

The association between negative muscle work and pedaling rate

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Abstract

The objective of this research was to use a pedal force decomposition approach to quantify the amount of negative muscular crank torque generated by a group of competitive cyclists across a range of pedaling rates. We hypothesized that negative muscular crank torque increases at high pedaling rates as a result of the activation dynamics associated with muscle force development and the need for movement control, and that there is a correlation between negative muscular crank torque and pedaling rate. To test this hypothesis, data were collected during 60, 75, 90, 105 and 120 revolutions per minute (rpm) pedaling at a power output of 260 W. The statistical analysis supported our hypothesis. A significant pedaling rate effect was detected in the average negative muscular crank torque with all pedaling rates significantly different from each other ($p < 0.05$). There was no negative muscular crank torque generated at 60 rpm and negligible amounts at 75 and 90 rpm. But substantial negative muscular crank torque was generated at the two highest pedaling rates (105 and 120 rpm) that increased with increasing pedaling rates. This result suggested that there is a correlation between negative muscle work and the pedaling rates preferred by cyclists (near 90 rpm), and that the cyclists' ability to effectively accelerate the crank with the working muscles diminishes at high pedaling rates. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In endurance cycling, a disparity exists between pedaling rates that minimize oxygen consumption and the pedaling rates preferred by cyclists that has received considerable attention in the literature (e.g. Hagberg et al., 1981; Marsh and Martin, 1993; Takaishi et al., 1994). Studies have shown that at low to moderate power outputs (below 200 watts), the pedaling rate that minimizes oxygen consumption is between 40 and 65 rpm (e.g. Seabury et al., 1977; Marsh and Martin, 1993). At higher power outputs (near 300 watts), the pedaling rate that minimizes oxygen consumption increases linearly and is between 70 and 80 rpm (e.g. Coast and Welch, 1985; Hagberg et al., 1981). But studies have shown that the pedaling rate freely selected by both experienced and inexperienced cyclists is between 85 and 100 rpm (e.g.

Hagberg et al., 1981; Marsh and Martin, 1993; Patterson and Moreno, 1990), and cycling experience does not change muscular efficiency during ergometer pedaling (Böning et al., 1984; Nickleberry and Brooks, 1996). These results suggest that there is a fundamental mechanism common to all people that influences pedaling rate selection other than minimizing oxygen consumption.

The power generated by a cyclist is a linear combination of crank torque and angular velocity ($P = \tau \cdot \omega$). Therefore, a given power can be achieved with an infinite number of combinations of pedaling rate and crank torque. Cyclists can freely choose pedaling rates by selecting the appropriate gearing, and this selection determines the applied crank torque the cyclists must produce to achieve the desired power output. Theoretically, the higher the pedaling rate, the lower the pedal forces a cyclist will have to produce with the working muscles to provide a given power, and therefore, delaying the onset of local neuromuscular fatigue (e.g. Takaishi et al., 1994). This relationship between pedal force and pedaling rate has been illustrated in studies showing that the peak forces on the pedal decrease as pedaling rate is increased at constant power output (e.g. Hull and Jorge, 1985;

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Patterson and Moreno, 1990; Sanderson, 1991). But Patterson and Moreno (1990) also showed that the average resultant pedal force across the crank cycle varied with pedaling rate reaching minimum values at 90 and 100 rpm for power outputs of 100 and 200 watts, respectively. These values also coincided closely with the pedaling rates preferred by the cyclists used in that study (94 and 98 rpm, respectively). Based on these results, Patterson and Moreno (1990) suggested that cyclists increase the pedaling rate until there is no further reduction in the resultant pedal force, and therefore, minimize fatigue by operating at a lower percentage of the cyclists maximum strength. This hypothesis is based on the assumption that the resultant pedal force is directly related to muscle force and that changing the duration of muscle activation at different pedaling rates does not substantially influence muscle fatigue.

