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Effective force and economy of triathletes and cyclists

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Abstract
The effective force applied on the crank, the index of pedalling effectiveness, and the economy of movement at 60, 75, 90, and 105 rev/min cadences were examined in nine cyclists and eight triathletes. Tests were performed on two days. Maximal oxygen uptake was measured and the second ventilatory threshold was estimated on day 1 using a stationary bicycle. On day 2, the four different cadences were tested at about 5% below the second ventilatory threshold. A strain gauge instrumented clip-less pedal mounted on the bicycle enabled us to measure the normal and tangential forces exerted on the pedal, while the pedal and crank angles were monitored with the aid of a video system. Based on this information, the effective force and the index of pedalling effectiveness were calculated. Cyclists produced significantly more effective force and a higher index of pedalling effectiveness at 60 and 75 rev/min and were significantly more economic at all cadences than triathletes. The significant and positive correlation between effective force and economy at all cadences suggests that improvement of the effective force would reflect on economy.

Keywords: *Cycling, economy, effective force, triathlon*

Introduction

Cycling technique has been examined using instrumented platforms that measure the components of force exerted on the pedal (Boyd, Hull, and Wootten, 1996; Davis and Hull, 1981; Hull and Davis, 1981; Gregor, 2000; Lafortune and Cavanagh, 1983; Too, 1990; Wheeler, Gregor, and Broker, 1992). Based on this information, the resultant force on the pedal has been calculated, and using the instantaneous geometry of the pedal and crank, the force perpendicular to the crank has been calculated and denoted the "effective force" (Broker and Gregor, 1996; Ericson and Nisell, 1988; Gregor, 2000; Patterson and Moreno, 1990). This latter force mixes information about technical aspects of pedalling with the ability to generate propulsive force. The ratio between the effective force and resultant pedal force has also been used in the analysis of pedalling and it has been denoted the "index of effectiveness" (Gregor, 2000; Lafortune and Cavanagh, 1983; Sanderson, 1991). As a ratio, however, the index of pedalling effectiveness only provides information about the technique itself; it does not take account of the physiological effort that the athlete is expending.

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Data relating to the effective force and index of pedalling effectiveness can be found in the literature for cyclists of different standards (Broker and Gregor, 1996; Gregor, 2000; Groot et al., 1994; Lafortune and Cavanagh, 1983) and can be used in the process of learning or training competitive cycling (Sanderson and Cavanagh, 1990).

A review of the literature reveals less information about triathletes than cyclists, and success in triathlon is very much dependent on cycling, irrespective of whether the race is short or long. Thus, triathletes must master the technique of cycling as best they can (Millet and Vleck, 2000; O'Toole, Douglas, and Hiller, 1989; Rowlands and Downey, 2000; Sleivert and Rowlands, 1996). In addition to cycling, triathletes need to practise swimming and running; therefore, it is likely that they will not perform as well as cyclists and may not develop the same technique as cyclists. There is evidence to support this, in that cyclists prefer to adopt higher cadences than triathletes (Brisswalter, Hausswirth, Smith, Vercruyssen, and Vallier, 2000; Gotshall, Bauer, and Fahrner, 1996). Although some authors have reported that pedalling at higher cadences, specifically between 90 and 110 rev/min, might be more economical (Chen, Jones, and Killian, 1999; Coast, 1996; Coast, Cox, and Welch, 1986; Hagberg, Mullen, Giese, and Spitznagel, 1981), particularly at high power outputs, others have shown the opposite to be true (Brisswalter et al., 2000; Gotshall et al., 1996; Marsh and Martin, 1997; Marsh, Martin, and Sanderson, 2000; Miura, Kitigawa, and Ishiko, 1997; Takaishi, Yamamoto, Ono, Ito, and Moritani, 1998). Therefore, as cyclists prefer higher cadences than triathletes, it would be interesting to compare the influence of cadence on the economy of triathletes and cyclists together with force parameters.

The aim of this study was to compare the effective force, index of effectiveness, and economy in triathletes and cyclists of state standard while pedalling at four different cadences. We speculated that when tested at four different cadences, state triathletes would produce less effective force, obtain lower indices of effectiveness, and be less economical than state cyclists, when evaluated at an effort close to their anaerobic threshold.

Methods

Participants

Nine cyclists and eight triathletes took part in the study, which was approved by the university ethics committee. Before participating, the athletes signed a written consent form. All athletes were involved in competitions that lasted at least 2 h and participated in state and national events. Information about age, years of practice, and physical characteristics is given in Table I.

