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Estimation of Oxygen Cost of Internal Power during Cycling Exercise with Changing Pedal Rate

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Abstract It has been reported that oxygen uptake ($\dot{V}O_2$) increases exponentially with levels of the pedal rate during cycling. The purpose of this study was therefore to test the hypothesis that the O_2 cost for internal power output (P_{int}) exerted in exercising muscle itself would be larger than for an external power output (P_{ext}) calculated from external load and pedal rate during cycling exercise under various conditions of P_{int} and P_{ext} in a large range of pedal rates. The O_2 cost ($\Delta\dot{V}O_2$/Δpower output) was investigated in three experiments that featured different conditions on a cycle ergometer that were carried out at the same levels of total power output (P_{tot}; sum of P_{int} and P_{ext}) (Exp. 1), P_{ext} (Exp. 2) and load (Exp. 3). Each experiment consisted of three exercise tests with three levels of pedal rate (40 rpm for a lower pedal rate: LP; 70–80 rpm for a moderate pedal rate: MP; and 100–120 rpm for a higher pedal rate: HP) lasting for 2–3 min of unloaded cycling followed by 4–5 min of loaded cycling. Blood lactate accumulations (2.3–3.4 mmol l^{-1}) at the HP were significantly higher compared with the LP (0.6–0.9 mmol l^{-1}) and MP (0.9–1.0 mmol l^{-1}) except for the LP in Exp. 1. The $\dot{V}O_2$ (360–432 ml min^{-1} for LP, 479–644 ml min^{-1} for MP, 960–1602 ml min^{-1} for HP) during unloaded cycling in the three experiments increased exponentially with increasing pedal rates regardless of $P_{ext}=0$. Moreover, the slope of the $\dot{V}O_2$-P_{int} (13.7 ml min^{-1} W^{-1}) relation revealed a steeper inclination than that of the $\dot{V}O_2$-P_{ext} (10.2 ml min^{-1} W^{-1}) relation. We concluded that the O_2 cost for P_{int} was larger than for P_{ext} during the cycling exercises, indicating that the O_2 cost for P_{tot} could be affected by the ratio of P_{int} to P_{tot} due to the levels of pedal rate. *J Physiol Anthropol 27(3): 133–138, 2008* http://www.jstage.jst.go.jp/browse/jpa2 [DOI: 10.2214/jpa2.27.133]

Keywords: pedal rate, internal work, metabolic cost, muscular efficiency, noncontractile processes, muscle fiber type

Introduction

An exercising muscle generates an internal power output (P_{int}) as well as an external power output (P_{ext}). P_{int} is defined as the power generated to overcome inertial and gravitational forces related to the movement of lower limbs during cycling, and has been estimated by various biomechanical and physiological models (Minetti et al., 2001; Sjøgaard et al., 2002; Wells et al., 1986; Willems et al., 1995; Winter, 1979). In the case of cycling exercise, P_{ext} is generally estimated from external load and pedal rate. It is argued that the total power output (P_{tot}), including P_{int} and P_{ext}, could be a determining factor in evaluating the oxygen (O_2) cost during exercise. If the O_2 cost for P_{tot} shows a constant value under various cycling conditions, the muscular efficiency should remain a constant value. However, we have recently reported that there is an inverted U-shaped relationship between the pedal rate and muscular efficiency and that muscular efficiency decreases remarkably at pedal rates above 80 rpm (Tokui and Hirakoba, 2007). Since muscular efficiency and the O_2 cost for P_{tot} have an inverse relation, the O_2 cost for P_{tot} would be expected to increase at higher pedal rates during cycling.

