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# A COMPARISON OF MUSCULAR MECHANICAL ENERGY EXPENDITURE AND INTERNAL WORK IN CYCLING

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**Abstract**—The hypothesis that the sum of the absolute changes in mechanical energy (internal work) is correlated with the muscular mechanical energy expenditure (MMEE) was tested using two elliptical chainrings, one that reduced and one that increased the internal work (compared to circular). Upper and lower bounds were put on the extra MMEE (work done by net joint torques in excess of the external work) with respect to the effect of intercompensation between joint torques due to biarticular muscles. This was done by having two measures of MMEE, one that allowed no intercompensation and one that allowed complete intercompensation between joints spanned by biarticular muscles. Energy analysis showed no correlation between internal work and the two measures of MMEE. When compared to circular, the chainring that reduced internal work increased MMEE, and phases of increased crank velocity associated with the elliptical shape resulted in increased power absorbed by the upstroke leg as it was accelerated against gravity. The resulting negative work necessitated additional positive work. Thus, the hypothesis that the internal work is correlated with MMEE was found to be invalid, and the total mechanical work done cannot be estimated by summing the internal and external work. Changes in the dynamics of cycling caused by a non-circular chainring may affect performance and must be considered during the non-circular chainring design process.

## NOMENCLATURE

| | |
|---|---|
| $E_B$ | energy balance index, J |
| $E_i$ | energy of two leg system at $i$th degree ($i=0, \ldots, 360$), J |
| $\Delta E$ | change in energy of two leg system, J |
| $E_l$ | total mechanical energy of single leg ($l=1, 2$), J |
| $\mathbf{F}_{hf}$ | reaction force vector applied by pelvis on thigh, N |
| $\mathbf{F}_p$ | reaction force vector applied by pedal on foot, N |
| $MMEE_I$ | muscular mechanical energy expenditure (intercompensated), J |
| $MMEE_N$ | muscular mechanical energy expenditure (no intercompensation), J |
| $P_E$ | net power associated with both pedal reaction forces, W |
| $P_{hf}$ | power associated with hip joint force, W |
| $P_{I_l}$ | intercompensated power single leg system ($l=1, 2$) W |
| $P_j$ | power associated with $j$th joint ($j=1, 2, 3, 4, 5, 6$), W |
| $P_l$ | power of single leg system ($l=1,2$), W |
| $P_p$ | power associated with pedal reaction force, W |
| $T_c$ | net torque about crank by applied pedal forces, Nm |
| $T_j$ | net torque of $j$th joint ($j=1, 2, 3, 4, 5, 6$), Nm |
| $\mathbf{V}_{hf}$ | hip joint center velocity vector, m/s |
| $\mathbf{V}_p$ | pedal velocity vector, m/s |
| $W_E$ | net external work done by legs for one crank revolution, J |
| $W_{hf}$ | net work done by hip joint forces for one crank revolution, J |
| $W_I$ | internal work, J |
| $W_j$ | net work done by the $j$th joint ($j=1, 2, 3, 4, 5, 6$), J |
| $W_{extra_I}$ | net work done beyond external work (intercompensated), J |
| $W_{extra_N}$ | net work done beyond external work (no intercompensation), J |
| $\omega_c$ | angular velocity of crank, rad/s |
| $\omega_j$ | angular velocity of $j$th joint ($j=1, 2, 3, 4, 5, 6$), rad/s |

