HUMAN MOVEMENT
2015, vol. 16 (1), 36–41

EFFECT OF CADENCE ON RESPIRATORY RESPONSE DURING UNLOADED CYCLING IN HEALTHY INDIVIDUALS

doi: 10.1515/humo-2015-0025

AGNIESZKA D. JASTRZĘBSKA*, MARCIN KOWALSKI
University School of Physical Education, Wrocław, Poland

ABSTRACT
Purpose. The aim of the study was to establish the respiratory response to unloaded cycling at different cadences. **Methods.** Eleven healthy participants performed a maximal graded exercise test on a cycle ergometer to assess aerobic fitness (maximal oxygen consumption: 46.27 ± 5.41 ml · min^{-1} · kg^{-1}) and eight 10-min unloaded pedaling (0 W) bouts at a constant cadence (from 40 to 110 rpm). Respiratory data were measured continuously during each effort and then averaged over 30 s. Blood samples were collected before and 2 min after each effort to monitor changes in acid–base balance. **Results.** The efforts were performed at an intensity of 16.5–37.5% VO_{2peak}. Respiratory response was not differentiated in cadences of 40, 50, 60 rpm. From 70 rpm, an increase in cadence was significantly associated with increased minute ventilation ($F = 168.11$, $p < 0.000$) and oxygen consumption ($F = 214.86$ $p < 0.000$) and, from 80 rpm, respiratory frequency ($F = 16.06$, $p < 0.001$) and tidal volume ($F = 54.67$, $p < 0.000$). No significant changes in acid-base balance were observed as a result of difference cadences. **Conclusions.** Unloaded cycling at a cadence of 70 rpm or above has a significant effect on respiratory function and may be associated with the involvement of large muscle ergoreceptors (mechanoreceptors) stimulated by the frequency of muscle contractions.

Key words: breathing pattern, cycling, work rate, ergoreceptors

Introduction

The frequency of voluntary muscle contractions affects the physiological response to exercise. In particular, the effects of pedaling frequency on physiological response was and still is the subject of numerous studies, addressing issues such as optimal cadence [1, 2], pedaling efficiency [3–5], or entrainment of breathing frequency to cadence [6–8].

Overall, the body's response to exercise is dependent on the intensity and, concurrently, on the number and type of motor units recruited to complete a task. When exercise intensity is increased and requires greater force, motor unit recruitment and firing rate also increase [9]. With this, the type of muscle fibers activated as a result increased intensity is also changed, initially from slow twitch fibers (ST) with slow contraction times and a high resistance to fatigue to fast twitch fibers (FTa and FTb) that are more susceptible to fatigue. When analyzing the effects of exercising on a cycle ergometer, intensity is the product of external resistance (load) and cadence. Besides a higher contribution of FT fibers in response to increased load or cadence, changes in load and cadence also affect respiratory function and oxygen utilization [9, 10]. This is the result of changes in metabolic activity, which stimulate the respiratory center by chemoreceptors and metaboreceptors. While the above processes in moderate to vigorous physical activity are viable, it is not entirely clear what occurs during light intensity exercise such as in unloaded pedaling.

Stimulation of the respiratory system during exercise, including changes in minute ventilation, can occur via three mechanisms. The first involves neural control of respiratory function at the onset of physical activity. It has been hypothesized that there exists a parallel command structure of impulses originating from nervous system motor centers (brain cortex, hypothalamus, spinal structures), where a feed-forward mechanism stimulates the respiratory and locomotion systems [11, 12]. The second mechanism involves a neural impulse feedback loop from the exercising muscle [13–15]. The third mechanism is through the metabolic/chemical regulation of respiratory function, whose contribution is dependent on exercise intensity and momentary disturbances to the acid–base balance.

During exercise, ventilation is subject to change so as to meet increasing oxygen demands without increasing the physiological cost of the work performed. In light and moderate intensity exercise, this is met by a rise in minute ventilation although this is more of a function of increased tidal volume per breath than the frequency of breaths per minute [16]. However, further increased minute ventilation is coupled with additional changes to tidal volume and respiratory frequency (including inspiratory and expiratory time).