First test day

The participants were tested using an ergometer (Cardio2 bicycle, Medical Graphics Corp., St. Louis, USA) fitted with competitive clip-less pedals, handlebars, and saddle. Maximal

Table I. Characteristics of the athletes (mean ± *s*).

	Age (years)	Years of practice	Body mass (kg)	Height (m)	Body fat* (%)
Cyclists ($n = 9$)	25.1 ± 7.6	7.7 ± 6.5	67.1 ± 5.6	1.73 ± 0.1	8.9 ± 1.8
Triathletes ($n = 8$)	27.5 ± 9.2	6.9 ± 4.2	68.1 ± 8.9	1.73 ± 0.1	8.1 ± 1.6

* Calculated using Yuhasz's equation.

oxygen uptake ($\dot{V}O_{2max}$) was measured (CPX/D Medical Graphics Corp., St. Louis, USA) and the protocol adopted consisted of a ramp test with increments of 0.5 W every second until exhaustion. The cadence was freely chosen.

The anaerobic threshold was estimated using the second ventilatory threshold, calculated according to the double-blind evaluation procedure (Wasserman and Koyke, 1992). This was necessary since our goal was to physiologically normalize the effort of all athletes and keep it, in all trials, close to that value during the second day of testing.

Second test day

Four cadences (60, 75, 90, and 105 rev/min) were randomly assigned and evaluated, while oxygen consumption was monitored continuously and kept approximately 5% below the second ventilatory threshold. Thus, it was necessary to adjust individually the load to keep the oxygen consumption close to that desired until each athlete reached his or her steady state (Coyle et al., 1991). The time taken for oxygen consumption to remain stable (steady state) was around 5 min; after that, no changes in the load were necessary and each trial was performed for 3 min more. Data were collected in the last 30 s of this period.

Reflective markers were placed on the axis of the crank and axis of the pedal. A rigid 0.25-m thin stick with reflective markers at each end was fixed to the pedal in parallel with the top of the pedal in an attempt to reduce error during the digitization procedure. A video system consisting of a video camera (Peak Performance Technologies Inc., Englewood, USA), operating at a nominal rate of 120 Hz, was used to obtain the angle of the crank (α) and angle of the pedal (β) as illustrated in Figure 1. Standard procedures for the use of video were observed for obtaining kinematic variables.

A clip-less instrumented pedal was constructed, calibrated, and mounted on the bicycle. This pedal enabled the tangential and normal forces exerted on the pedal to be monitored continuously throughout each revolution of the crank. Briefly, the pedal consisted of four aluminium (Al 6351T6) beams in balance, instrumented with eight strain gauges (full Wheatstone bridges). The pedal was connected to a force coupler (MSC6, Entran Ltd., UK) and an analog-to-digital system with a 16-channel board (Dataq Instruments Inc., Akron, USA). The system was calibrated using a load machine and known loads. Within the range of measured forces, the correlation coefficients between the known loads and voltage output were 0.999 and 0.998 for the normal and tangential components, respectively. The natural frequency of the system was 730 Hz. The data were collected using a specially developed software acquisition system (SAD32) and a personal computer (Pentium 200). The sampling frequency of each channel was 1818 Hz (20 kHz total sampling frequency divided by 11 channels). The data obtained from the video and force systems were synchronized and data were collected during the last 30 s of a 3-min period in each trial.

Data processing

Data corresponding to ten consecutive complete cycles were extracted from each 30 s of information acquired and used in the analysis. The kinematic and force data were processed using MATLAB® (version 5.3, Mathworks, 1966) as described by Candotti and colleagues (Candotti, Soares, Loss, and Guimarães, 2002). Two coordinate systems were defined. A rotation matrix was used to transfer the data initially obtained with respect to the pedal reference system to the crank coordinate system. The pedal reference XY system was set to allow the normal and parallel forces exerted on the pedal to be defined, and the resultant pedal force to be calculated. The second reference (crank) system $x'y'$ was set to allow the

