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Travail de master en médecine

Measure of efficiency and knee isokinetic strength in bike messengers and non-cyclist athletes

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Abstract

Introduction:

Gross efficiency (GE) appears to be correlated with strength. The purpose of this study was to investigate GE at 4 different pedaling rates (60, 70, 90, 100 rpm) and its relationship with maximal strength in a population of 8 bike messengers (BMs) and 8 experienced non-bicycle messenger (NBMs) athletes.

Methods:

Each of the 8 BMs, (mean age, 25.2 years ±3,2), who work in at a delivery company, who ride 218.7 (±65.1) km/week, and participate in an average of 19.6 (±11.1) hours of sport related exercise per week, and the 8 NBMs, (mean age 25.4 years ±2.2), who ride an average of 5 (+ 14.1) km/week and participate in an average of 6.5 (±3.8) hours of sport related exercise per week underwent 2 laboratory sessions. The first laboratory session determined Maximum Aerobic Power (MAP) and maximal oxygen consumption ($\dot{V}O_2max$) with steps of 30W/min. The second session included an efficiency test at 50% of MAP. GE, oxygen consumption ($\dot{V}O_2$), heart rate (HR) and Blood Lactate Concentration (BLC) were measured at four randomly selected cadences (60,70,90,100 rpm). The subjects then underwent an isokinetic test, 5 repetitions at 60°/sec and 20 repetitions at 120°/sec, to measure concentric strength for extension and flexion of both knees. Fatigability and peak torque/body weight ratio were then calculated.

Results:

A difference in GE (at 60, 90 100rpm), BLC (all cadences) and MAP/kg in favor of BMs was found (all P-value<0.05). No difference in $\dot{V}O_2/\dot{V}O_2max$ (all cadences) was found (p-value>0.05). The most efficient cadence was 60 rpm in both groups. Increased cadence resulted in decreased GE and increased HR and $\dot{V}O_2$ in both groups. BLC only increased in the NBMs group. In both groups, a clear relationship between MAP/kg and low BLC was found. NBMs were found to have stronger hamstring muscles than BMs (p-value: 0.038). Few relationships between GE at different cadences, peak-torque/Bw or muscle fatigability were found.

Discussion/Conclusion:

BMs had a higher GE than NBMs. These results are in line with previously described analyses and are explained by higher aerobic capacity, better training status, different muscle fiber type, and better pedaling technique. At the same power output, anaerobic glycolysis, which is linked to lower economic GE, plays a greater role for NBMs. Stronger hamstring muscles of the NBMs might be explained by the diversity of their practiced sports and therefore their use of a greater diversity of muscle groups. Isokinetic knee maximal strength and fatigability was not linked with GE. Thus, isokinetic strength testing is not a good choice for evaluating GE in cycling.

Introduction

Today, with the development of our crowed cities, it can be challenging to quickly go from one point to another, especially for delivery company drivers that spend their entire day driving around and racing against the clock to make their deliveries on time. Thus, new delivery companies who use bicycles as their main means of transportation have emerged. These companies are able to make much quicker deliveries thanks to bicycle messengers (BMs).

Some of these BMs have a history in competitive road cycling, mountain biking or cyclocross, while others developed their physical fitness on the job. These cyclists must be able to deliver orders within short time frames while carrying loads of up to 20kg during five-hour shifts.

A steep city like Lausanne (Switzerland), which is covers over 500 meter of elevation difference, demands very good physical fitness on a bicycle. The on/off efforts required by this job are completely different than the steadier exercise experienced by competitive athletes during their training or races.

At present, hundreds of studies have been made on the theme of efficiency. We realized that most of these were realized on a population composed of competitive or ex-competitive road-cyclists, or non-cyclists. As far as we know, no studies have been realized with a more heterogeneous group of trained cyclist such as bicycle messengers. This group is particularly interesting due to the fact that they usually don't follow any special training regimen or diet. Most of their fitness is built by going around the city to earn a living.

To understand the concept of efficiency, it is important remember the basics of thermodynamics. The first law of thermodynamic says that in an isolated system "no energy can be produced or lost, it only can be transformed" (1). The total energy of a closed system does not vary but the energy can be converted to another form within the same system (2). We can understand from the second law of thermodynamic that, to convert energy, a certain part of it must be irreversibly transformed into heat and will be considered as lost (2). The human body is a non-isolated system since it can gain chemical potential energy through food intake, transform it, and loose it in the form of work and heat (1). A perfect machine would convert chemical energy directly into work without any heat loss.

Efficiency is defined as the ratio between the measured conversion of energy of a machine and the theoretical maximum. Every movement of the human body has its own efficiency and this efficiency varies enormously from one sport to another. This variation depends on mechanical power and metabolic expenditure. Mechanical power itself is influenced by many factors such as the amount and direction of applied force, the use or not of sports equipment, and kinetic and potential energies, amongst others. Metabolic expenditure also varies due to muscle mass and fiber type in use, for example (2).

In the case of cycling, efficiency is related to the loss of energy during the conversion of an energy substrate into the mechanical force applied by the legs on the bicycle at a given cadence.

During this process, a lot of energy is lost in the form of heat. This loss takes place during 3 key steps (2):

1. Metabolic efficiency:
   A human receives energy though food (carbohydrates, proteins, fatty acids), yet ingested energy substrates won't be directly used by the body. Loss of energy happens when cells, through glycolysis, the Krebs cycle and oxidative phosphorylation, transform those substrates into ATP. Metabolic efficiency can reach 60% meaning that already 40% of the energy is lost in the form of heat (2).
2. Muscular efficiency:

   Some ATP is used in the sarcomere to produce muscle contraction. By attaching itself to myosin heads, ATP breaks the bridge attaching myosin and actin filaments. The hydrolysis of ATP in ADP +P_i activates the myosin heads. They then change their shape and attach themselves to actin filaments while freeing the remaining phosphate. ADP is then released in order to let myosin heads return to their original positions, while still being attached to the actin filaments. During this process, another 50% of the energy is transformed into heat. Thus, efficiency of a concentric muscle contraction is 60% divided by 2 which results in 30% efficiency (2, 3).