Besides the energy used to maintain an upright sitting position, the physiological cost of pedaling on a cycle ergometer without load is based solely on lower extremity locomotion. The aim of this study was to establish the effects of different cadences on respiratory response during

* Corresponding author.

unloaded ergometry. The lack of an external load can help identify the most optimal cadence that induces distinct exercise-based changes in the body without disturbing intrasystemic homeostasis.

Material and methods

Eleven male university students were recruited; they were not informed about the purpose of the study. Basic characteristics of the sample are presented in Table 1. Approval of the local research ethics committee was obtained and signed consent was provided by the participants after the study protocol was explained. All procedures were performed at the same ambient temperature, humidity (21°C and 55%, respectively), and time of day (± 1 h). The study involved nine visits to a university laboratory each separated by a two day interval.

The first visit had the participants complete a maximal graded exercise test on an Excalibur Sport cycle ergometer (Lode, Netherlands) to determine physical fitness level by measuring maximal oxygen uptake (VO_{2max}). Initial load was set at 50 W and increased every 3 min by an additional 50 W. The test was performed until volitional exhaustion or when no increase in VO_2 was observed with a concordant increase in load or minute ventilation.

The remaining eight visits involved testing the effects of cadence on respiratory response. On each visit, participants completed 10-min of unloaded pedaling (0 W) on the same cycle ergometer; cadence on the first visit was 40 rpm and progressively increased by 10 rpm to 110 rpm on the last visit. A threshold of 110 rpm was adopted in order to avoid the effects of inertia. Cadence was displayed and monitored on a RPM meter located on the front of the ergometer.

The composition of expired air on a breath-by-breath basis was analyzed 3 min before, throughout the 10 min of pedaling, and during a 10 min period of recovery with a K4b2 gas analysis system (Cosmed, Italy). The device was calibrated in accordance with the manufacturer's instructions. Measurements were taken of respiratory frequency (R*f*), tidal volume (VT), total respiratory time (T_{tot}), inspiratory time (T_i), expiratory time (T_e), oxygen uptake (VO_2), and minute ventilation (VE); data were averaged over 30 s. In order to assess changes in acid–base homeostasis, arterialized capillary blood was sampled before and 2 min after each effort and examined with a RapidLab 385 (Bayer, Germany) to monitor the partial pressures of oxygen (pO_2) and carbon dioxide (pCO_2) and concentrations of hydrogen ions (H^+) and bicarbonate anions (HCO_3^-). A LT400 blood analyzer (dr Lange, Germany) was used to examine changes in blood lactate concentration (BLa).

Data were analyzed with the Statistica 10.0 software package (StatSoft, USA). Variability in cadence and respiratory frequency was assessed by calculating the relative standard deviation (absolute coefficient of variation = 100**SD*/*M* [%]). The Shapiro–Wilk test was used to test the normality of the distribution.of the data. The effect of cadence on the physiological variables was analyzed using repeated measures analysis of variance (ANOVA). Results bearing statistical significance were analyzed post hoc with Tukey's honest significant difference (HSD) test. The results are presented as mean ± *SD*. Statistical significance was adopted at the 5% level.

Results

The results of the maximal graded exercise test (Table 1) show that the participants presented a moderate level of physical fitness. All of the physiological variables were within norms for males of this age.

The 10-min efforts were performed at an intensity from 16.5 to 37.5% VO_{2peak}, indicative that they were performed within the range of aerobic work and involved little metabolic change as evidenced by the blood test results. Analysis of the blood variables showed significant differences only in H^+ concentrations at cadences of 40 ($p < 0.03$) and 80 rpm ($p < 0.01$) and pCO_2 at 40 ($p < 0.01$) and 110 ($p < 0.01$) rpm. For pCO_2, this involved an increase of 2 mmHg at 40 rpm and a decrease of 1 mmHg

Table 1. Characteristics of the sample

	Age (years)	Body height (m)	Body mass (kg)	BMI	VO_{2max} (ml · min^{-1} · kg^{-1})	VE_{max} (l · min^{-1})	HR_{max} (bpm)
M ± *SD*	19.9 ± 0.8	178.9 ± 5.5	73.6 ± 7.6	22.9 ± 1.9	46.2 ± 5.4	118.7 ± 25.5	189.1 ± 8.4