Although pedaling at high rates is appealing from a purely mechanical perspective (decreased crank torque), the activation dynamics associated with muscle force development has adverse effects on force generation at high speeds. The activation dynamics defines the delay between the muscle force rise and decay. Time constants for the working muscles in cycling are in the range of 20–110 ms (Winters and Stark, 1988). Therefore, at high pedaling speeds, co-contraction and negative muscle work appear inevitable because of the activation dynamics and the increased need for movement control (e.g. to prevent knee hyperextension). Computer simulations have provided supporting data showing substantial negative muscle work occurs throughout the crank cycle (Neptune and Bogert, 1998). In addition, other pedaling simulations have shown that there is a trade-off between decreasing the duration of muscle excitation to reduce negative muscle work and not having the muscles activated long enough to generate the required power (Raasch, 1995). These results suggest that effective muscle coordination at high pedaling rates may be more difficult to achieve than at low pedaling rates.

Gross muscular efficiency, defined as the ratio of energy input ($\dot{V}O_2$) to power output, has been shown to remain constant or decrease with increasing pedaling rates during high intensity (greater than 80% $\dot{V}O_{2max}$) pedaling (e.g. Faria et al., 1982; Coast et al., 1986; Sidossis et al., 1992). But during low to moderate intensities, gross muscular efficiency has been shown to decrease with increasing pedaling rates (e.g. Böning et al., 1984; Gaesser and Brooks, 1975; Sidossis et al., 1992). Although the exact mechanism behind the decrease in efficiency with increasing pedaling rates is not known, the decrease may be related to a lack of skill in performing the pedaling task (e.g. Faria et al., 1982; Sidossis et al., 1992). Difficulty in coordinating muscle force at high pedaling rates may be reflected in the amount of negative muscular crank torque generated during the pedal cycle. Any negative muscle work must be overcome by additional positive

work to maintain a given power output. This additional positive work would decrease muscular efficiency, and hence, may be influential in pedaling rate selection.

Kautz and Hull (1993) developed a decomposition technique to quantify the muscular and non-muscular (gravity and inertial effects) contributions to the pedal reaction force. Examining one subject during constant workload conditions, they found a substantial non-muscular component relative to the muscular component that increased with pedaling rate. Therefore, the hypothesis of Patterson and Moreno (1990) may not be valid if the increase in resultant pedal force beyond 90 rpm is caused primarily by the increase in the non-muscular forces. A pedal force decomposition analysis during constant power conditions across a wide range of pedaling rates would support or disprove their hypothesis and provide insight into the relationships between muscle work, efficiency and pedaling rate selection.

Therefore, the objective of this research was to use a pedal force decomposition approach to quantify the amount of negative muscular crank torque generated by a group of competitive cyclists. We hypothesized that negative muscular crank torque increases at high pedaling rates and that there is a correlation between negative muscular crank torque and pedaling rate.

2. Methods

To test the stated hypothesis, kinetic and kinematic data were collected from eight male competitive cyclists (avg. and std. dev. of height = 1.80 ± 0.10 m; mass = 73.7 ± 6.0 kg; age = 22.6 ± 2.3 yr.). The subjects rode a conventional road racing bicycle adjusted to match their own bicycle's geometry. The bicycle was mounted on an electronically braked Schwinn Velodyne ergometer to provide constant power riding conditions. The protocol consisted of a 10-min warm-up period at a workrate of 120 W at 90 rpm. Then, each subject cycled at a power output of 260 W at five different pedaling rates (60, 75, 90, 105 and 120 rpm) randomly assigned to control for possible interactions and fatigue. These pedaling conditions were chosen to encompass the riding conditions normally encountered by competitive cyclists. After a three-minute adaptation period, data collection was randomly initiated five times for a duration that captured five consecutive cycles each during the following three minutes.

The necessary kinematic data were recorded using a combination of video-based motion analysis and direct measurement. The intersegmental joint centers were measured (60 Hz) using a high speed video system (Motion Analysis Corp., Santa Rosa, CA) with reflective markers located over the right anterior-superior iliac spine (ASIS), greater trochanter, lateral epicondyle, lateral malleolus and pedal spindle. The hip joint center was

located relative to the marker over the ASIS based on the methodology presented by Neptune and Hull (1995). The video data were filtered using a fourth-order zero phase-shift Butterworth low pass filter with a cutoff frequency of 9 Hz. All derivatives to determine segment or angle velocity and acceleration were calculated by fitting a quintic spline to the position data and differentiating the resulting equations (GCVSPL, Woltring, 1986).

