of an AWU.

	Afternoon vs Morning	AWU vs CC
$T_{central}$ (rest)	+1.3% ($P < 0.01$)	NS
$T_{central}$ (after warm-up)	+1.3% ($P < 0.01$)	+0.8% ($P < 0.01$)
T_{musc} (rest)	NS	NS
T_{musc} (after warm-up)	NS	+4.8% ($P < 0.01$)
P_{max}	+4.5% ($P < 0.05$)	+3.7% ($P < 0.05$)
F_{max}	+3.8% ($P < 0.05$)	NS
V_{max}	NS	+3.1% ($P < 0.05$)

NS, not significant.

The estimated T_{musc} failed to show a diurnal variation but was significantly higher during the cycling sprint in AWU than in CC ($P < 0.01$, Fig. 1).

Muscular power parameters. The P_{max} developed for the cycling sprint was significantly higher in the afternoon than in the morning and in AWU than in CC ($P < 0.05$, Fig. 2). There was no significant interaction between these two factors.

Time of day significantly enhanced F_{max} ($P < 0.05$), whereas AWU significantly enhanced V_{max} ($P < 0.05$, Fig. 3).

The P_{max}, F_{max}, and V_{max} failed to be significantly influenced by the timing of the sprint repetition (sprints 1, 2, and 3 performed 5, 10, and 15 min after the end of the warm-up, respectively).

DISCUSSION

The major finding of this study was a significant increase in muscular power both with time of day and with an active warm-up, with no interaction effect between these two factors. Our results showed that an AWU improves P_{max} regardless of the diurnal increase in central temperature.

Methodology. The times of testing were chosen with regard to the data of the literature. For example, Bernard et al. (4) showed that cycle sprint power was significantly higher at 6:00 p.m. than at 9:00 a.m.

The cycling tests in the control condition were performed after 3 min of cycle ergometer exercise for several reasons.

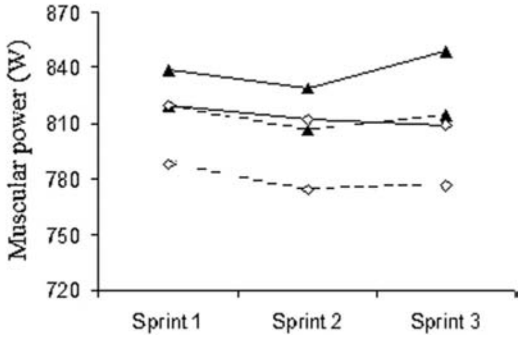

FIGURE 2—Mean values of muscular power were improved both by time of day (afternoon values (*solid line*) vs morning values (*dashed line*), $P < 0.05$) and by the performance of an AWU (AWU condition (*closed triangle*) vs CC (*open diamond*), $P < 0.05$).

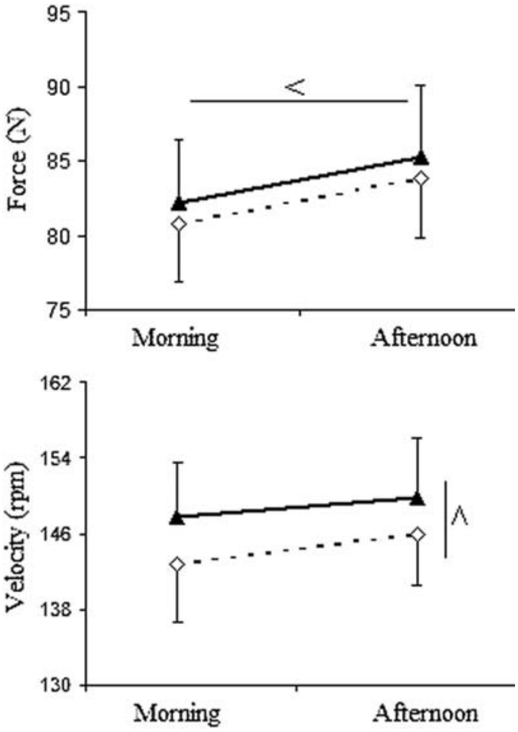

FIGURE 3—The maximal force developed during the cycling sprints (upper graph) was increased by time of day (afternoon values vs morning values, <$P < 0.05$), whereas the velocity attained during the cycling sprints (bottom graph) was increased by the performance of an AWU (AWU condition (*closed triangle*) vs CC (*open diamond*), $P < 0.05$). Data in mean ± SD.