P_{int} shows an exponential increase as a function of pedal rates during cycling (Hansen et al., 2004; Minetti et al., 2001). Consequently, the ratio of P_{int} to P_{tot} would increase at higher pedal rates in cycling. Previously, we have reported that $\dot{V}O_2$ increases exponentially with increasing pedal rates under unloaded cycling conditions ($P_{ext}=0$) (Morimoto et al., 2005), and this finding is consistent with previous studies that showed a similar relation between $\dot{V}O_2$ and pedal rates (Coast and Welch, 1985; Foss and Hallén, 2004; Seabury et al., 1977; Sidossis et al., 1992). Therefore, it seems likely that the O_2 cost for P_{int} would be larger than for P_{ext} and would decrease muscular efficiency at higher pedal rates. However, there has been no study of the difference in O_2 cost between P_{int} and P_{ext} based on the levels of pedal rates during a cycling exercise.

The purpose of this study was to test the hypothesis that the

O_2 cost for P_{int} would be larger than for P_{ext} during cycling exercises under various conditions of P_{int} and P_{ext} in a large range of pedal rates.

Methods

Subjects

Seven healthy male subjects (age: 22.4±0.4 yr; height: 169.6±1.9 cm; mass: 64.1±2.9 kg; $\dot{V}O_{2max}$: 43.6±2.9 ml kg^{-1} min^{-1}) volunteered to participate in Experiment 1 (Exp. 1), and nine healthy male subjects (age: 20.7±0.8 yr; height: 170.3±1.6 cm; mass: 62.6±1.6 kg, $\dot{V}O_{2max}$: 47.8±2.1 ml kg^{-1} min^{-1}) volunteered in Experiments 2 and 3 (Exp. 2 and Exp. 3, respectively). All subjects were physically active, but none was specifically trained. They were all informed of the purpose and procedure of this study, and gave their informed, written consent prior to testing. The experimental protocol used in this study was approved by the Ethics Committee for Human Subjects of the Kyushu Institute of Technology.

Experimental protocol

To investigate the difference of O_2 cost between P_{int} and P_{ext}, the cycling exercise test should be carried out under experimental conditions with various levels of ratios of P_{int} and P_{ext} to P_{tot} due to changing pedal forces in a large range of pedal rates. Consequently, the three experiments were carried out at the same levels of P_{tot} (Exp. 1), P_{ext} (Exp. 2), and load (Exp. 3), respectively. In each experiment, the subjects performed three exercise tests on a friction-braked cycle ergometer (Monark 818E, Crecent AB, Sweden) with lower pedal rates (LP), moderate pedal rates (MP), and higher pedal rates (HP), which corresponded to 40, 80, and 120 rpm in Exps. 1 and 2, and 40, 70, and 100 rpm in Exps. 3, respectively. The pedal rates in Exp. 3 were set lower than those in the other two experiments, because power output would be too high to be performed at a similar metabolic rate as in Exps. 1 and 2 if the HP test were cycled at 120 rpm. The exercise tests consisted of 3 min rest, 2 min unloaded cycling, and 5 min loaded cycling in Exp. 1, and 3 min rest, 3 min unloaded cycling, and 4 min loaded cycling in Exp. 2 and Exp. 3. An electrical metronome was set to assist subjects in maintaining the target pedal rates. The three exercise tests in each experiment were carried out within one day in randomized order separated by a reasonable recovery period (~30 min).

Measurements

Breath-by-breath pulmonary gas exchange parameters were measured continuously throughout the exercise tests using a metabolic analysis system (A-E 300S, Minato Medical Science, Japan). Pulmonary gas exchange parameters were averaged for 1 min (from the 1st to 2nd min) at rest and during the unloaded cycling exercise, and for 2 min (the last 2 minutes) during the loaded cycling exercise.

Arterialized capillary blood samples were taken from the fingertips immediately before and after each exercise test, and the blood lactate concentration ([La]) was analyzed by a semi-automated lactate analyzer (YSI-1500 Sport, Yellow Springs Ins., USA). Blood lactate accumulation (Δ[La]) was measured as the difference of [La] between rest and loaded cycling.

The flywheel frequency during cycling was measured by an IC hall sensor attached to the cycle ergometer in order to analyze pedal frequency.