The angular orientation of the crank arm and right pedal were measured with optical encoders. The horizontal and vertical pedal forces from the right leg were measured with a pedal dynamometer designed by Newmiller et al. (1988). The encoder and pedal force data were collected simultaneously with the video data at 100 Hz. The pedal force and encoder data were filtered using a fourth-order zero phase-shift Butterworth low pass filter with a cutoff frequency of 20 Hz. The filtered data were linearly interpolated to correspond in time with the video coordinate data.

To quantify the muscular and non-muscular (inertia and gravity) contributions to the applied crank torque, a pedal force decomposition was performed (Kautz and Hull, 1993) and the crank torque associated with the non-muscular and muscular pedal force components was computed. The intersegmental joint moments necessary for the pedal force decomposition were calculated using a previously described standard inverse dynamics approach (Neptune and Bogert, 1998).

To test our hypothesis, a one-way repeated measures analysis of variance was performed on the amount of negative muscular crank torque to see if there were significant pedaling rate effects ($p < 0.05$). Negative muscular crank torque was quantified by computing the average negative muscular crank torque throughout the crank cycle. When significant pedaling rate effects were detected, a paired t-test was used to identify which pedaling rates were significantly different ($p < 0.05$).

3. Results

Our hypothesis that negative muscular crank torque would increase at high pedaling rates was supported by the data. The muscular component of the crank torque was identical in pattern and phasing across pedaling rates and systematically decreased in magnitude with increasing pedaling rates (Fig. 1a). A significant pedaling rate effect was detected in the average negative muscular crank torque with all pedaling rates significantly different from each other ($p < 0.05$). There was no negative muscular crank torque generated at 60 rpm and negligible amounts at 75 and 90 rpm (Fig. 1a, Table 1). But substantial negative muscular crank torque was generated at the two highest pedaling rates (105 and 120 rpm) that increased with increasing pedaling rates.

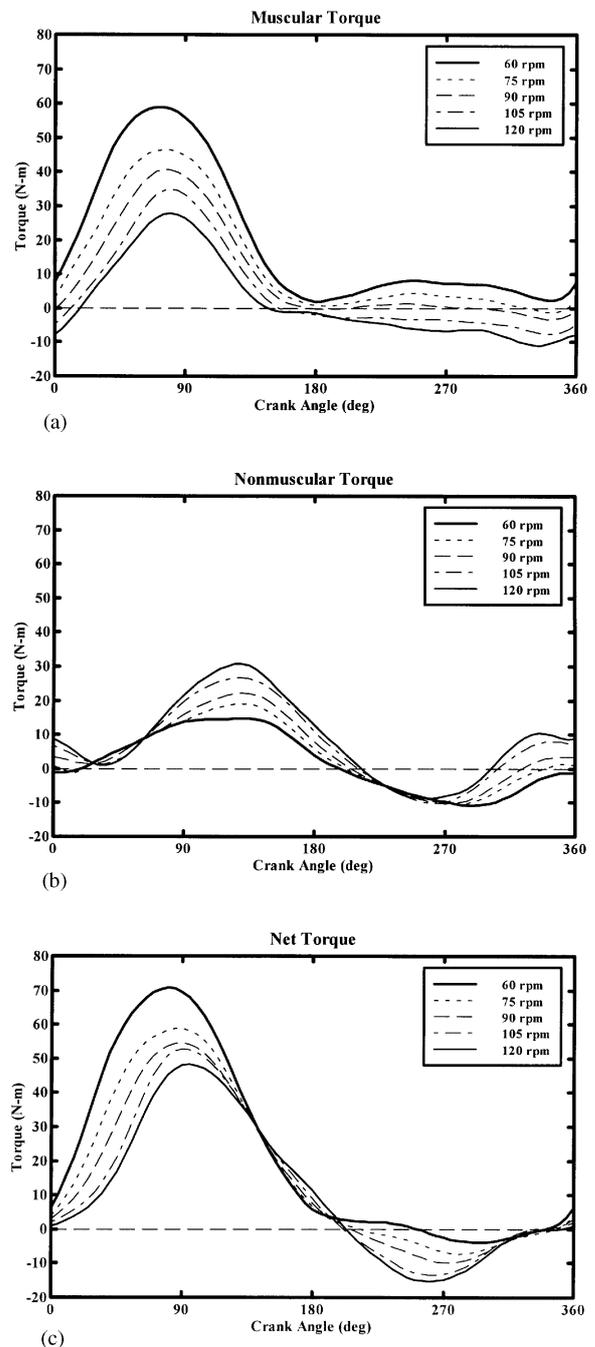


Fig. 1. (a)–(c) Group average (a) muscular crank torque, (b) non-muscular crank torque and (c) net crank torque across pedaling rates. Crank angle is defined as 0 degrees at top-dead-center and positive in the clockwise direction.