3. Mechanical efficiency:

   Finally, the mechanical energy delivered by muscles will be used to put the bicycle in motion. Here, we have another transformation of energy as mechanical energy is converted through the motion of the different mechanical components of the bicycle, and finally to the road. During this process energy is lost to the rub between the different components and to friction of the tires on the road (4). Since the metabolic and muscular efficiency will not vary between sports, the efficiency of any specific sport will be determined by its mechanical efficiency. The maximal efficiency for any sport can not be greater than 30% since it will never overtake the metabolic and muscular efficiency (2). For example, swimming has an efficiency that varies between 5 to 8%, pedaling with the upper limbs: 10-12%, and using a wheelchair: 2-8% (5). The most efficient form of locomotion is by a bicycle, which can reach 20-23% (2, 5).

Gross efficiency

In cycling or in any other kind of sport, gross efficiency (GE) can be defined as the ratio of work during exercise, to the total energy expended, expressed as a percentage (1, 6).

$$\mathrm{e} = \frac{\text{mechanical work}}{\text{energy cost}}$$

GE takes in account metabolic, muscular and mechanical efficiency. It also includes the influence of basal metabolism, digestion, muscle activation, body stabilization, etc. This results in a low and underestimated value for muscular efficiency between 20-23% (2, 7). Some alternative solutions have been developed to try to calculate efficiency more precisely.

Net efficiency

Net efficiency can be defined as the ratio of the mechanical work, to the energy cost, minus the resting metabolic cost.

$$\mathrm{e}_{\mathrm{net}} = \frac{\text{mecanical work}}{\text{enery cost} - \text{rest metabolic cost}}$$

However, as Ettema and Loras explain in their study, this net efficiency definition considers that the resting metabolic cost is an independent constant and that it is not influenced by an increase in work rate (power). We currently know that the body adapts, when exposed to high intensity exercise by decreasing blood flow to non-vital organs or by raising cardiac and respiratory rate. Maintaining basic body functions has a cost and necessitates more energy at high intensity exercise (1, 6). Net efficiency, unlike GE, would, therefore, overestimate the real efficiency.

Work efficiency

Work efficiency tries to correct this by including a measure of the unloaded pedaling metabolic rate into the formula. The goal is to eliminate the portion of the work that is not part of the exercise. This portion is referred to as internal work. The internal work includes energy spent on basal metabolism, holding the handlebars, stabilizing the upper body, breathing and all other energy expenditures not core to the performance of the mechanical work.. The formula of the work efficiency can be written as (1):

$$\mathrm{e_{work}} = \frac{\text{mecanical work (J)}}{\text{energy cost(J)} - \text{internal work(J)}}$$

A study showed that the unloaded pedaling metabolic rate was increased with a higher pedaling cadence. Since we want to measure the influence of pedaling rate on efficiency, it would not be appropriate to use this formula for our study (8). Another study reports that the challenge involved with coordination may increase the metabolic rate in passive cycling (1, 8). We can assume that this is particularly true for those unaccustomed to cycling. Since our study will include a control group of non-cyclist, we decided not to use this formula.

Delta efficiency

Another way to measure efficiency is the Delta efficiency (DE). Similar to work efficiency, the main goal is to eliminate the energy expended that is not part of the exercise. Delta efficiency can be defined as the ratio between the change in power expended to the change in metabolic rate (1):

$$\mathrm{e_{\Delta}} = \frac{\Delta\text{power}}{\Delta\text{metabolic rate}} = \frac{\Delta\text{work}}{\Delta\text{energy cost}}$$

The main benefit of using this formula is that it does not require a measurement the energy expenditure of basal metabolism or of the unloaded pedaling metabolic rate. The major drawback is that it requires measurements at various work intensities (2).

In summary: net efficiency, by considering basal metabolism as a constant, would over estimate real efficiency; work efficiency reduces the influence of pedaling rate but is influenced by pedaling technique; and using delta efficiency would complicate the measuring process. Therefore, these formulas are not well adapted for our study. GE was chosen for this study since it is easy to measure, it provides an accurate expression of efficiency for cycling, and the influence of basal metabolic rate decreases at higher intensity (1, 9).

Among markers of exercise performance such as $\dot{V}O_2max$, metabolic thresholds, peak power output and breathing pattern, efficiency is considered to be one of the most important (10), (1, 6, 11). In their study, Moseley and Jeukendrup predicted that a "1% improvement in efficiency will give a 63 seconds improvement in a 40km time-trial time at 300W" (6, 12). Efficiency can be affected by many factors in cycling (13) such as cadence (9) body mass (14), cycling position (15, 16), pedaling technique (17), prior exercise (18), muscle fiber type (11, 19), training status and maximal strength training (20-23).

During important competitions on television such as the Tour de France, commentators often mention pedaling rate differences among athletes. Studies have shown that the average freely chosen pedaling rate in professional cycling is approximately 90rpm (24). However, the most efficient pedaling rates calculated were between 30-60 rpm (25, 26).

Chavarren and Calbet (1999) studied the influence of pedaling rate on GE. They have demonstrated that at a determined intensity (in watts), when increasing the pedaling rate, GE will automatically drop. They also showed that at a determined pedaling rate, when increasing intensity of the exercise, GE rises. This is explained by the fact that basal metabolism has a smaller impact on GE as exercise intensity increases (1, 9). Exercise intensity can be defined as the power output of the exercise. Power is calculated in watts (W) and is the expression of a velocity multiplied by a force. To simplify, in the case of our study, cadence is the expression of velocity, and strength of force. Since exercise intensity directly influences GE, it can therefore be expected that strength would have a direct influence on GE.