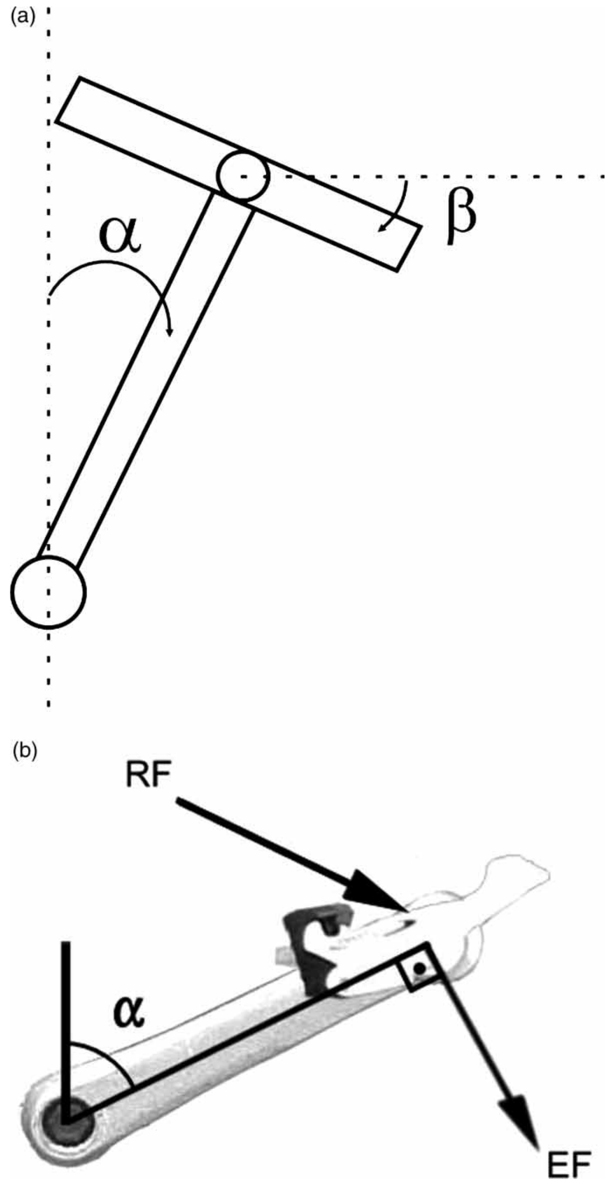

Figure 1. (a) Crank angle (α) and pedal angle (β). (b) Resultant force (RF) and effective Force (EF).

forces normal and parallel to the crank to be computed. The perpendicular component to the crank was defined as the effective force and the parallel component to the crank as the ineffective force. The effective force was assumed to be positive when it acted in the same direction as the crank was rotating, and the ineffective force was positive when it acted away from the axis of the crank.

Individual and mean graphs of resultant force and effective force expressed as a function of the crank angle were produced for cyclists and triathletes at each cadence. After that, the individual and mean indices of pedalling effectiveness were calculated as proposed by

Sanderson (1991): IE = EF/RF, where IE = index of pedalling effectiveness, EF = effective force, and RF = resultant force.

Individual and mean economy of movement were calculated for each condition tested using the monitored oxygen consumption and the corresponding power obtained from the ergometer as proposed by Moseley and Jeukendrup (2001): EC = $P/\dot{V}O_2$, where EC = economy of movement, P = power, and $\dot{V}O_2$ = oxygen consumption.

Statistical analysis

A casual block design was adopted for each dependent variable (index of pedalling effectiveness, effective force, and economy of movement): two groups (cyclists and triathletes) and four cadences (60, 75, 90, and 105 rev/min). Ten consecutive revolutions recorded from each participant, under each condition tested, were used to calculate the mean and standard error of each variable. Subsequently, the mean and standard error were calculated for cyclists and triathletes and submitted to Levene's normality test. Variables that were normally distributed were submitted to a one-way analysis of variance (ANOVA) and, in the case of significant differences, also submitted to a Tukey *post-hoc* test. Variables that were not normally distributed were initially submitted to a logarithmic transformation and subsequently to a non-parametric Wilcoxon-Mann-Whitney test. The Pearson product–moment correlation was used to evaluate the association between effective force and economy of movement using the pooled data of the two groups for each cadence. Statistical significance was set at $P < 0.05$ and all statistical procedures were performed using SPSS version 10.0.

Results

Maximal oxygen uptake, the second ventilatory threshold, and the corresponding load of cyclists and triathletes on the first day of testing are presented in Table II, together with the second ventilatory threshold at each cadence obtained on the second day of testing. The mean cadences adopted by cyclists and triathletes were 105 ± 15 rev/min and 90 ± 10 rev/min, respectively, on day 1.