Calculations

The exercising muscle generates both P_{int} and P_{ext} (Cavagna and Kaneko, 1977). The definitions of power outputs (P_{int}, P_{ext}, and P_{tot}) and $\dot{V}O_2$ for P_{int} and for P_{ext} are illustrated in Fig. 1. The P_{int} and P_{ext} were measured during unloaded and loaded cycling, respectively. It is assumed that the $\dot{V}O_2$ for P_{int} corresponds to the $\dot{V}O_2$ increase from a resting level during unloaded cycling and that the $\dot{V}O_2$ for P_{ext} is the difference in the $\dot{V}O_2$ between unloaded and loaded cycling.

According to Minetti et al. (2001), P_{int} was estimated from body mass (BM; kg) and pedal frequency (*f*; Hz) that was calculated by actually measured flywheel frequency (*ff*; Hz) and the ratio of pedal to flywheel rotations (3.64) as follows:

$$f(\mathrm{Hz}) = ff(\mathrm{Hz})/3.64$$

$$P_{int}(\mathrm{W}) = 0.153 \cdot \mathrm{BM(kg)} \cdot f^3(\mathrm{Hz})$$

P_{ext} was estimated from the load (kp) and *f* as follows:

$$P_{ext}(\mathrm{W}) = \mathrm{load(kp)} \cdot 9.8\ (\mathrm{m\,s^{-2}};\ \text{gravitational acceleration}) \cdot 6\ (\mathrm{m\,rev.^{-1}}) \cdot f(\mathrm{Hz})$$

Statistics

All data are presented as means±SEM. A one-way ANOVA with repeated measures was used to test the differences in physiological variables between the three exercise tests in each experiment. If a significant F ratio was obtained, then a Student-Newman-Keuls *Post hoc* test was performed to obtain the differences in the selected variables. The relations between physiological variables were analyzed by a non-linear and linear regression analysis with a least square method.

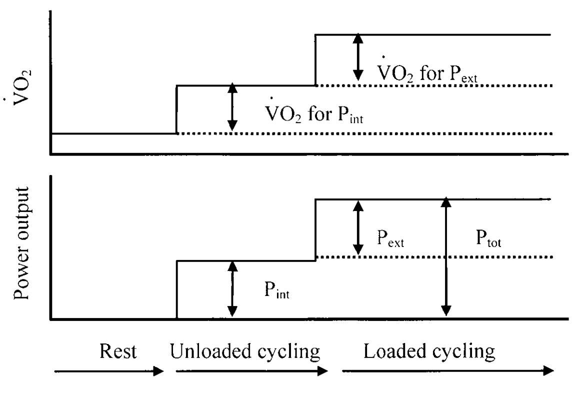

Fig. 1 Illustration and definitions of internal (P_{int}), external (P_{ext}) and total power output (P_{tot}) and oxygen uptake ($\dot{V}O_2$) for P_{int} and P_{ext}.

Statistical significance was accepted at $p<0.05$.

Results

Target and actually measured values in pedal rate, load, and power outputs (P_{int}, P_{ext}, and P_{tot}) during unloaded and loaded cycling in the three experiments are given in Table 1. It was found that there were no large differences between target and measured pedal rates. The P_{int} during unloaded and loaded cycling at HP (47–90 W) rose markedly with increasing pedal rates (~3 W for LP and 16–25 W for MP).

In the three experiments, although $\dot{V}O_2$ at rest did not differ among three experimental conditions, the unloaded and loaded $\dot{V}O_2$ changed depending on the levels of pedal rate (i.e., P_{int} and P_{tot}), respectively (Table 2). The unloaded $\dot{V}O_2$ revealed the highest values at the HP compared with at the LP and MP regardless of $P_{ext}=0$ ($p<0.05$, Table 2). As a result, the $\dot{V}O_2$ during unloaded cycling in the three experiments increased exponentially with increasing pedal rates (Fig. 2). On the other hand, the $\dot{V}O_2$ was linearly related to P_{int} and P_{ext} (Fig. 3). The slope (13.7 ml min^{-1} W^{-1}) of the $\dot{V}O_2$-P_{int} relation obtained in this study revealed a steeper inclination than that (10.2 ml min^{-1} W^{-1}) of the $\dot{V}O_2$-P_{ext} relation in the combined data from Exps. 1 to 3.