Studies on the influence of strength on GE, especially the influence of muscle fiber type have been controversial (2). Some studies have not found any difference in GE between subjects with differing quantities of rapid or slow muscle fibers (26-28). Others have demonstrated that cyclists with similar $\dot{V}O_2$ and more slow muscle fibers (type 1), have a better GE (19). It has also been shown that long-term endurance training increases the amount of slow muscle fibers (29) and that the concentration of slow muscle fibers is correlated with a higher GE at a faster preset pedaling rate (30).

Studies have also shown that maximal strength training improves efficiency and performance of not only elite cyclist (20, 22, 23, 31), but also of previously untrained subjects (21). It appears then that a link exists between strength level and GE. Since isokinetic testing is the gold standard in strength testing (32), we decided to use it in our study to test the strength of knee extension and flexion of our subjects. We have not found any study that used an isokinetic strength test to compare the relationship between peak torque-to-body weight ratios and GE at specific cadences.

Isokinetic testing forces the subject to move at constant angular speed by automatically adapting the resistance to the muscular force. It is commonly used by physiotherapist for diagnosis and rehabilitation of neuromuscular disorders (33). In addition, with an isokinetic test it is possible to test muscular fatigability.

As observed in some studies, athletes that have been training endurance have a higher percent of type 1 muscle fibers (29). Type 1 muscle fibers are known to be less powerful but have greater fatigue resistance. In this context we can imagine that bicycle-messengers would have fewer fast-twitch muscle fibers (type 2), thus less muscular fatigability and a lower peak torque/body-weight ratio than non-cyclists. It has also been demonstrated that cyclists with a higher percent of type 1 muscle fibers tend to choose a higher cadence (30). Therefore, we can imagine that cyclists with less fatigability and lower peak torque to body-weight would have a better GE at higher cadence than those with a lower peak torque to body weight ratio and more fatigability.

This study will therefore address 4 different questions:

1. What are the anthropometric and cardiovascular fitness differences between a group of bicycle messengers and a group of trained non cyclists matched for age and sex?
2. At 50% of maximal aerobic power, do the bicycle messengers have a better GE than trained non-cyclists?
3. Is the muscular fatigability greater in trained non-cyclists than in bicycle messengers?
4. Is there a correlation between GE at defined cadences and the peak torque/body weight ratio?

Methods

The study was approved by the canton de Vaud ethics committee in November 2015 (n° 392/15)

Subjects

Eight bicycle messengers and eight competitive athletes were included in the study. All the bicycle messengers were men, (mean 25.2 years old ± 3.2), currently working at delivery companies, who ride an average of 218.7 (± 65.1) kilometres during an average of 19.6 (±11.1) hours per week.

All non-bicycle messenger athletes were men, (mean 25.4 years old ± 2.2), who participate in an average of 6.5 (± 3.8) hours of sport related exercise per week, but almost no cycling (5 ± 14.1 km/week).

All participants were requested to attend both visits under similar physical conditions, with clipless[1] shoes. They were also instructed not to ingest any food at least 1 hour prior the visit. All the participants understood and signed a consent form and submitted to a clinical check up by an approved physician that included: a complete clinical history, an ECG, blood pressure measurement and resting heart rate.

Experimental procedure

The study was divided into two laboratory sessions and average of 6.8 (±2.7) days apart. All the visits took place in the sport medicine center of the Lausanne University Hospital (CHUV). Main results were directly available for the subjects and processed results are to be mailed to them at the end of the study.

During the first visit, all subjects signed an informed consent form. Measurements of their weight, height, blood pressure and heart rate were then taken. All subjects were then examined by a qualified physician in order ensure that they could safely participate in the study. All subjects were informed that if they experienced any pain they were to inform the investigators immediately so that the test could be stopped at once.

Subjects completed a maximal intensity exercise test using a cycle ergometer CycleOps Pro 400 (CycleOps, Madison, USA) mounted with clipless pedals to determinate the power to

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[1] Clipless pedals require a special shoe to fit into the mechanism and hold the foot firmly to the pedal.

be used during the second visit for the efficiency test. After a 6 minutes warmup period at a 100W power output, power was increased by 30W every minute until the maximal effort was reached. During the test, $\dot{V}O_2$, $\dot{V}O_2max$, $\dot{V}CO_2$, ventilation and heart rate (HR) were measured using Cortex Metalyzer 3B (Cortex Biophysik GmbH, Leipzig, Germany) and Metasoft Studio installed on a computer. At the beginning and at the end of the test, a sample of fingertip capillary blood was taken to measure blood lactate concentration using a Biosen C-Line analyzer (EKF Diagnostics, Cardiff, England) (13).

All subjects were asked to present themselves under similar physical conditions a few days later. The following were done during this visit: an efficiency test and a strength test; four cadences were randomly tested (60-70-90-100) for a duration of 5 minutes each using a metronome to regulate the subject's pedaling rate; and a rest break of 1 to 2 minutes was taken between each cadence. The power output used for the test was 50% of the maximal power developed during the first visit. $\dot{V}O_2$ and $\dot{V}CO_2$ were measured during the last 60 second of every interval. Fingertip blood samples were taken at the 5th minute of every interval (9).

Subjects then underwent an isokinetic test on the Humac Norm (CSMi, Stoughton, MA). Before the test, all subjects participated in a rigorous warm-up to prevent injury but also to acclimate to the machine. The concentric strength of extension and flexion of both knees was tested with 5 times repetitions at 60°/sec, and 20 repetitions at 120°/sec. Fatigability and peak torque/body weight ratio were then calculated. In order to simplify the analysis, only the results of the right leg were used.

Statistical analysis

Mean and standard deviation were calculated for all assessments. A Spearman correlation test with bootstrap p-values was used to assess intra-group relationships. Since data were not normally distributed, non-parametric methods were used. Differences between the two groups were examined using an exact Wilcoxon-Mann-Whitney test. Significant difference was set at 0.05. Data were analysed using R software 3.3.1 (The R Foundation, 2016).

Results

Intergroup differences

Both, the BMs and the NBMs were accomplished athletes. Age, height, and weight were similar in both groups. As expected, we found a notable difference in $\dot{V}O_2$max and maximal aerobic power per body weight (MAP/kg) between both groups that is explained by differences in cycling experience. Table 1. presents these significant differences between the two groups.