Three minutes of cycling corresponds to the control procedure that has generally been used (20) and was the protocol used in a study that revealed a significant diurnal increase in cycling muscular power (18). Most importantly, the purpose of the present study was to determine whether the effect of an AWU depends on the diurnal increase in T_{rect}, as was observed for the effect of a PWU (warm environment (21)): we thus needed to use the same control procedure as in this last study. Concerning the AWU procedure, our AWU lasted 12 min because rectal temperature increases after 3–5 min of exercise and stabilizes after a minimum of 10 min (24) as a function of the environmental conditions and the exercise intensity. Our AWU intensity was 50% of $\dot{V}O_{2max}$ because it has been shown that a warm-up intensity higher than 60% of $\dot{V}O_{2max}$ could alter performance during a subsequent cycling sprint (25). Finally, in line with the reports in the literature, the subjects were allowed a 5-min recovery between the end of the warm-up and the first sprint (6,25).

The cycle ergometer test has been used to show increases in muscular power after an AWU (25) and with time of day (4,13,18). Moreover, by determining the cycling sprint power in a single exercise, we were able to calculate the real power integrating flywheel inertia, which is underestimated with the traditional force–velocity test (17). The braking resistive force applied on the flywheel was set at 60 $g \cdot kg^{-1}$ of body mass on the basis of previous results showing that a load between 50 and 75 $g \cdot kg^{-1}$ of body mass is suitable for the determination of maximal power in young adults (10).

The sample size of this study (i.e., eight subjects) could be responsible of nonsignificant variations in statistical values; however, our data show that our sample size was sufficient enough to verify our hypothesis (with $\alpha < 0.05$). Statistical data revealed that the differences in the mean values of power among the different levels of both time of day ($F_{1,7} = 5.738$, $P < 0.05$) and warm-up ($F_{1,7} = 8.368$, $P < 0.05$) were greater than would be expected by chance. Statistical data also revealed that both the difference in the mean values of F_{max} among the different times of day ($F_{1,7} = 6.591$, $P < 0.05$) and the differences in the mean values of V_{max} among the warm-up conditions ($F_{1,7} = 8.113$, $P < 0.05$) were greater than would be expected by chance.

Diurnal increase in P_{max} and F_{max}. In line with previous work (4,18,21,26), our results displayed a significant diurnal increase in P_{max} during a cycling sprint exercise. Several factors could explain this increase. Mathematically, power is the product of force multiplied by velocity. The data regarding the optimal velocity for P_{max} during a force–velocity test on cycle ergometer are conflicting. Bernard et al. (4) observed no diurnal variation in optimal velocity, whereas Souissi et al. (26) observed a significant circadian rhythm probably linked to the time of testing (daytime for Bernard et al. (4), the entire circadian cycle including night for Souissi et al. (26)). Our results (obtained during the daytime as for Bernard et al. (4)) *failed to* show a significant variation in V_{max} between morning and afternoon. In contrast, the data on force production revealed the significantly lower values of isometric force in the morning than in the afternoon, and these findings were reproducible between studies (7,22). Moreover, our results showed a significant diurnal increase in the F_{max} (Fig. 3, Table 1), which is generally attributed to a variation in muscle contractile properties rather than to a variation in central nervous command (16,22). The effect of time of day on muscle contractile properties could be attributed in part to intracellular variations in the muscle (e.g., a circadian variation in inorganic phosphate concentration, as suggested by Martin et al. (16)) and/or in part to the circadian rhythm in central temperature (which could influence calcium release by the sarcoplasmic reticulum, as suggested by Racinais et al. (22)).