The average values of Δ[La] at the three levels of pedal rates in each experiment are listed in Table 3. The Δ[La] at the HP in Exp. 1 under the same P_{tot} condition was significantly higher than only at the MP ($p<0.05$), while the Δ[La] at the HP was significantly higher than at both the LP and MP in Exps. 2 and 3 ($p<0.05$).

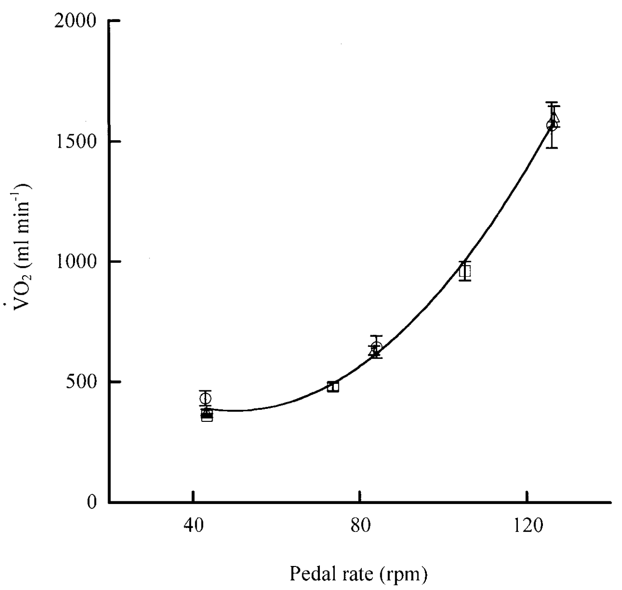

Fig. 2 Relationship between oxygen uptake ($\dot{V}O_2$) and pedal rate during unloaded cycling in Experiment 1 (open circle), 2 (open triangle) and 3(open square) ($y=900.49-20.739x+0.207x^2$, $R^2=0.997$).

Table 1 Target pedal rates, measured values in pedal rates, load and power output during cycling exercises under three experimental conditions

	Exp. 1			Exp. 2			Exp. 3		
	LP	MP	HP	LP	MP	HP	LP	MP	HP
TPR (rpm)	40	80	120	40	80	120	40	70	100
$MPR_{unloaded}$ (rpm)	43±0.5	84±1.0^{a,b}	126±0.6^{b}	43±0.3	83±0.6^{a,b}	127±0.5^{b}	43±1.0	74±0.4^{a,b}	105±0.8^{b}
MPR_{loaded} (rpm)	41±0.3	82±0.2^{a,b}	126±0.3^{b}	41±0.2	82±0.2^{a,b}	124±0.4^{b}	42±0.4	71±0.2^{a,b}	102±0.3^{b}
Load (kp)	2.7	1	0.25	1.5	0.75	0.5	1	1	1
P_{int} (W)	3±0.2	25±1.1^{a,b}	90±4.1^{b}	3±0.1	24±0.6^{a,b}	84±1.8^{b}	3±0.1	17±1.1^{a,b}	48±1.3^{b}
P_{ext} (W)	109±3.0	86±3.7^{a,b}	31±0.1^{b}	60±0.2	60±0.2	61±0.2	41±0.3	71±1.2^{a,b}	100±0.3^{b}
P_{tot} (W)	113±3.2	110±4.7^{a}	121±4.1^{b}	63±0.3	85±0.7^{a,b}	145±1.8^{b}	44±0.4	88±2.2^{a,b}	148±1.2^{b}

Exp. 1 Exercise tests under same total power output level; Exp. 2 Exercise tests under same external power output level; Exp. 3 Exercise tests under same load level; LP Lower pedal rate; MP Moderate pedal rate; HP Higher pedal rate; TPR Target pedal rate; $MPR_{unloaded}$ Measured pedal rate during unloaded cycling; MPR_{loaded} Measured pedal rate during loaded cycling; P_{int} internal power output; P_{ext} external power output; P_{tot} total power output; ^{a} Significantly different from HP in the same experiment; ^{b} Significantly different from LP in the same experiment.