Although cyclists recorded a higher $\dot{V}O_{2max}$ and load at the second ventilatory threshold than triathletes, no significant differences were observed when the second ventilatory threshold of the two groups was compared. The largest mean difference between the targeted

Table II. Maximal oxygen uptake ($\dot{V}O_{2max}$), second ventilatory threshold, and corresponding load on the first day of testing; and second ventilatory oxygen threshold at different cadences obtained during the second day of testing (mean ± standard error).

	First day			Second day			
	$\dot{V}O_{2max}$* (l/min)	Second ventilatory threshold (l/min)	Load* (W)	Second ventilatory threshold (l/min)			
				60 rev/min	75 rev/min	90 rev/min	105 rev/min
Cyclists	4.0 ± 0.2	3.2 ± 0.1	272 ± 21	3.1 ± 0.1	3.2 ± 0.1	3.2 ± 0.2	3.2 ± 0.1
Triathletes	3.4 ± 0.2	2.9 ± 0.1	249 ± 8	2.8 ± 0.1	2.9 ± 0.1	2.9 ± 0.1	2.8 ± 0.1

* Significant difference ($P < 0.05$).

second ventilatory threshold (day 1) and the mean obtained second ventilatory threshold (day 2) at different cadences was 3%. This difference can be calculated using information shown in Table II.

Figure 2 shows mean curves of effective force expressed as a function of the crank angle obtained by one cyclist and by one triathlete at 75 rev/min and 90 rev/min. The mean and standard error of effective force obtained for the ten cycles are shown in Figure 3 for cyclists and triathletes. The values obtained by cyclists were consistently higher than the corresponding values of triathletes, although significant differences between groups were found only for the 60 and 75 rev/min cadences. When within-group comparisons were performed, both cyclists and triathletes showed a trend, as effective force decreased as cadence increased. Cyclists showed significant differences between 60 and 90 rev/min, 60 and 105 rev/min, and 75 and 105 rev/min, whereas triathletes showed significant differences between 60 rev/min and the other three cadences, between 75 and 90 rev/min, and between 90 and 105 rev/min.

The mean and standard error of the index of pedalling effectiveness obtained for the ten cycles are shown in Figure 4 for cyclists and triathletes. Cyclists obtained higher indices of pedalling effectiveness than thriathletes at all four cadences, but only those at 60 and 75 rev/min were significantly different. Within-group comparisons did not reveal any significant differences.

The mean and standard error of the economy of movement obtained for the ten cycles are shown in Figure 5 for cyclists and triathletes. When the economy of movement of the two groups was compared, cyclists were found to be more economical than triathletes at all cadences. Within-group comparisons did not reveal any significant differences.

There were significant correlations between effective force and economy of movement at 60 rev/min ($r = 0.66$), 75 rev/min ($r = 0.72$), 90 rev/min ($r = 0.57$), and 105 rev/min ($r = 0.57$) when the pooled data of cyclists and triathletes were examined (Figure 6). The positive sign of these correlations indicated that the athletes were more economical as effective force increased.

Discussion and implications

Previous studies concerned with the technique of pedalling have used non-athletes (Broker, Gregor, and Schmidt, 1993; Ericson and Nisell, 1988; Patterson and Moreno, 1990), national calibre athletes (Sanderson, 1991; Smak, Neptune, and Hull, 1999), and international standard athletes (Caldwell, Li, McCole, and Hagberg, 1998; Coyle et al., 1991; Kautz, Feltner, Coyle, and Baylor, 1991; Sanderson and Black, 2003) and, as stated in the Introduction, the literature contains much less information about triathletes than cyclists. In the present study, we compared cyclists and triathletes based on the premise that cyclists would perform better and have a better technique than triathletes, with the comparison being made on the basis of effective force, index of pedalling effectiveness, and economy of movement. The participants of both groups in this study were classified as state calibre athletes, as indicated by their competitive results. Thus, as anticipated, $\dot{V}O_{2max}$ and the second ventilatory threshold of both cyclists and triathletes (Table II) were below values reported in the literature for international athletes (Gregor, 2000; Rowlands and Downey, 2000). Although cyclists recorded a significantly higher mean $\dot{V}O_{2max}$, a non-significant difference was found between the second ventilatory threshold of the two groups.