Table 2. Changes in blood variables with increased cadence

	Cadence							
	40 rpm	50 rpm	60 rpm	70 rpm	80 rpm	90 rpm	100 rpm	110 rpm
ΔH^+ (nM)	1.10* ± 0.82	–0.57 ± 1.31	–0.18 ± 1.15	0.55 ± 1.54	–1.44* ± 1.46	0.18 ± 0.94	0.27 ± 2.24	0.69 ± 1.15
ΔHCO_3^- (mM · l^{-1})	–0.67 ± 1.27	–0.40 ± 1.08	–0.26 ± 0.56	0.19 ± 0.73	–0.49 ± 0.59	–0.31 ± 0.77	–0.31 ± 1.63	0.45 ± 0.90
BLa (mM)	2.25 ± 1.35	1.17 ± 0.95	1.0 ± 0.68	0.90 ± 0.69	1.04 ± 0.62	1.24 ± 0.76	1.13 ± 0.84	1.15 ± 0.83

ΔH^+ – difference in hydrogen ion concentration, ΔHCO_3^- – differences in bicarbonate anion concentrations pre- and post-exercise, BLa – blood lactate concentration post-exercise; * $p < 0.05$, a negative value denotes a decrease in concentration at 110 rpm. The remaining changes observed in pO_2, pCO_2, and H^+ were not statistically significant. Acute response to exercise was observed in the first minute of ergometer pedaling from 40 to 70 rpm and in the second minute from 80 to 110 rpm (Figure 1). Oxygen uptake in the first three tests (40, 50, 60 rpm) did not differ significantly and ranged from 541 ml · min^{-1} at 40 rpm to 597 ml · min^{-1} at 60 rpm. Only at a pedaling cadence of 70 rpm were significant differences in oxygen uptake noted compared with those recorded at 40 and 50 rpm. From 80 rpm, statistically significant differences were found when comparing measures with those recorded at lower cadences.

Variability in cadence and respiratory frequency was evaluated by calculating the relative standard deviation. Variability in cadence was 3.5% and similar to the values reported by Kohl et al. [6]. From 40 rpm, variability gradually decreased to 1.1% at 70 rpm, then rose to 1.8% at 80 rpm and 2.8% at 90 rpm, only to decrease again to 1.2% at 100 and 110 rpm. Respiratory frequency (R*f*) variability ranged from 7.46% to 9.84%. Similar to what was observed in cadence variability, after an initial decrease to the lowest value at 70 rpm, variability increased to 9.6% at 80 rpm and 9.8% at 90 rpm and then decreased to 9.2%. Total respiratory frequency variability was below 10% and considered satisfactory.

Figure 2 presents the effects of different cadences on respiratory response, with significant effects noted for VE ($F = 168.11$, $p < 0.000$), R*f* ($F = 16.06$, $p < 0.001$), VT ($F = 54.67$, $p < 0.000$), and VO_2 ($F = 214.86$ $p < 0.000$). As a result of increased cadence, VE rose from 14.4 ± 2.8 l · min^{-1} at 40 rpm to 32.2 ± 5.9 l · min^{-1} at 110 rpm (Figure 2). Statistically significant differences in VE were observed when comparing 70 rpm with 40 and 50 rpm ($p < 0.000$). Afterwards, all pedaling frequencies above 80 rpm were significantly different from the slower cadences for VE at $p < 0.001$. Differences in respiratory frequency (R*f*) were significant at 80 rpm compared with 40 rpm ($p < 0.002$). R*f* was significantly higher at 90 rpm compared with all lower cadences ($p < 0.005$) and remained at a similar level regardless of increased pedaling frequency. The increase of 160 ml in VT between 40 and 50 rpm and 70 rpm was not statistically significant. Only at 80 rpm was the increase in VT of 280 ml significantly different compared with VT at 40, 50, and 60 rpm. VT increased by 110 and 200 ml in the subsequent pedaling rates; this difference was also statistically significant (Figure 3).

The difference in oxygen uptake between 40 and 50 rpm and 70 rpm was 120 ml ($p < 0.005$). From 70 rpm, an increase of approximately 180 ml was observed in each subsequent pedaling rate. These differences were also significant at $p < 0.000$ (Figure 3).