The non-muscular component of the crank torque was positive during the downstroke (0 to 180°) and negative during the upstroke (180 to 360°) at all pedaling rates (Fig. 1b). The negative component during the upstroke decreased with increasing pedaling rates (Table 1). The combination of the muscular and non-muscular components yielded a total crank torque that decreased

Table 1
Group net, positive and negative muscular and non-muscular crank torque over the crank cycle (average \pm 1 standard deviation)

Pedaling rate (rpm)	Average crank torque (N-m)				
	Muscular		Non-muscular		Net
	Positive	Negative ^a	Positive	Negative	
60	19.7 \pm 0.9	0.0 \pm 0.1	4.6 \pm 0.6	-2.9 \pm 0.3	21.4 \pm 1.0
75	13.9 \pm 0.6	-0.3 \pm 0.2	5.6 \pm 0.6	-2.4 \pm 0.2	16.8 \pm 0.8
90	10.5 \pm 0.4	-0.8 \pm 0.5	6.7 \pm 0.6	-2.1 \pm 0.4	14.3 \pm 0.7
105	7.6 \pm 0.3	-2.4 \pm 0.9	8.7 \pm 0.6	-1.7 \pm 0.4	12.2 \pm 0.9
120	5.8 \pm 0.8	-3.8 \pm 0.5	10.0 \pm 0.9	-1.5 \pm 0.6	10.5 \pm 0.8

^aAll crank torques were significantly different from each other.

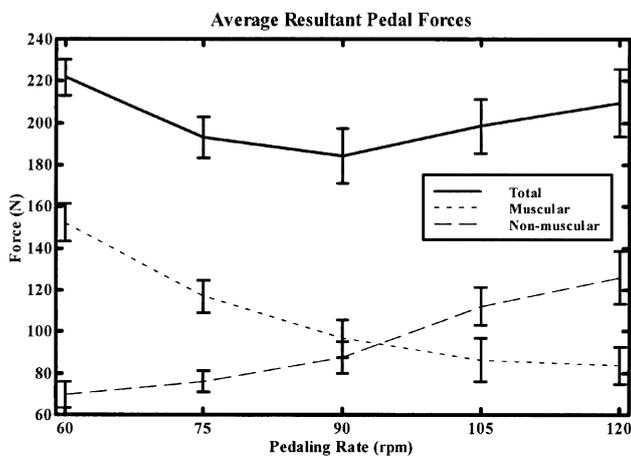


Fig. 2. Average resultant, muscular and non-muscular pedal forces.

systematically during the downstroke and increased in the negative direction during the upstroke as pedaling rate increased (Fig. 1c).

The pedal forces behaved similar to the crank torques. The average resultant muscular and non-muscular pedal force components systematically decreased and increased, respectively, as pedaling rates increased (Fig. 2). The total average resultant pedal force varied with pedaling rate reaching a minimum value at 90 rpm.

4. Discussion

The objective of this research was to use a pedal force decomposition approach to quantify the amount of negative muscular crank torque generated by a group of competitive cyclists across a range of pedaling rates. The pedal force decomposition used in this analysis included the effects of ligament, bone, skin and clothing in the muscular torque component. But these effects have negligible contributions compared to the muscles themselves,

and therefore, have minimal impact on the results. We hypothesized that negative muscular crank torque increases at high pedaling rates and that there is a correlation between negative muscular crank torque and pedaling rate. The statistical analysis supported our hypothesis. There were significant differences in the average negative muscular crank torque generated at each pedaling rate. There was no negative muscular crank torque generated at 60 rpm and negligible amounts at 75 and 90 rpm. But the negative muscular crank torque increased substantially at the two highest pedaling rates (105 and 120 rpm). This result suggests that there is a correlation between negative muscular work and pedaling rate. Further, the critical pedaling rate in terms of negative muscle work production is 90 rpm, above which negative muscle work increases substantially. This pedaling rate also corresponds with the pedaling rate preferred by cyclists.