The adoption of the second ventilatory threshold as a criterion to establish the effort in all conditions tested was an attempt to ensure that all participants performed at a normalized physiological level and all tests were conducted close to an exertion that supposedly reflected

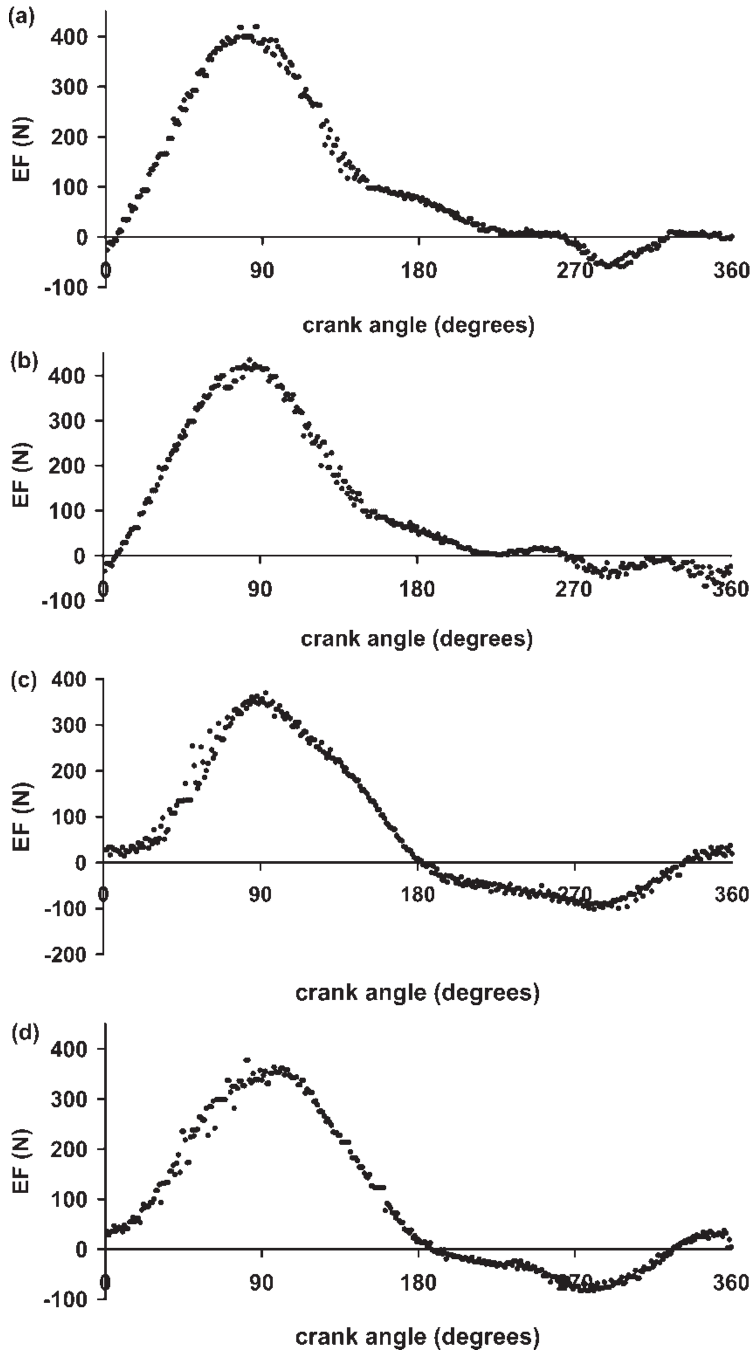

Figure 2. Mean curves of effective force (EF) expressed as a function of crank angle: (a) cyclist at 75 rev/min; (b) cyclist at 90 rev/min; (c) triathlete at 75 rev/min; (d) triathlete at 90 rev/min.

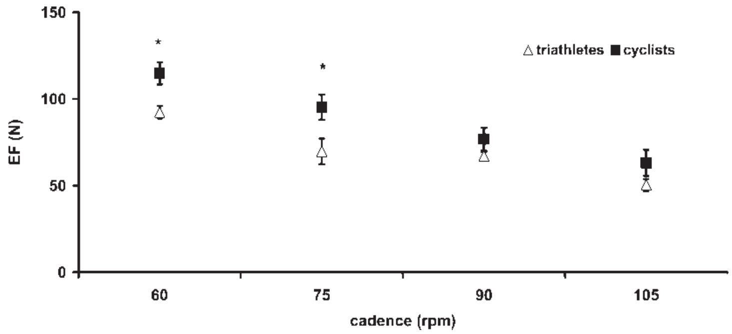

Figure 3. Mean and standard error of effective force (EF) for cyclists and triathletes at the four cadences (* $P < 0.05$).

the effort that athletes maintain for considerable periods during a race. It was also an attempt to avoid any mechanical advantages that cyclists have, as they have a much greater power output, which could presumably translate into a greater effective force. This procedure was based on a previous study reported by Coyle et al. (1991).