Parameters	**Bike messengers (n=8)**	**Non-bike messengers (n=8)**	**P-Value**
Age (year)	25.2 ± 3.2	25.4 ± 2.2	0.878
Height,(cm)	179.8 ± 8.1	178.1 ± 2.4	0.574
Weight,(kg)	70.9 ± 6.2	73.3 ± 4.1	0.382
Km/week	218.7 ± 65.1	5 ± 14.1	<0.001
MAP/kg	5.8 ± 0.4	4.9 ± 0.3	<0.001
$\dot{V}O_{2max}$	63.4 ± 4.3	56.7 ± 3.2	0.005

Table 1. *Subjects characteristic, and performances achieved during incremental test with steps of 100W/min. Results are given in means ±SD ($\dot{V}O_{2max}$, Maximal oxygen uptake, MAP/kg, Maximal aerobic power per bodyweight during the incremental test).*

	Bike messenger (n=8)	**Non-bike messenger (n=8)**	**P-value**
Cadence 60/min			
Gross efficiency (%)	22.489 ± 1.093	20.890 ± 1.326	0.028
Lactate (mmol·L^{-1})	1.669 ± 0.765	3.229 ± 0.600	0.002
$\dot{V}O_2$ (ml·min^{-1}·kg^{-1})	37.264 ± 2.475	33.938 ± 2.221	0.030
$\dot{V}O_2/\dot{V}O_2$max	0.589 ± 0.048	0.599 ± 0.027	0.505
Cadence 70/min			
Gross efficiency (%)	21.986 ± 1.151	20.522 ± 1.212	0.050
Lactate (mmol·L^{-1})	1.543 ± 0.408	3.320 ± 0.655	<0.001
$\dot{V}O_2$ (ml·min^{-1}·kg^{-1})	38.663 ± 3.670	35.650 ± 4.062	0.078
$\dot{V}O_2/\dot{V}O_2$max	0.611 ± 0.060	0.629 ± 0.069	0.878
Cadence 90/min			
Gross efficiency (%)	20.544 ± 0.624	19.491 ± 1.324	0.105
Lactate (mmol·L^{-1})	1.679 ± 0.435	3.848 ± 0.642	<0.001
$\dot{V}O_2$ (ml·min^{-1}·kg^{-1})	40.583 ± 2.157	36.213 ± 2.365	0.005
$\dot{V}O_2/\dot{V}O_2$max	0.642 ± 0.053	0.639 ± 0.036	0.442
Cadence 100/min			
Gross efficiency (%)	20.210 ± 0.721	18.602 ± 0.981	0.001
Lactate (mmol·L^{-1})	1.758 ± 0.723	4.185 ± 1.207	0.002
$\dot{V}O_2$ (ml·min^{-1}·kg^{-1})	41.276 ± 2.696	37.838 ± 2.794	0.101
$\dot{V}O_2/\dot{V}O_2$max	0.652 ± 0.046	0.668 ± 0.043	0.442

Table 2. *Intergroup differences at every cadence during the efficiency test in gross efficiency, blood lactate concentration, $\dot{V}O_2$, $\dot{V}O_2/\dot{V}O_2$max. Results are given in means ±SD. ($\dot{V}O_2$ for oxygen uptake, $\dot{V}O_2$max for maximal oxygen uptake during the incremental test).*

Efficiency tests showed a significant intergroup difference (see table 2.) in blood lactate concentration (BLC) at every cadence. They also showed that BMs had a better GE at every cadence except at 90 rpm. As expected we found a significant difference in $\dot{V}O_2$ at specific pedaling rates. However, when divided by their personal $\dot{V}O_2$max, this difference disappears with an equivalent $\dot{V}O_2/\dot{V}O_2$max between the groups.