The effects of pedaling cadence also influenced total respiratory time ($F = 8.659$, $p < 0.001$) and its components inspiratory and expiratory time ($F = 21.96$, $p < 0.001$). Total respiratory time (T_{tot}) was significantly reduced at cadences of 70 and 80 rpm compared with 40 rpm. Comparisons with subsequent pedaling rates and the value recorded at 50 rpm were also significantly different.

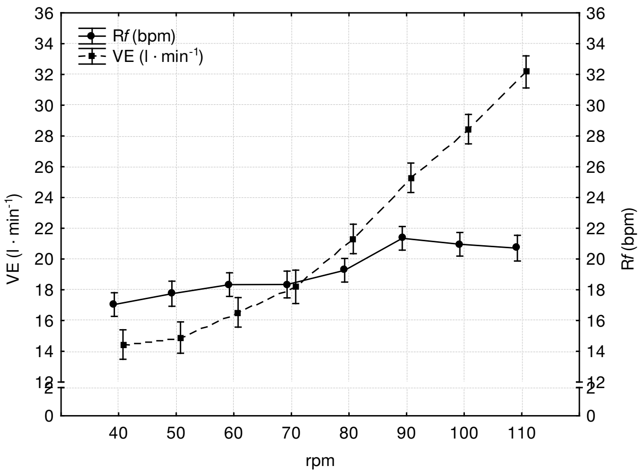

Figure 2. Changes in minute ventilation (VE) and respiratory frequency (R*f*) with increased cadence

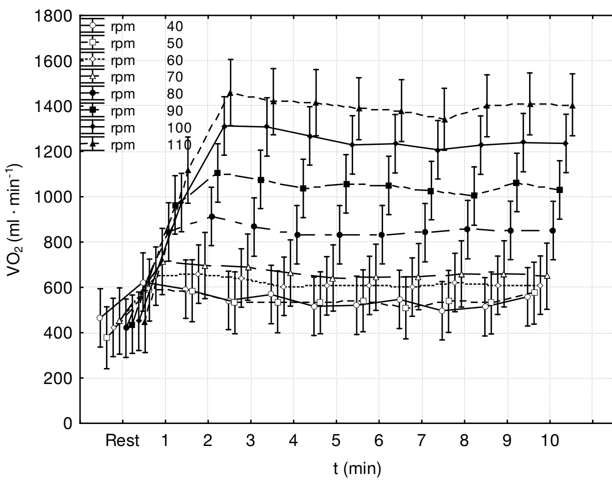

Figure 1. Changes in oxygen uptake (VO_2) with increased cadence

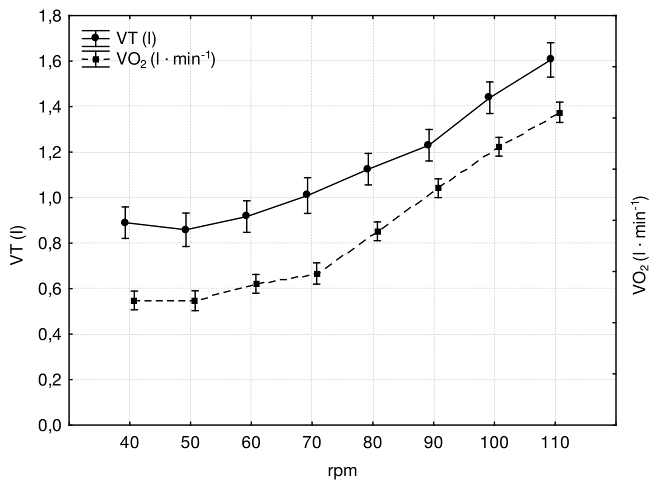

Figure 3. Changes in oxygen uptake (VO_2) and tidal volume (VT) with increased cadence