Effective force × cadence

The magnitude and orientation of the resultant pedal force change constantly throughout one entire revolution of the crank. While the magnitude of the resultant force expresses the physical capacity of the athlete to generate force, the orientation of this force determines how much of it will actually be converted into effective force. The effective force, consequently, provides information about the physical and technical characteristics of the athlete; therefore, its use is convenient when the goal is to evaluate performance (Broker and Gregor, 1996).

A qualitative inspection of Figures 2a (75 rev/min) and 2b (90 rev/min) reveals that the overall shapes and values of the effective force were similar to those reported previously (Broker and Gregor, 1996). Positive effective force (propulsive) and negative effective force (resistive) values were primarily associated with the propulsion phase (between 0 and 180°) and recovery phase (between 180 and 360°), respectively, in most participants. Only three cyclists were able to generate some propulsive effective force during the recovery phase, but that happened only during brief periods. Thus, these findings are in line with those reported

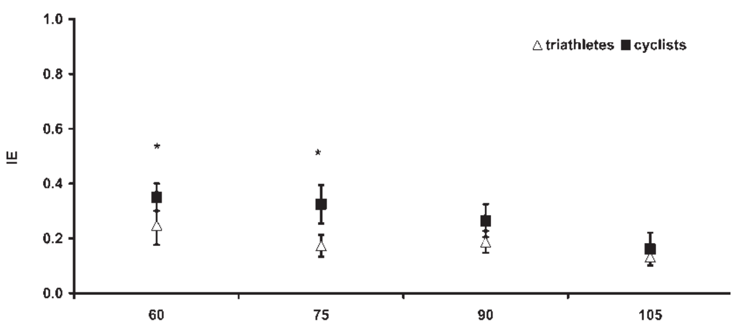

Figure 4. Mean and standard error of index of pedalling effectiveness (IE) for cyclists and triathletes at the four cadences (* $P < 0.05$).

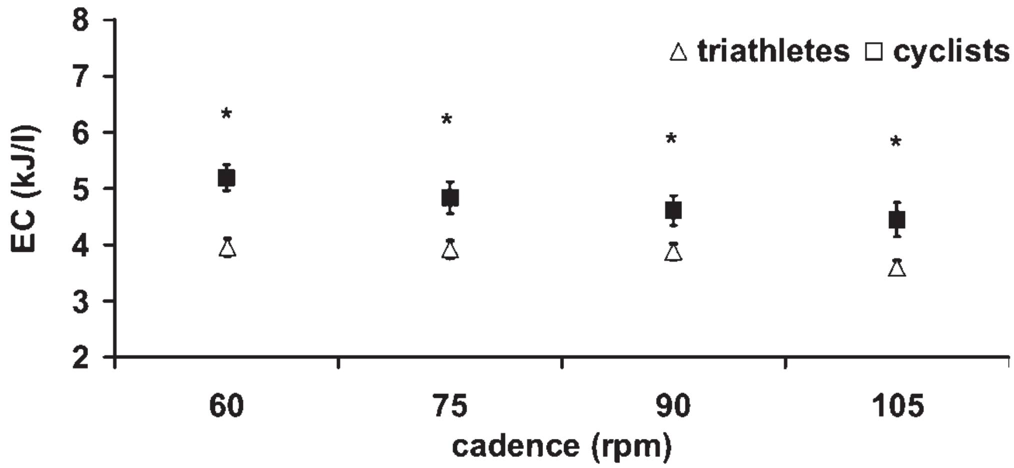

Figure 5. Mean and standard error of economy of movement (EC) for cyclists and triathletes at the four cadences (* $P < 0.05$).

in the literature, as it is uncommon for athletes to generate propulsion during the recovery phase (Groot et al., 1994).

A clear trend for a decrease in the effective force as cadence increased is seen in Figure 3 for both cyclists and triathletes, although not all within-group comparisons were significantly different. These results compare well with previously reported data (Patterson and Moreno, 1990; Takaishi et al., 1998), and it has been postulated that athletes may prefer to cycle at relatively higher cadences even though this option tends to reduce the effective force. One possibility is that higher cadences demand less muscle torque, implying the use of low force-producing, fatigue-resistant type 1 fibres, and may not produce as much muscle fatigue as lower cadences (Marsh et al., 2000).