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## INTRODUCTION

In cycling, efficiency was related to performance in a combined physiological and biomechanical study which found that the absolute rate of oxygen consumption at lactate threshold ($\dot{V}_{O_2LT}$) was the best predictor of performance for a population of national and state level 40 km time trialists (Coyle *et al.* 1991). The correlation $\dot{V}_{O_2LT}$ with performance implied a maximum energy expenditure rate for cyclists that was related to $\dot{V}_{O_2LT}$. Thus, improving efficiency by increasing external work done for the same energy expenditure rate would lead directly to increased performance in endurance cycling. Unfortunately for those interested in improving performance, efficiency is very difficult to predict in human movements (Cavanagh and Kram, 1985) due in large part to problems in measuring the mechanical work associated with muscular effort and its corresponding energetic cost (Williams, 1985). A definition of mechanical efficiency has been proposed where the total work done is easily calculated as the external work plus internal work (Winter, 1979; Pierrynowski *et al.*, 1980), where internal work was introduced to account for the energetic cost of moving the individual segments and was defined as the sum of the absolute changes in the whole body mechanical energy of the subject. If the definition of internal work is valid, then reducing internal work during cycling would reduce energy expenditure at a given external work rate, theoretically allowing an increased external work rate at the maximum energy expenditure rate. The possibility of improved endurance cycling performance motivated Hull *et al.* (1991) to develop a chainring to test the internal work hypothesis in cycling.

The relationship between changes in system mechanical energy and increased efficiency was examined in a pair of articles by Aleshinsky (1986a, b) who determined that muscular mechanical energy expenditure (MMEE—defined as the time integral of the sum of the individual absolute joint powers) need not be equal to the sum of the internal and external work. Therefore, in general, it should not be expected that a reduction of internal work will produce an equal reduction of MMEE in cycling. Supporting this idea is the study by Hull *et al.* (1992), which showed that significant reductions in internal work during constant power steady-state cycling did not correspond with reduced oxygen consumption. However, this study did not perform a mechanical power analysis, so relationships between internal work, physiological energy expenditure and MMEE during cycling could not be determined.

Van Ingen Schenau *et al.* (1990) performed a power analysis of cycling that revealed most of the decreases in the total energy of the leg were coincident with external work done through power transfer to the pedal, and not with equal amounts of work absorbed at joints, implying that internal work did not represent either the work required to move the limbs or the work absorbed by muscles. Additionally, they suggested that the actual power lost in changing the segmental energy was less than measured (19 J), possibly even negligible, because biarticular muscles allow intercompensation between the joint power sources by allowing power absorbed at one joint to be transported to another joint spanned by the muscle where it is liberated as positive joint power. While the study of van Ingen Schenau *et al.* (1990) elucidated some of the difficulties with the internal work hypothesis, they did not calculate the internal work. Thus, an explicit test is lacking of the correlation between estimates of the total work done in cycling using MMEE analysis and internal work analysis.

The objective of this study was to test the hypothesis that internal work (Winter, 1979) in cycling is correlated with the total done in excess of the external work as measured by the difference between external work and MMEE (with intercompensation allowed and disallowed). The novel aspect of this study was that two specially designed non-circular chainrings, as well as a conventional circular chainring, forced each cyclist to produce three distinct levels of internal work while average power and cadence were held constant.

A second objective of the study was to determine whether MMEE varied between chainrings. The theoretical background for the chainring design was provided by Hull *et al.* (1991) who designed a crank angular velocity profile that reduced internal work by a minimum of 48% relative to constant angular velocity cycling over the range of cadences generally preferred by endurance cyclists.

## METHODS

Ten experienced male cyclists rode a conventional racing bicycle mounted on a Velodyne road simulation trainer using three different chainrings [circular (CIR), reduced internal work (RIW) and increased internal work (IIW)]. The angular velocity profile determined by Hull *et al.* (1991) for reduced internal work cycling was approximated by using an elliptical chainring with the major axis oriented perpendicular to the crank (peak crank angular velocity when crank is vertical). However, this approximation resulted in a smaller decrease in internal work than predicted for the theoretical profile in Hull *et al.* (1991). Increased internal work cycling was achieved by rotating the RIW chainring by 90° so that the major axis of the ellipse was oriented parallel to the crank arm (peak crank angular velocity when crank is horizontal). Therefore, RIW and IIW were the same elliptical shape 90° out of phase. Assuming constant velocity for the rear wheel, the elliptical chainrings induced a crank angular velocity variation of 22% relative to peak angular velocity. The bicycle was set to match the preferred geometry of each subject's own bicycle, so that seat height was not controlled.