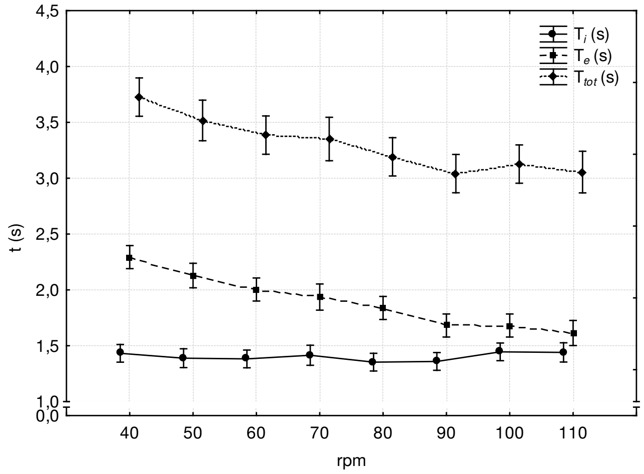

Figure 4. Changes in total respiratory (T_{tot}), inspiratory (T_i) and expiratory (T_e) times with increased cadence

The rate of change of T_{tot} was the largest when comparing 70 and 80 rpm and 80 and 90 rpm ($p < 0.000$). The decrease in T_{tot} was mainly an effect of reduced expiratory time (Figure 4). In turn, inspiratory time (T_i) remained steady in all analyzed pedaling rates ($F = 1.11$, $p < 0.353$).

Discussion

The body's control of respiratory function during physical exertion involves the central processing of neural and biochemical information. The aim of the present study was to determine the effects of different pedaling cadences on respiratory response. In order to control for the large effects of load on physiological response, the study adopted a cycle ergometer test protocol involving no external load. This allowed the pedaling efforts to be performed with minimum variability in cadence (below 3.5%), which controlled for the effects of cycling rhythm on respiratory response (Figure 1). The results indicate that only from a cadence of 70–80 rpm are significant changes noted in respiratory function, in which increased cadence induced greater respiratory response. Lower pedaling rates (40–60 rpm) did not have an effect on respiratory response.

Acute respiratory response was similar in cadences of 40–70 rpm, with the body adapting within the first minute of ergometer pedaling at these rates. At higher cadences, physiological adaptation to exercise was attained in the second minute of pedaling (Figure 1). The tempo in which physiological response plateaued and the differences between the pedaling rates (16.5% of VO_{2max} at 40 rpm and 37.5% of VO_{2max} at 110 rpm) are indicative that all efforts were performed at light intensity and largely taxed the aerobic system. Foss et al. [17] demonstrated that VO_2 increased with increasing cadence. After comparing oxygen uptake values at a load of 0 W between different cadences (60, 80, 100, and 120 rpm), they established that extrapolating this data to cadences of 40 and even 20 rpm would show a continued decrease in oxygen uptake. While our study did not analyze the effects of pedaling at 20 rpm, the mean differences in oxygen uptake was only 6 ml · min^{-1} between 40 and 50 rpm and 56 ml · min^{-1} between 40 and 60 rpm. These small differences fall within the margin of error for the entire sample. This finding indicates that pedaling on a cycle ergometer without load at a frequency of 40 to 60 rpm does not modulate VO_2. Only when comparing VO_2 between 40 and 70 rpm is a significant difference found in the amount of oxygen used by working muscle.

Similar changes and statistically significant differences were observed with regard to minute ventilation (VE), tidal volume (VT), and respiratory frequency (R*f*) (Figure 2, 3). R*f* and VT increased only slightly between 40 and 70 rpm. This small and not statistically significant change in both variables did, however, cause a significant increase in VE already at 60 rpm compared with 40 rpm (Figure 2). Only at a cadence of 80 rpm was the increase in R*f* and VT significant in relation to the values measured at lower pedaling cadences. Noteworthy is also the fact that the increase in VE at 100 and 110 rpm is only associated with an increase of VT (Figure 3) and that pedaling between 90 and 110 rpm is characterized by similar respiratory frequency (approximately 21 bpm) (Figure 2).