Evolution of lactate, GE and heart rate over the cadences

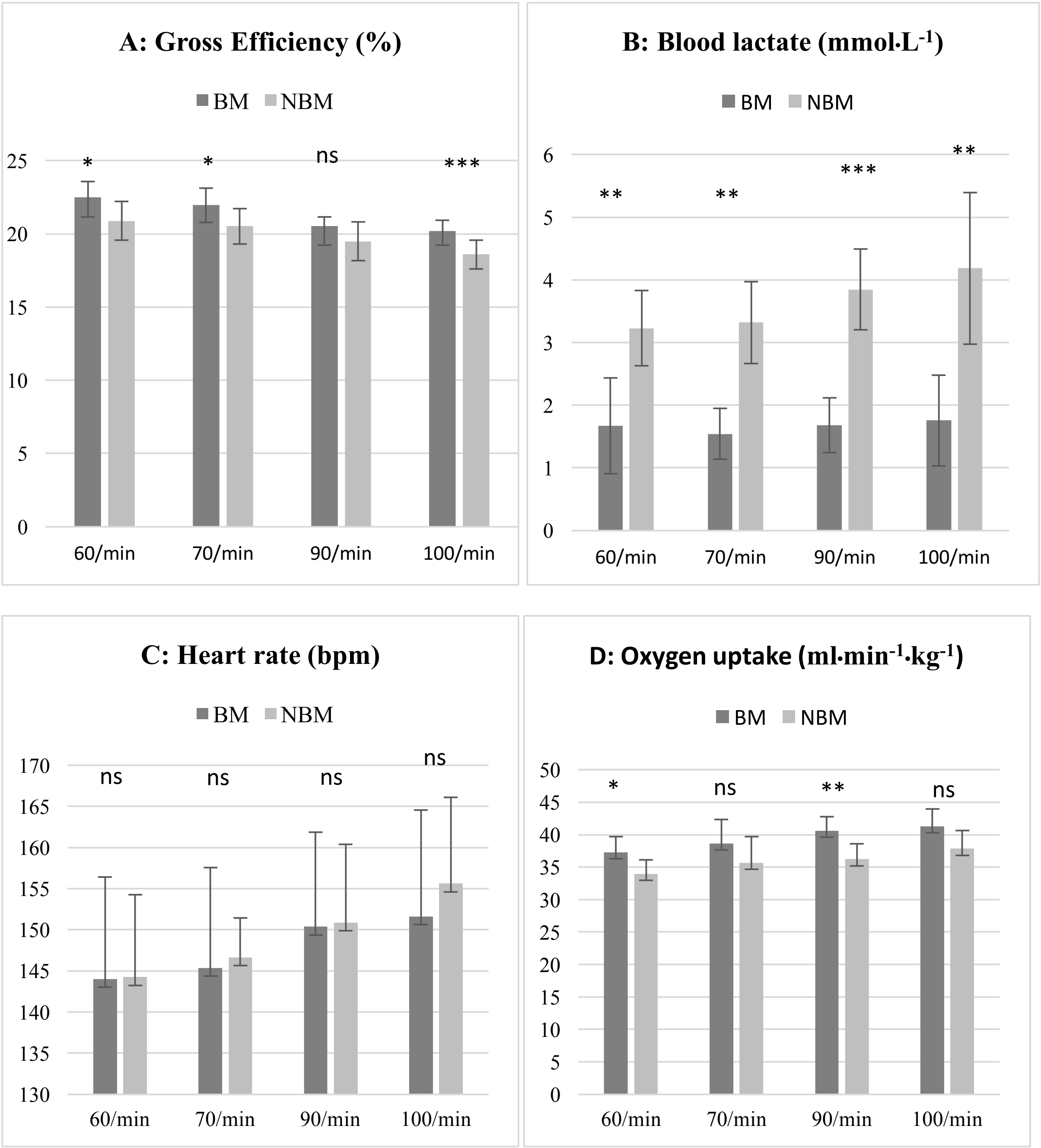

Figure 1. *Evolution and intergroup differences in mean ±SD GE, BLC, HR and* $\dot{V}O_2$ *over the cadences (BM: bicycle messengers, NBM: non-bicycle messengers, GE: gross efficiency, BLC: blood lactate concentration, HR: heart rate,* $\dot{V}O_2$*: oxygen uptake at the specified cadence, ns: p-value>0.05, *: p-value ≤ 0.05, **: p-value ≤ 0.01, ***: p-value ≤ 0.001).*

The greatest GE was found at the slowest pedaling rate tested and decreased as the cadence increased. In contrast, BLC, HR and $\dot{V}O_2$ all increased as the pedaling rate increased. These results indicate that the most efficient preselected pedaling rate is the slowest (60 rpm) tested.

Intergroup correlations

A correlation was found in both groups combined between MAP per kilogram and GE at 60, 90 and 100 rpm and between MAP per kilogram and low blood lactate at all pedaling rates