A potentially confounding factor in the correlation between negative muscle work and pedaling rate in the present study was that the subjects were asked to perform the pedaling task at rates substantially higher than their preferred rate. It is possible that sustained training at the higher rates (105–120 rpm) would produce a more efficient pedaling style that might reduce the amount of negative muscle work. But both experienced and inexperienced cyclists prefer pedaling rates near 90 rpm suggesting that factors other than sustained training influences pedaling rate selection.

Examination of the pedal forces revealed that the resultant pedal force varied with pedaling rate and reached a minimum value at 90 rpm (Fig. 2). This result is consistent with that of Patterson and Moreno (1990) who suggested that cyclists increase pedaling rates until there is no further reduction in the resultant pedal force in order to operate at the lowest percentage of the cyclist's maximum strength. But the pedal force decomposition showed that the muscular component of the pedal force continued to decrease linearly with increasing pedaling rates and that the increase in the resultant pedal force is

the result of an increase in the non-muscular component of the pedal force (Fig. 2). Therefore, the hypothesis of Patterson and Moreno (1990) appears invalid.

The activation dynamics associated with muscle force development may play an important role in the negative work production. Neptune et al. (1997) examined muscle EMG timing during similar pedaling conditions as studied here and found that the muscle excitation duration remained relatively constant for all muscles as pedaling rate increased. Typical time constants for muscle rise and decay range from 20–110 ms (Winters and Stark, 1988). Assuming equal time constants for muscle rise and decay, a muscle in the middle of this range (i.e. 65 ms) would require about one-fifth of the crank cycle duration at 120 rpm to establish a full active state and completely relax muscle force. Considering this delay in muscle force rise and decay, one would expect to see a decrease in the duration of muscle excitation to avoid co-contraction and negative muscle work as pedaling rates increase. But the data from Neptune et al. (1997) do not support this expectation. In addition, pedaling simulations have shown that more negative work is generated than expected due to the muscle activation dynamics and the need for movement control (Neptune and Bogert, 1998). As pedaling rate increases, the influence of these factors on negative muscle work also increases. Other pedaling simulations have shown that there is a trade-off between decreasing the duration of muscle excitation to reduce negative muscle work and not having the muscles activated long enough to generate the required power (Raasch, 1995). These results suggest that negative muscle work is inevitable at high pedaling rates due to activation dynamics, the need for movement control and maintaining the required power level.

Negative muscle work must be overcome by additional positive work to maintain a given power output, and therefore, will affect gross muscular efficiency. Muscular efficiency decreases with an increase in negative muscle work. This relationship is supported by experimental studies examining muscular efficiency across different pedaling rates and power outputs similar to the present study (e.g. Böning et al., 1984; Coast et al., 1986). But Faria et al. (1982) and Sidossis et al. (1992) found that muscular efficiency did not decrease at power outputs above the level used in the present study. If the present study was repeated at a higher power level, it is possible that the amount of negative muscle work would be more consistent across pedaling rates.

The force–velocity relationship is an intrinsic property of skeletal muscle that may also play an important role in pedaling rate selection. The force-velocity relationship dictates that a muscle's ability to generate force decreases with increasing speeds of contraction, and consequently, there is a defined velocity of muscle shortening for which power production is maximal. Several studies have indicated that maximum power during cycling is achieved

at a pedaling rate near 120 rpm (Sargeant et al., 1981; McCartney et al., 1983; Beelen and Sargeant, 1991; MacIntosh and MacEachern, 1997). Assuming that maximum power is achieved at 120 rpm, cyclists would be on the ascending limb of the power-velocity relationship when pedaling at their preferred rate of about 90 rpm. For a given activation level, greater power output is achieved as pedaling rates are increased up to 120 rpm. The increase in power production combined with the decrease in required crank torque favor pedaling at high rates. But the results of this study suggest that increasing pedaling rates beyond 90 rpm increases negative muscle work, and therefore, decreases muscular efficiency. Thus, there is a trade-off in selecting pedaling rates. High pedaling rates up to 120 rpm take advantage of the force–velocity–power relationship of skeletal muscle, but at pedaling rates beyond 90 rpm, the cyclist's ability to effectively accelerate the crank with the working muscles diminishes and negative muscle work increases. A pedaling rate of 90 rpm also coincides with the rates preferred by cyclists, therefore suggesting there is a correlation between negative muscle work and the preferred pedaling rate.

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