The changes observed in R*f* were a result of reduced total respiratory time (T_{tot}), which was mainly an effect of shortened expiratory time (T_e) (Figure 4). Inspiratory time (T_i) was similar at rest and and in all of the pedaling rates considered in the present study (Figure 4). Takano [18] considered inspiratory (T_i) and expiratory (T_e) times during cycle exercise, although they only analyzed cadences of 30 and 60 rpm and pedaling at a load of 0 W was performed for only 4 min and also preceded by cycling with incremental load. A marked reduction was found in both T_i (approx. 50 ms) and Te (approx. 70 ms) at these cadences compared with at-rest values. Such an effect was not observed in the present study, but in can be inferred that this may be due to the different protocols. In our study, T_i in all of cadences averaged 1.39 ± 0.09 s, whereas T_e decreased with increased pedaling cadence and did not concur with the results obtained by Takano at a cadence of 60 rpm. In fact, a similar response was obtained by the sample of the present study only at a pedaling rate of 110 rpm. Similarly, Scheuermann and Kowalchuk [19] observed an increased respiratory response to pedaling at 60 rpm than what was found in this study – VO_2 (839 ± 199 vs. 624 ± 123 ml), VE (20 ± 4 vs. 16 ± 2.7 ml · min^{-1}) VT (1093 ± 270 vs. 925 ± 120 ml), T_e (1997 ± 0.488 vs. 2001 ± 0.446 ms), and T_i (1502 ± 0.471 vs. 1385 ± 0.197 ms), respectively. The values reported by Scheuermann and Kowalchuk at 60 rpm were achieved by the participants of the present study at 80 rpm. One factor which may explain the difference between the results of the studies may also lie with the adopted protocol.

Although both studies used a cycle ergometer with a magnetic resistance mechanism, the participants in Scheuermann and Kowalchuk were informed that they would be performing a graded exercise test until volitional exhaustion. Hence, the psychological effect of motivation may have played a role here, leading to increased activity of the sympathetic nervous system and therefore improved respiratory response to pedaling at a load of 0 W.

Although statistically significant differences in respiratory response (e.g., decreased T_{tot} and increased V_T with increasing cadence) were observed at and above 70 and 80 rpm, no such changes were evident in post-exercise metabolic response. Differences among the analyzed blood variables as a result of unloaded pedaling were not significant, with values similar to those recorded at rest. The highest concentration of lactate (BLa) was observed at 40 rpm. On the one hand, this may be the effect of a higher contribution of slow twitch fibers in muscle contraction and an extended muscle contraction phase. Ahlquist et al. [20] observed greater glycogen depletion by slow twitch fibers at a pedaling rate of 50 rpm compared with 100 rpm. Support for this is found in the statistically significant increase in H^+ ions when pedaling at 40 rpm (Table 2). On the other hand, the significant increase in pCO_2 at this cadence is indicative of increased aerobic response in meeting the energy demands of working muscle. During light intensity exercise, such as the unloaded pedaling in the present study, pCO_2 is determined by the amount of CO_2 produced during aerobic metabolism and excreted from muscle tissue. However, changes in the above variables were not reflected in modified respiratory function. The respiratory response to pedaling at 40 rpm was not significantly different from respiratory measures registered at rest. For the remaining cadences considered in the present study, BLa was maintained at approximately 1 mM (Table 2).

The lack of significant differences among the biochemical parameters and the maintenance of normocapnia regardless of increased ventilation suggests that stimulation of respiratory function during unloaded cycling is neurogenic via cortical stimulation and muscle ergoreceptors, specifically mechanoreceptors. Mechanoreceptors, which are sensitive to changes in muscle deformation (pressure and tension) that occur during muscle contraction by group III afferents (A delta fibers), stimulate the respiratory system in response to exercise [13, 21–23]. Their increased sensitivity may be the result of continuous changes in the recruitment pattern during unloaded pedaling in order to maintain a constant cadence and optimize pedal forces, especially by biarticular muscle such as the quadriceps and biceps femoris [24, 25].

Conclusions

Pedaling at a frequency between the optimal shortening velocities of slow twitch (70 rpm) and fast twitch (100 rpm) muscle with no external load on a cycle ergometer has an effect on respiratory response. It is known that the mechanical efficiency of slow twitch muscle fibers decreases at a cadence of approximately 70 rpm, whereas the efficiency of fast twitch fibers increases from 100 rpm. It is also known that the greater recruitment of fast twitch fibers with increased cadence is not due to an inherent inefficiency of slow twitch fibers to perform at higher pedaling rates but rather the faster activation rates of fast twitch fibers [26, 27]. Pedaling at a frequency outside the optimal cadence for these two types of muscle fibers may be the cause of differences in muscle activation in order to maintain a constant cadence [25]. As muscle activation is also influenced by increased pedaling frequency [5, 28, 29], this may have also been a factor contributing to the statistically significant changes in respiratory function. While pedaling between 70 and 100 rpm is considered to be outside the optimal frequency for untrained and trained individuals [1, 2], the findings of the present study indicate that these frequencies are effective in stimulating respiratory system in unloaded conditions on a cycle ergometer. As a result, this type of pedaling protocol can be used in elderly, inactive, or obese populations.