Table 2 Oxygen uptake at rest and during cycling exercises under three experimental conditions

	Exp. 1			Exp. 2			Exp. 3		
	LP	MP	HP	LP	MP	HP	LP	MP	HP
$\dot{V}O_{2rest}$ (ml min^{-1})	264±21	283±18	288±20	249±11	266±13	251±9	242±13	263±10	259±8
$\dot{V}O_{2unloaded}$ (ml min^{-1})	432±31	644±46^{a,b}	1567±95^{b}	373±12	630±18^{a,b}	1602±42^{b}	360±8	479±16^{a,b}	960±39^{b}
$\dot{V}O_{2loaded}$ (ml min^{-1})	1626±63	1424±70^{a,b}	1829±101^{b}	998±10	1178±17^{a,b}	2061±59^{b}	763±14	1177±17^{a,b}	1831±29^{b}

$\dot{V}O_{2rest}$ Oxygen uptake at rest; $\dot{V}O_{2unloaded}$ Oxygen uptake during unloaded cycling; $\dot{V}O_{2loaded}$ Oxygen uptake during loaded cycling; [a] Significantly different from HP in the same experiment; [b] Significantly different from LP in the same experiment; for abbreviations, see Table 1.

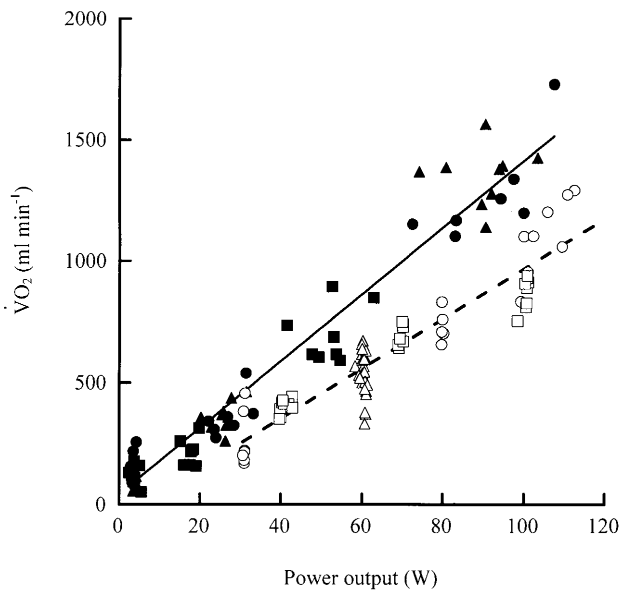

Fig. 3 Relationships between oxygen uptake ($\dot{V}O_2$) and power outputs during cycling under three experimental conditions. Symbols indicate oxygen uptake for internal power (P_{int}) in Exps. 1 (filled circle), 2 (filled triangle) and 3 (filled square) and for external power (P_{ext}) in Exps. 1 (open circle), 2 (open triangle) and 3 (open square). The solid line indicates the relationship between oxygen uptake and internal power ($y=13.70x+42.08$, $R^2=0.95$). The dotted line indicates the relationship between oxygen uptake and external power ($y=10.23x-54.02$, $R^2=0.87$).

Table 3 Blood lactate accumulation during cycling exercises under three experimental conditions

	Δ[La] (mmol l^{-1})		
	LP	MP	HP
Exp. 1	1.4±0.5	1.0±0.3^{a}	2.3±0.5
Exp. 2	0.9±0.2	1.0±0.2^{a}	3.4±0.3^{b}
Exp. 3	0.6±0.2	0.9±0.2^{a}	3.0±0.4^{b}

Δ[La] Blood lactate accumulation; [a] Significantly different from HP in the same experiment; [b] Significantly different from LP in the same experiment; for abbreviations, see Table 1.