The significantly higher values found for cyclists at 60 and 75 rev/min but not at 90 and 105 rev/min were somewhat surprising. It has been documented that cyclists prefer to pedal at higher cadences than triathletes (Brisswalter et al., 2000; Gotshall et al., 1996), and the present study produced further evidence in support of this. One could expect that significant differences would be found at the relatively higher cadences of 90 and 105 rev/min, but not at 60 and 75 rev/min. However, the results obtained indicated the opposite: in terms of effective force, cyclists performed significantly better than triathletes at 60 rev/min and 75 rev/min. For some reason, however, this advantage disappeared as cadence increased, which could be associated with the fact that non-muscular forces (gravity and inertial effects) tend to increase as cadence increases (Kautz and Hull, 1993). Since effective force mixes technical with physical aspects, a better evaluation of the technique would be obtained by analysing the index of pedalling effectiveness.

Index of effectiveness × cadence

Cyclists obtained higher indices of pedalling effectiveness at all four cadences tested, and significant differences were observed between the two groups of athletes only at 60 and 75 rev/min (Figure 4). Since the effort in all trials was normalized using the second ventilatory threshold, the two groups of athletes were performing at a similar physiological cost, and can,

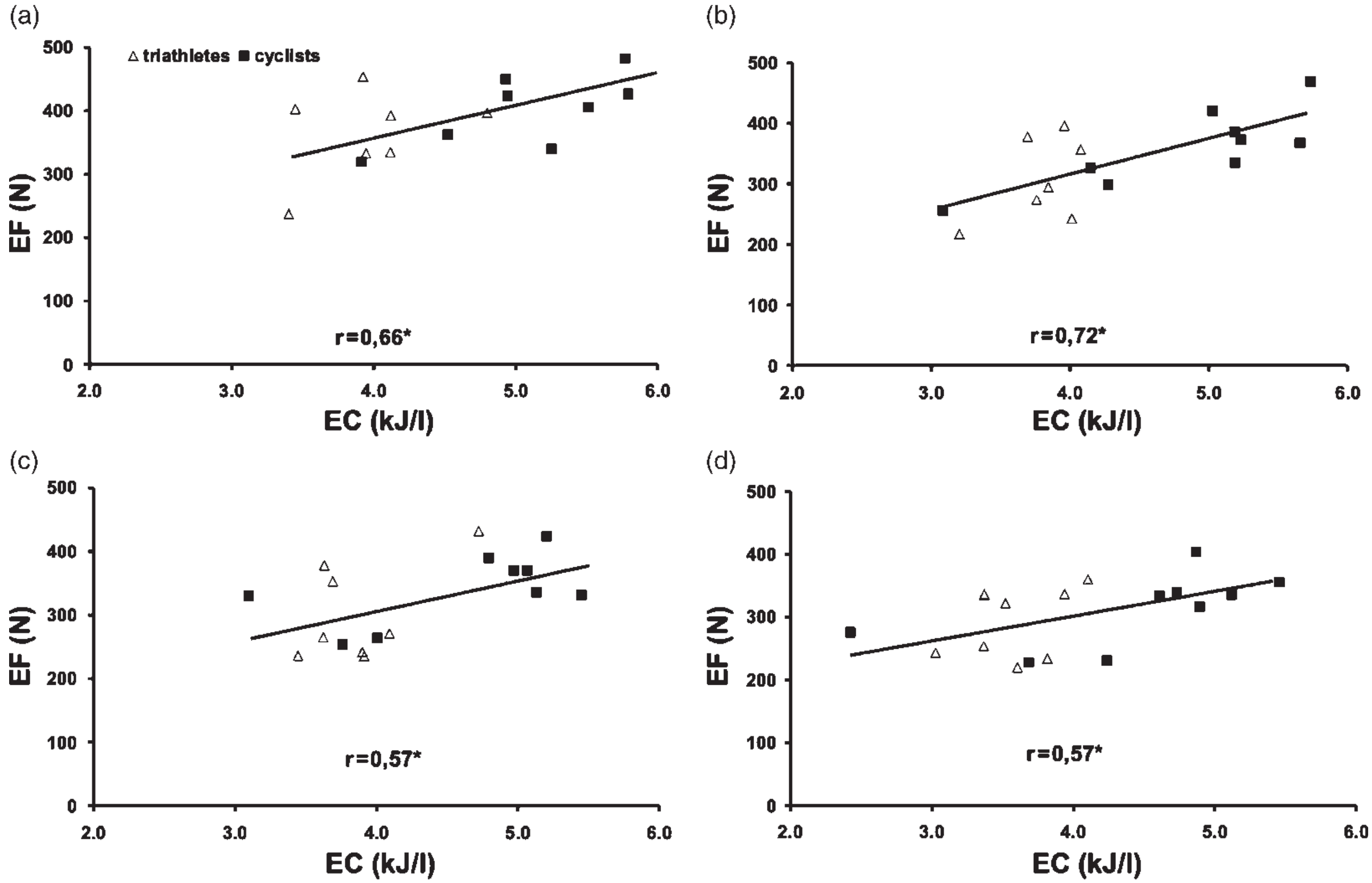

Figure 6. Association between effective force (EF) and economy of movement (EC) for cyclists and triathletes at the four cadences: (a) 60 rev/min, (b) 75 rev/min, (c) 90 rev/min, (d) 105 rev/min.

therefore, be compared in terms of their technique. In that regard, the speculation that cyclists would have a better technique than triathletes was not totally confirmed. One explanation for the decreasing index of pedalling effectiveness for cyclists' higher cadences could be an increase in both co-contraction and muscle effort with an increase in velocity. These findings would be related to coordination between the agonist and antagonist muscles (Neptune and Herzog, 1999).

As a ratio, the index of pedalling effectiveness simply expresses technical aspects without expressing the exertion of the athletes. Comparing a novice and an elite cyclist, for instance, the novice could have a better index of pedalling effectiveness, but the elite cyclist could have a larger effective force and thus go faster. In relative terms, elite cyclists' technique is poor but in absolute terms they produce more power, thus overcoming any difference in technique. Thus, although the index of pedalling effectiveness can be a useful tool when teaching or doing technical drills (Sanderson, 1991; Sanderson and Cavanagh, 1990), its isolated use is limited when the goal is to evaluate performance, when the effective force is more appropriate. Therefore, together, the results of Figures 3 and 4 suggest that the differences found between cyclists and triathletes were due to both physical and technical aspects, as anticipated.