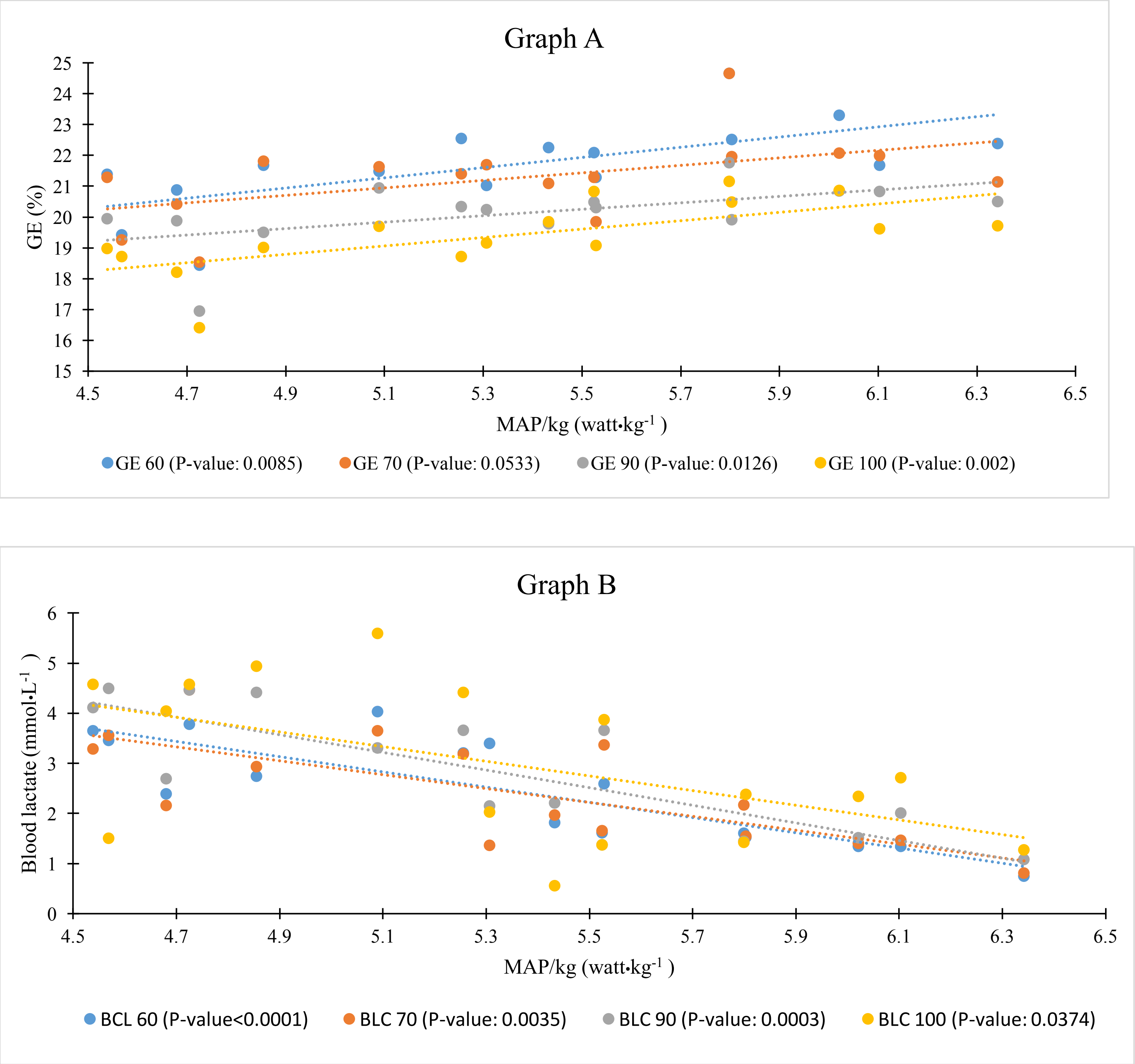

Figure 2. *Graph A: Correlation between GE at different cadences and MAP/kg. Graph B: Correlation between BLC at different cadences and MAP/kg. (GE: Gross efficiency, BLC: Blood lactate concentration at 50% of MAP, MAP/kg: Maximal aerobic power per body weight)*

These results show that in both groups, subjects with a high MAP tend to be more efficient and have a higher aerobic capacity than subjects with a low MAP.

Isokinetic strength test

During the isokinetic strength test, NBMs had significantly stronger hamstring muscles (0.036). No other significant intergroup differences were found during the isokinetic strength test (see table 4).

PT/bw (%)	**Bike messenger (n=8)**	**Non-bike messenger (n=8)**	**P-Value**
Right quadriceps	284.2 ± 37.1	304.7 ± 32.5	0.396
Right hamstring	147.5 ± 11.3	167.4 ± 22.2	0.036
Endurance			
Right quadriceps	89.5 ± 5.2	85.7 ± 6.6	0.314
Right hamstring	83 ± 4.1	77.7 ± 11.2	0.245

Table 4. *Intergroup differences in Peak Torque per body weight calculated as a percentage of body weight lifted and intergroup difference in endurance of the quadriceps and the hamstring muscles of the right leg. Results are given in mean ± S). (PT/bw: peak torque/body weight)*

Few relationships between GE and isokinetic test were found in BMs. GE at 60 rpm is correlated with total work done by right hamstring muscles at 180°/s in BMs (p-value: 0.0225). GE at 70 rpm is correlated with peak torque to body-weight ratio of the right quadriceps at 60°/s in BMs (p-value: 0.0453). No clear correlation between GE and the isokinetic strength test was found in NBMs.

Finally, other dispersed correlations were found in BMs between GE at 90rpm and $\dot{V}O_2max$ (p-value: 0.0463), GE at 90 rpm and MAP (p-value: 0.0407), GE at 90rpm and GE at 70rpm (p-value: 0.0369), and GE at 100rpm and GE at 60rpm (p-value: 0.0154). In NBMs GE at 60rpm is correlated with GE at 70rpm (p-value: 0.004).

Discussion

The goal of this study was to measure and compare an isokinetic strength test and gross efficiency in two groups: bicycle messengers and athletic non-bike messengers. Results showed a significant difference in $\dot{V}O_2max$ MAP/kg and GE at almost all pedaling rates. Results also showed, in both groups, that the most efficient cadence is 60 rpm, the lowest tested, and that GE linearly decreases as pedaling rate increases. It has also been found that in parallel with increasing cadence, heart rate and $\dot{V}O_2$ also increase. In NBMs, blood lactate concentration tends to increase with pedaling rate. But, on the other hand, blood lactate stays stable in the BM group.

NBMs have significantly stronger hamstring muscles than BMs, but there is no intergroup difference in muscle fatigability. Few correlations between isokinetic strength test and GE at different cadences were found in BMs. No correlations were found in the NBM group. Finally, some expected relationships were found. In both groups, subjects with a high MAP/kg ratio tend to have a better GE and lower blood lactate at every pedaling rate.

As mentioned in the introduction, efficiency can be affected by many factors in cycling (13): cadence (9); body mass (14); cycling position (15, 16); pedaling technique (17); prior exercise (18); muscle fiber type (11, 19); training status; and maximal strength training (20-23). Some of these factors are similar in both of groups, but others, such as training status, muscle fiber type and pedaling technique may differ and explain the differences.

Some studies, unlike ours, show no difference in GE between trained and non-trained cyclist, concluding that years of experience and specific training does not improve efficiency (34). It was long thought that training had no effect on GE. However, as explained by Hopker & al. in their review, investigation and statistical methods of these studies were not appropriate (35). Another study by Hopker & al. found that, similar to this study, there is a significant difference in GE between trained and untrained cyclists, reflecting the effect of experience and specific training on efficiency (36).

It has been shown that that long-term endurance training increases the amount of slow muscle fiber (type 1) (29). It has also been shown that cyclists with higher amount of slow muscle fibers tend to have better GE at equivalent $\dot{V}O_2max$ (19). This reinforces the idea that training and experience has a beneficial effect on GE.

Pedaling technic is another important factor in the difference in GE between BMs and NBMs (17). Cyclists with better pedaling technique are able to apply perpendicular force on the crank almost all along the pedal revolution, greatly limiting the dead centers, which are the moments without applied force (17). As illustrated in the introduction, GE does not take into account the influence of basal metabolism, muscle activation, coordination, etc. Since pedaling technique influences GE, a less experienced cyclist will consume more energy to accomplish the same effort (17). This results in a lower GE for NBMs caused by their lack of experience in cycling and, therefore, probably by their less effective pedaling.

Another important finding of this study is that, in both groups, the most efficient pedaling rate is the lowest tested (60 rpm). This result is in accordance with many studies on the subject. Most studies state that the most efficient pedaling rate lies between 30-60rpm (9, 25). As Chavarren and Calbet explain, at a determined intensity, increased pedaling rate causes an increase in internal work, which provokes a decrease in GE (7, 9, 37). This phenomenon is even more important for non-skilled-cyclists, like NBMs, due to their lack of pedaling technique (25). As said before, at high intensity, the influence of pedaling rate on GE becomes less significant. Similar to the present study, other studies conducted at low intensity (30-60% of $\dot{V}O_2$max), have found better efficiency at low pedaling rates (9).