References

1. Takaishi T., Yamamoto T., Ono T., Ito T., Moritani T., Neuromuscular, metabolic and kinetic adaptation for skilled pedaling performance in cyclists. *Med Sci Sport Exerc*, 1998, 30 (3), 442–449.
2. Jameson C., Ring C., Contribution of local and central sensations of the perception of exertion during cycling: effect of work rate and cadence. *J Sports Sci*, 2000, 18 (4), 291–298, doi: 10.1080/026404100365027.
3. Nickleberry Jr. B.L., Brooks G.A., No effect of cycling experience on leg cycle ergometer efficiency. *Med Sci Sports Exerc*, 1996, 28 (11), 1396–1401.
4. Candotti C.T., Ribeiro J., Soares D.P., de Oliveira A.R., Loss J.F., Guimaraes A.C.S., Effective force and economy of triathletes and cyclists. *Sports Biomech*, 2007, 6 (1), 31–43, doi: 10.1080/14763140601058490.
5. Dantas J.L., Smirmaul B.P., Altimari L.R., Okano A.H., Fontes E.B., Camata T.V. et al., The efficiency of pedaling and the muscular recruitment are improved with increase of the cadence in cyclists and non-cyclists. *Electromyogr Clin Neurophysiol*, 2009, 49 (6–7), 311–319.
6. Kohl J., Koller E.A., Jäger M., Relation between pedaling- and breathing rhythm. *Eur J Appl Physiol*, 1981, 47 (3), 223–237, doi: 10.1007/BF00422468.
7. Garlando F., Kohl J., Koller A.E., Pietsch P., Effect of coupling the breathing- and cycling rhythms on oxygen uptake during bicycle ergometry. *Eur J Appl Physiol*, 1985, 54 (5), 497–501, doi: 10.1007/BF00422959.
8. Bonsignore M.R., Morici G., Abate P., Romano S., Bonsignore G., Ventilation and entrainment of breathing during cycling and running in triathletes. *Med Sci Sports Exerc*, 1998, 30 (2), 239–245, doi: 10.1097/00005768-199802000-00011.
9. Vollestad N.K., Blom P.C.S., Effect of varying exercise intensity on glycogen depletion in human muscle fibers.

Acta Physiol Scand, 1985, 125 (3), 395–405, doi: 10.1111/j.1748-1716.1985.tb07735.x.