Discussion

An estimation of P_{int} in this study was made using a model proposed by Minetti et al. (2001) which was easily calculated from the pedal rate and body mass in cycling. This model was also used in a study by Ferguson et al. (2002) that investigated the influence of pedal rate and muscle temperature on muscular efficiency. Hansen et al. (2004) compared P_{int} from various biomechanical and physiological models including Minetti's model (2001) and showed that P_{int} from Minetti's model (2001) corresponded to that from other models but was underestimated slightly. However, we confirmed the validity of Minetti's model (2001) in our previous study (Tokui and Hirakoba, 2007), which showed a high, significant correlation

(r=0.95, p<0.001) between P_{int} estimated using the biomechanical model of Minetti et al. (2001) and the physiological model of Sjøgaard et al. (2002). Thus, when considering small differences of P_{int} between biomechanical and physiological models, it is indicated that the P_{int} level estimated in this study would be adequate.

The $\dot{V}O_2$ during unloaded cycling in the present results was observed to rise exponentially with increasing pedal rates (Fig. 2). This is consistent with our previous study regarding P_{int} and the metabolic rate, which observed that the $\dot{V}O_2$ during unloaded cycling at five different pedal rates (40–120 rpm) increased exponentially with increasing pedal rates (Morimoto et al., 2005). Moreover, several previous studies have reported similar results (Coast and Welch, 1985; Foss and Hallén, 2004; Seabury et al., 1977; Sidossis et al., 1992). Thus, it would be thought that a higher muscle contraction velocity and frequency at higher pedal rates could cause greater O_2 consumption and decrease muscular efficiency. From this result and Minetti's model (2001) on the relationship between $\dot{V}O_2$, P_{int}, and pedal rates, it could be expected that P_{int} is linearly related to $\dot{V}O_2$. In fact, the $\dot{V}O_2$ was observed to increase linearly as a function of P_{int} and P_{ext}. The main finding obtained in the present study was that the slope of the $\dot{V}O_2$-P_{int} relation showed a steeper inclination than that of the $\dot{V}O_2$-P_{ext} relation (Fig. 3), indicating that the oxygen cost for P_{int} (13.7 ml min^{-1} W^{-1}) was larger than that for P_{ext} (10.2 ml min^{-1} W^{-1}), which was almost equal to the values reported by Jones et al. (2004) and Koga et al. (2005). Previous studies demonstrated that higher frequency muscle contractions required a greater energy cost than lower frequency ones (Abbate et al., 2001; Bergström and Hultman 1988; Chasiotis et al., 1987; Hogan et al., 1998). This would be due to an extra energy cost related to an energy turnover for noncontractile processes, particularly the Ca^{2+} pump of the sarcoplasmic reticulum (Abbate et al., 2001; Barclay, 1994; Blinks et al., 1978). In addition, it has been reported that a large proportion of ATP consumed by noncontractile processes derives mainly from anaerobic metabolism (Baker et al., 1994; Hogan et al., 1998). This finding is supported by the present data that Δ[La] was higher at the HP than at the LP and MP (Table 3). Thus, it is possible that the larger O_2 cost for the increased P_{int} with increasing pedal rates would be related to a higher energy cost for noncontractile processes.

Another possible explanation for a higher O_2 cost for P_{int} would be different patterns of muscle fiber recruitment associated with the power-velocity (frequency) relationship. The ratio of type I and type II fiber in exercising muscle, which have different contractile and metabolic properties, is altered by tension exerted in exercising muscle or by exercise intensity (Sargeant et al., 1981; Sargeant, 1994). A higher ratio of type II muscle fiber recruitment could cause a greater energy consumption (Coyle et al., 1992; Jones et al., 2004; Hansen et al., 2002; Horowitz et al., 1994; Mogensen et al., 2006). Consequently, the higher O_2 cost for P_{int} could be partially accounted for by the recruitment of low efficiency type II muscle fibers at higher pedal rates with a higher ratio of P_{int} to P_{tot}.

We concluded that the O_2 cost for P_{int} was larger than for P_{ext} during the cycling exercises, indicating that the O_2 cost for P_{tot} could be affected by the ratio of P_{int} to P_{tot}, due to the levels of pedal rate.

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