Economy × cadence

Economy of movement (Figure 5) produced results that were partially consistent with those obtained for effective force and the index of pedalling effectiveness (Figures 3 and 4). Cyclists were significantly more economical than triathletes at all cadences but only produced significantly higher effective force and index of pedalling effectiveness at 60 and 75 rev/min. These results support the idea that triathletes should be less economical than cyclists. When comparing 60 and 75 rev/min to 90 and 105 rev/min, cyclists showed worse technique for higher cadences, evidenced by the effective force and index of pedalling effectiveness. This could justify the economy of movement difference between the groups: triathletes were less economical than cyclists at all cadences. Because at higher cadences cyclists exhibit a poorer but more economical technique, it is speculated that other factors contribute more to economy. Cyclists' preference for higher cadences could have caused a functional adaptation, not assessed by effective force and the index of pedalling effectiveness, but decisive to economy.

Pooling the data of the two groups (Figure 6), positive significant correlations were obtained between economy of movement and effective force at all cadences. At the lower cadences, the correlations are strongest at those cadences at which the effective force is higher (60 and 75 rev/min). The relatively weaker correlations at the higher cadences support the idea that the economy on the usual cadences depends on other factors. Figure 6 provides an indication of individual variation among the participants within their respective group. Even those athletes who performed outside of the group mean values could not be considered outliers for a correlation analysis, suggesting that improvement of the effective force would reflect on economy, subject to individual considerations.

Looking at all results together (oxygen consumption, second ventilatory threshold, effective force, index of pedalling effectiveness, and economy of movement at the different cadences tested), it becomes clear that cycling is a multi-factorial activity (Broker and Gregor, 1996; Burke, 2000) and that the importance of the variables changes as cadence increases. It remains unclear which factors contribute to performance as cadence increases.

Conclusion

Cyclists were more effective in transferring propulsive forces from the pedal to the crank than triathletes at 60 and 75 rev/min and more economical at all cadences. The significant correlation between effective force and economy at all cadences suggests that a good pedalling technique should improve economy.

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