10. Gollnick P.D., K. Piehl K., Saltin B., Selective glycogen depletion pattern in human muscle fibres after exercise of varying intensity and at varying pedaling rates. *J Physiol (Lond)*, 1974, 241 (1), 45–57, doi: 10.1113/jphysiol.1974.sp010639.
11. Eldridge F.L., Millhorn D.E., Kiley J.P., Waldrop T.G., Stimulation by central command of locomotion, respiration and circulation during exercise. *Respir Physiol*, 1985, 59 (3), 313–337, doi: 10.1016/0034-5687(85)90136-7.
12. Romaniuk J.R., Kasicki S., Kazennikov O.V., Selionov V.A., Respiratory responses to stimulation of spinal or medullary locomotor structures in decerebrate cats. *Act Neurobiol Exp*, 1994, 54 (1), 11–17.
13. McCloskey D.I., Mitchell J.H., Reflex cardiovascular and respiratory responses originating in exercising muscle. *J Physiol (Lond)*, 1972, 224 (1), 173–186, doi: 10.1113/jphysiol.1972.sp009887.
14. Palisses R., Persegol L., Viala D., Viala G., Reflex modulation of phrenic activity through hindlimb passive motion in decorticate and spinal rabbit preparation. *Neuroscience*, 1988, 24 (2), 719–728, doi: 10.1016/0306-4522(88)90364-8.
15. Potts J.T., Rybak I.A., Paton J.F.R., Respiratory rhythm entrainment by somatic afferent stimulation. *J Neurosci*, 2005, 25 (8), 1965–1978, doi: 10.1523/JNEUROSCI.3881-04.2005.
16. Wasserman K., Hansen J.E., Sue D.Y., Stringer W.W., Whipp B.J., Normal values. Arterial and end-tidal carbon dioxide tensions. In: Wasserman K., Hansen J.E., Sue D.Y., Stringer W., Whipp B. (eds.), Principles of exercise testing and interpretation, 4th Edition. Lippincott Williams & Wilkins, Philadelphia 2005, 42–55.
17. Foss O., Hallen J., The most economical cadence increases with increasing workload. *Eur J Appl Physiol*, 2004, 92 (4–5), 443–451, doi: 10.1007/s00421-004-1175-5.
18. Takano N., Effects of pedal rate on respiratory responses to incremental bicycle work. *J Physiol*, 1988, 396 (1), 389–397, doi: 10.1113/jphysiol.1988.sp016968.
19. Scheuermann B.W., Kowalchuk J.M., Breathing patterns during slow and fast ramp exercise in man. *Exp Physiol*, 1999, 84 (1), 109–120, doi: 10.1111/j.1469-445X.1999.tb00076.x.
20. Ahlquist L.E., Bassett Jr. D.R., Sufit R., Nagle F.J., Thomas D.P., The effect of pedaling frequency on glycogen depletion rates in type I and type II quadriceps muscle fibers during submaximal cycling exercise. *Eur J Appl Physiol*, 1992, 65 (4), 360–364, doi: 10.1007/BF00868141.
21. Mateika J.H., Duffin J., A review of the control of breathing during exercise. *Eur J Appl Physiol*, 1995, 71 (1), 1–27, doi: 10.1007/BF00511228.
22. Kalia M., Mei S.S., Kao F.F., Central projections from ergoreceptors (C fibers) in muscle involved in cardiopulmonary responses to static exercise. *Circ Res*, 1981, 48 (Suppl 1), 48–62.
23. Schmidt H., Francis D.P., Rauchhaus M., Werdan K., Piepoli M.F., Chemo- and ergoreflexes in healthy, diseases and ageing. *Int J Cardiol*, 2005, 98 (3), 369–378, doi: 10.1016/j.ijcard.2004.01.002.
24. Chapmann A.R., Vicenzino B., Blanch P., Hodges P.W., Patterns of leg muscle recruitment vary between novice and highly trained cyclists. *J Electromyogr Kinesiol*, 2008, 18 (3), 359–371, doi: 10.1016/j.jelekin.2005.12.007.
25. Rouffet D.M., Mornieux G., Zameziati K., Belli A., Hautier C.A. Timing of muscle activation of the lower limbs can be modulated to maintain a constant pedaling cadence. *J Electromyogr Kinesiol*, 2009, 19 (6), 1100–1107, doi: 10.1016/j.jelekin.2008.11.014.
26. Beelen A., Sargeant A.J., Effect of prior exercise at different pedaling frequencies on maximal power in humans. *Eur J Appl Physiol*, 1993, 66 (2), 102–107, doi: 10.1007/BF01427049.
27. MacIntosh B.R., Neptun R.R., Horton J.F., Cadence, power and muscle activation in cycle ergometry. *Med Sci Sports Exerc*, 2000, 32 (7), 1281–1287.
28. Baum B.S., Li L., Lower extremity muscle activities during cycling are influenced by load and frequency. *J Electromyogr Kinesiol*, 2003, 13 (2), 181–190, doi: 10.1016/S1050-6411(02)00110-4.
29. Priego J.I., Bini R.R., Lanferdini F.J., Carpes F.P., Effects of workload level on muscle recruitment in cycling. *Hum Mov*, 2014, 15 (1), 45–50, doi: 10.2478/humo-2014-0001.

Paper received by the Editor: November 4, 2014
Paper accepted for publication: January 13, 2015

Correspondence address
Agnieszka D. Jastrzębska
Katedra Fizjologii i Biochemii
Akademia Wychowania Fizycznego
al. I.J. Paderewskiego 35
51-612 Wrocław, Poland
e-mail: jasagn@hotmail.com