This begs the question, “Why do cyclists choose a higher pedaling rate on the field?” Some studies have tried to answer this question and have shown that an increase in intensity and pedaling technique results in a higher optimal pedaling rate (25) with less force needed on the crank (38). This may allow the use of type 1 muscle fibers, which are weaker than type 2 muscle fibers, but have a higher oxidative capacity and are therefore more suited to endurance activities such as cycling.

As with many other studies, this study tested efficiency during a short time period, which does not exactly reflect the exercise usually performed by cyclists outside a laboratory. A study followed a protocol with longer exercise period, testing the pedaling rate during 30 minutes at 85% of $\dot{V}0_2$max. This tries to simulate the effort made during a real bike tour. It resulted in a 60 to 80rpm optimum cadence which tends to get closer to the preferred pedaling rate approximately calculated at 90rpm (24, 39). This point reveals another weakness of our study, for a more realistic exercise we should have tested our subjects during a longer time period. This was unfortunately not possible for practical reasons.

In their 2015 study, Beneke and Alkhatib explained that an increase in cadence causes an increase in BLC. They also emphasized that variations in BLC are even greater when increasing the exercise intensity (40). At all cadences, BLC is a robust endurance predictor (41). Results in this study show a significant increase in BLC with as cadence increases in the

NBM group. The BMs, on the other hand, showed a more stable BLC throughout the different pedaling rates, indicating that they were still pedaling below their maximal lactate steady states (MLSS). MLSS is defined as “the highest exercise intensity at which blood lactate remains stable,” and it has been shown that trained cyclists reach a higher MLSS than non-trained cyclists (41). This difference in BLC between the groups shows that NBMs have a lower oxidative capacity suggesting that anaerobic glycolysis is significantly during exercise. We calculated the consumed energy by measuring oxygen exchange during the tests. Since anaerobic glycolysis does not use oxygen to produce energy, it cannot be measured. This means that the actual energy spent to complete the test is underestimated by the measurements in the NBM group. GE is, therefore incorrect in the NBM group

The results also showed a close relationship between MAP/kg and low BLC in both groups. Not many studies have been conducted on this exact topic but we can try to explain it this way. Both BLC and MAP are considered to be excellent cycling performance predictors (41). In this study, BMs have a significantly higher MAP/kg and significantly lower BLC than NBMs. Furthermore, unlike untrained cyclists, trained cyclists, with their better oxidative capacity are able to maintain a low BLC at much higher intensity (41). It is then not hard to believe that those with a greater MAP/kg tend to have low BLC at 50% of their MAP.

Chavarren and Calbet, in their study, state that pedaling rate has no influence on heart rate and that heart rate is related to exercise intensity (9). In contrast, other studies find the lowest HR occurs at 80 rpm and that HR increases simultaneously with pedaling rate. These findings are consistent with this study, in which different pedaling rates were tested at the same intensity. These results show a clear increase in heart rate with increasing cadence.

Isokinetic strength test showed that NBMs had stronger hamstring muscles than BMs. This can be explained by the diversity of sport practiced by NBMs and thus the probable use of more muscular groups. Cycling implies very repetitive movements and these results show that even with good pedaling technique and the use of clipless shoes that allow for push and pull on the pedal, most of the strength is applied during the pushing phase of the pedal revolution. Therefore, quadriceps are more involved than hamstring muscles in the pedal’s movement.

On the other hand, many studies have shown that maximal strength training is correlated with increased GE (20-23, 31). We presumed that maximal strength indexes like isokinetic peak torques could be correlated with GE at different cadences. The results of this study do not clearly validate this hypothesis.

It is important to add that this study only contained 8 subjects per group. For more accurate results, it would have been interesting to conduct this study with a larger number of subjects.

In conclusion, this study demonstrates that there is a clear difference in GE, $\dot{V}O_2$max, BLC and MAP/kg in favor of BMs and that this increased oxidative capacity can in large part be explained by differences in specific endurance training. The most efficient cadence was 60 rpm in both groups. Along with increased cadence, GE worsens and $\dot{V}O_2$, and heart rate increase in both groups. BLC only increases in the NBM group. We also found a clear relationship between MAP/kg and low BLC in both groups. One of the main objectives of this study was to see if there was any relationship between GE at different cadences and maximal strength test on an isokinetic machine. A secondary objective was to see if muscular fatigability calculated with this same test was correlated with efficiency. Few correlations between GE and the muscular strength test were found in BMs. Thus, isokinetic strength testing, which only measures knee extensors and flexors strength, does not appear to be useful for evaluating GE in cycling, in contrast to one repetition maximum in squats, which are closed-chain multi-joint movements , (21). Finally, these results showed that NBMs have significantly stronger hamstring muscle than BMs, and that despite clipless shoes and good pedaling technique, quadriceps muscles are naturally more involved than knee flexors in the pedal's revolution.

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References

1. Ettema G, Loras HW. Efficiency in cycling: a review. Eur J Appl Physiol. 2009;106(1):1-14.

2. Grappe F. Cyclisme et optimisation de la performance: Science et méthodologie de l’entraînement: De Boeck Supérieur, 2009

3. Hill AV. The maximum work and mechanical efficiency of human muscles, and their most economical speed. The Journal of physiology. 1922;56(1-2):19-41.

4. W B, A. Arfaoul, S. Duc. Le rendement en cyclisme.

5. Hintzy F, Tordi N, Perrey S. Muscular efficiency during arm cranking and wheelchair exercise: a comparison. International journal of sports medicine. 2002;23(6):408-14.

6. L. MOSELEY AEJ. The reliability of cycling efficiency. Medicine & Science in Sports & Exercise. 2001;33(4):507-683.

7. Gaesser GA, Brooks GA. Muscular efficiency during steady-rate exercise: effects of speed and work rate. J Appl Physiol. 1975;38(6):1132-9.