This second theory suggests that the diurnal increase in central temperature could be considered as a PWU (21,22). Indeed, the circadian rhythm in central temperature has been considered to be the cause of the circadian variation in muscular power (4,18). In agreement, our results showed a significant diurnal increase in T_{rect} at rest. As did Reilly and Brooks (23), we observed a persistence of this diurnal variation after exercise and during recovery (Fig. 1). However, Asmussen and Boje (1) suggested that muscle temperature influences muscular performance more than central temperature, which was recently confirmed after both PWU and AWU. Concerning PWU, Falk et al. (12) observed an increase in P_{max} with a change in local temperature due to warm environment but no change in rectal temperature. Concerning AWU, Stewart et al. (27) observed an increase in P_{max} following an AWU that increased both skin and muscle temperatures but not aural temperature. This suggests that a variation in muscle temperature accounts for the diurnal increase in P_{max} more than a variation in central temperature. But, because our results failed to show a significant diurnal variation in estimated T_{musc} (Table 1, Fig. 1), the effect of time of day (and of the variation in T_{rect}) on P_{max} could be different from the effect of an increase in T_{musc}. However, our T_{musc} values were estimated from the skin temperature of height subjects. As a consequence, from our data, it is impossible to conclude about the absence of a possible influence of the circadian rhythm on muscle temperature. To our knowledge, the circadian variation in T_{musc} has never been recorded and future study will be needed to describe this phenomenon.

Warm-up effects on P_{max} and V_{max}. In this study, our results showed that i) the values of both T_{rect} and T_{musc} (Fig. 1) and ii) the values of P_{max} (Fig. 2) were higher in the AWU condition than in the CC condition. It is generally considered that most of the effects of an AWU are dependent on the temperature increase (for a review, see 6). However, Drust et al. (11) failed to observe an effect of a warm environment on P_{max} despite a significant increase in T_{rect} and T_{musc}. Moreover, it has been shown that a warm environment increases muscular power in the morning only, when central temperatures are at their lowest level (21). This points to the existence of a "ceiling" after which power does not increase even though central temperature does (22). Interestingly, our results showed that the AWU increased P_{max} in both the morning and afternoon (Fig. 2), independently of the initial central temperature. This suggests that factors other than temperature increase P_{max} after an AWU. Indeed, the beneficial effects of an AWU are not only dependent on the temperature increase (6) because decreased muscle and joint stiffness are caused notably by the breaking of the stable bonds between actin and myosin filaments (28).

Moreover, our results suggest that the beneficial effects of the diurnal increase in central temperature and AWU occur through different mechanisms. Indeed, our results showed a significant increase in F_{max} from morning to afternoon (see above), whereas we observed a significant increase in V_{max} from the CC to AWU conditions. The finding that an AWU improved V_{max} but not F_{max} agrees with previous observations concerning the effect of T_{musc} on muscular performance. In this study, estimated T_{musc} was higher in AWU than in CC (Fig. 1, Table 1). Researchers have generally reported no effect of increasing T_{musc} above normal on isometric force (5). Despite no changes in the maximum isometric strength, Stewart et al. (27) observed a significant increase in maximal power after AWU. This observation could be explained by an improved maximal shortening velocity and concomitant changes in the force–velocity relationship with the increase in T_{musc} (3). But it seems erroneous to conclude that there is no effect of AWU on force. We can suggest that this effect could be significant with a larger sample size. Despite the practical interest regarding AWU, very few data are available on this topic.

Implications and applications of the findings. In spite of the beneficial effect of the active warm-up, our data confirm that maximal power is lower in the morning than in the evening. Several practical recommendations arise from this result. First, we suggest that time of testing has to be controlled and specified in future studies involving brief muscular exercise performance. Second, we also suggest that athletes should practice an AWU at any time of day in order to improve their short-term dynamic performance. Third, previous results showed that a PWU improves muscle contractility (22) in the morning only and blunts the diurnal variation in muscle power (20,21). This raises important questions concerning the use of both a PWU and AWU performed together in order to enhance muscular power, especially in the morning. Further research is needed to investigate the beneficial effect of a PWU in the morning before performing an AWU.

Conclusions. Our results suggest that time of day enhances muscular power by increasing force, whereas an AWU failed to increase this parameter. The difference in mechanisms could be in part explained by three observations. First, an AWU has a stronger effect on T_{musc} than time of day. Second, the effects of an AWU are not completely temperature dependent. Third, the effects of time of day are not yet fully understood but are surely not only temperature dependent. The finding that the diurnal variation in muscular power persisted after an AWU was in accordance with the data of Callard et al. (7), who observed that muscular force varied with time of day both at rest without prior exercise and during a continuous submaximal physical exercise of 24 h.

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