8. Neptune RR, Herzog W. The association between negative muscle work and pedaling rate. Journal of biomechanics. 1999;32(10):1021-6.

9. Chavarren J, Calbet JA. Cycling efficiency and pedalling frequency in road cyclists. European journal of applied physiology and occupational physiology. 1999;80(6):555-63.

10. Faria EW, Parker DL, Faria IE. The science of cycling: physiology and training - part 1. Sports medicine (Auckland, NZ). 2005;35(4):285-312.

11. Horowitz JF, Sidossis LS, Coyle EF. High efficiency of type I muscle fibers improves performance. International journal of sports medicine. 1994;15(3):152-7.

12. Jeukendrup AE, Craig NP, Hawley JA. The bioenergetics of World Class Cycling. Journal of science and medicine in sport / Sports Medicine Australia. 2000;3(4):414-33.

13. Hopker J, Jobson S, Carter H, Passfield L. Cycling efficiency in trained male and female competitive cyclists. Journal of sports science & medicine. 2010;9(2):332-7.

14. Berry MJ, Storsteen JA, Woodard CM. Effects of body mass on exercise efficiency and VO2 during steady-state cycling. Medicine and science in sports and exercise. 1993;25(9):1031-7.

15. Harnish C, King D, Swensen T. Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs. Eur J Appl Physiol. 2007;99(4):387-91.

16. Peveler WW. Effects of saddle height on economy in cycling. Journal of strength and conditioning research / National Strength & Conditioning Association. 2008;22(4):1355-9.

17. Leirdal S, Ettema G. Pedaling technique and energy cost in cycling. Medicine and science in sports and exercise. 2011;43(4):701-5.

18. Passfield L, Doust JH. Changes in cycling efficiency and performance after endurance exercise. Medicine and science in sports and exercise. 2000;32(11):1935-41.

19. Coyle EF, Sidossis LS, Horowitz JF, Beltz JD. Cycling efficiency is related to the percentage of type I muscle fibers. Medicine and science in sports and exercise. 1992;24(7):782-8.

20. A. Sunde ØS, M. Bjerkaas, Morten H. Larsen, J. Hoff, J. Helgerud. Maximal strenghth training improves cycling economy in competitive cyclist. Journal of Strength and Conditioning Research. 2010;24(8)/2157–2165.

21. Loveless DJ, Weber CL, Haseler LJ, Schneider DA. Maximal leg-strength training improves cycling economy in previously untrained men. Medicine and science in sports and exercise. 2005;37(7):1231-6.

22. Bastiaans JJ, van Diemen AB, Veneberg T, Jeukendrup AE. The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists. Eur J Appl Physiol. 2001;86(1):79-84.

23. Louis J, Hausswirth C, Easthope C, Brisswalter J. Strength training improves cycling efficiency in master endurance athletes. Eur J Appl Physiol. 2012;112(2):631-40.

24. Lucia A, Hoyos J, Chicharro JL. Preferred pedalling cadence in professional cycling. Medicine and science in sports and exercise. 2001;33(8):1361-6.

25. Coast JR, Welch HG. Linear increase in optimal pedal rate with increased power output in cycle ergometry. European journal of applied physiology and occupational physiology. 1985;53(4):339-42.

26. Hintzy F, Belli A, Grappe F, Rouillon JD. Optimal pedalling velocity characteristics during maximal and submaximal cycling in humans. European journal of applied physiology and occupational physiology. 1999;79(5):426-32.

27. Stuart MK, Howley ET, Gladden LB, Cox RH. Efficiency of trained subjects differing in maximal oxygen uptake and type of training. Journal of applied physiology: respiratory, environmental and exercise physiology. 1981;50(2):444-9.

28. Suzuki Y. Mechanical efficiency of fast- and slow-twitch muscle fibers in man during cycling. Journal of applied physiology: respiratory, environmental and exercise physiology. 1979;47(2):263-7.

29. Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, et al. Physiological and biomechanical factors associated with elite endurance cycling performance. Medicine and science in sports and exercise. 1991;23(1):93-107.

30. Hansen EA, Andersen JL, Nielsen JS, Sjogaard G. Muscle fibre type, efficiency, and mechanical optima affect freely chosen pedal rate during cycling. Acta physiologica Scandinavica. 2002;176(3):185-94.

31. Ronnestad BR, Hansen J, Hollan I, Ellefsen S. Strength training improves performance and pedaling characteristics in elite cyclists. Scandinavian journal of medicine & science in sports. 2015;25(1):e89-98.

32. P. Edouard FD. Guide d'isocinétisme. Elsevier/Masson, editor2016 09/2016. 352 p.

33. Isocinetisme, guide clinique [Internet]. Elite Médicale. 2009.

34. Moseley L, Achten J, Martin JC, Jeukendrup AE. No differences in cycling efficiency between world-class and recreational cyclists. International journal of sports medicine. 2004;25(5):374-9.

35. Hopker J, Passfield L, Coleman D, Jobson S, Edwards L, Carter H. The effects of training on gross efficiency in cycling: a review. International journal of sports medicine. 2009;30(12):845-50.

36. Hopker JG, Coleman DA, Wiles JD. Differences in efficiency between trained and recreational cyclists. Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme. 2007;32(6):1036-42.

37. Sidossis LS, Horowitz JF, Coyle EF. Load and velocity of contraction influence gross and delta mechanical efficiency. International journal of sports medicine. 1992;13(5):407-11.

38. Patterson RP, Moreno MI. Bicycle pedalling forces as a function of pedalling rate and power output. Medicine and science in sports and exercise. 1990;22(4):512-6.

39. Coast JR, Cox RH, Welch HG. Optimal pedalling rate in prolonged bouts of cycle ergometry. Medicine and science in sports and exercise. 1986;18(2):225-30.

40. Beneke R, Alkhatib A. High cycling cadence reduces carbohydrate oxidation at given low intensity metabolic rate. Biology of sport. 2015;32(1):27-33.

41. al. Fe. The Science of Cycling: Part 1 293 ed2005.