The protocol consisted of a 10 min warm-up period at a workrate of 100 W and 90 rpm using each of the chainrings for a portion of the period. Then the Velodyne setting was changed to a constant workload that elicited a power output of 245 W at 90 rpm. The subjects pedalled for 3 min to become accustomed to the chainring and to become steady at a nominal cadence of 90 rpm. Then data collection occurred within a second 3 min period. The chainring was switched and the 3 min adaptation and data collection periods followed immediately for the second and third chainrings. Thus, the subjects pedalled for 18 min at 245 W. The order of chainring presentation was random to control for possible effects of fatigue.

The time history of the applied force on the right pedal was collected using a pedal dynamometer (Newmiller *et al.*, 1988) and optical encoders mounted to the bicycle and pedal recorded the angle between the crank and vertical and between the pedal and crank. The pedal dynamometer allowed the subjects to wear conventional clip-in cycling shoes, and weight was added to the opposite pedal so that the inertial characteristics of the two pedals were similar. A video camera placed at right angles to the subject's sagittal plane recorded leg movements. The positions of markers placed over the pedal spindle, lateral malleolus, lateral epicondyle of the tibia, superior aspect of the greater trochanter of the femur, and the anterior superior iliac spine (ASIS) were determined using a motion analyzer (Motion Analysis). Actual two-dimensional coordinates were reconstructed using a scale object filmed within the plane of motion. The position of the hip joint center, which was assumed to be fixed to the pelvis, was determined from the ASIS. A vector of fixed magnitude and orientation in the sagittal plane was attached to the ASIS to represent the position of the hip joint center relative to the pelvis allowing the hip joint center to be located from the coordinates of the ASIS. The fixed vector was determined from the average positions of the ASIS and the trochanter marker locations. This method was used because another study in our laboratory determined that this method is significantly more accurate in tracking hip joint center movement than a marker over the superior aspect of the greater trochanter (Neptune, 1993).

Within each 3 min data collection period, four separate data collections of 5 s each were initiated by a random signal which simultaneously began the collection of both the pedal and video data. The pedal data were collected at 100 Hz while the video data were collected at 60 Hz. Pedal force data were filtered using a fourth-order zero-phase shift Butterworth low pass filter with a cutoff frequency of 20 Hz, while coordinate and angular orientation data were filtered using a fourth-order zero phase shift Butterworth low pass filter with a cutoff frequency of 9 Hz. The filtered pedal force and angular orientation data were linearly interpolated to correspond in time with the video coordinate data. Positions of segmental centers of gravity and segment masses were calculated based on the data of Dempster (1955), and moments of inertia were calculated from the data of Whittsett (1963) and personalized to the subject using a procedure presented by Dapena (1978). All derivatives required from the position data were calculated using a quintic spline (reported in Vaughan, 1980). Then the segmental kinematics were used in a standard Newton–Euler inverse dynamics method to calculate net intersegmental moments (Redfield and Hull, 1986).

After calculating net intersegmental moments, an energy analysis was performed. Each leg (modeled as thigh, shank and foot segments) was defined as a separate system for a single leg work–energy analysis, with an additional system including both legs defined due to energy transfer through the crank. Since only one dynamometer was used, identical kinematics (180° out of phase) were assumed for the left leg when both legs were considered. The net work done on the leg by external sources was defined as equal to the change in the total mechanical energy of the leg (sum of potential and kinetic energies). The energy analysis was performed in terms of power, with work values computed by intergrating the appropriate power expressions.

As identified previously by van Ingen Schenau *et al.* (1990), the external moments applied to the leg were the net joint torques at the hip, knee and ankle, and the external forces were the pedal reaction force and the joint force acting on the thigh at the hip. Figure 1 is a sketch of the leg identifying the external forces and moments. Notice that the net joint torques were considered external moments for the energy analysis because they acted upon the rigid bodies comprising the system. External forces and moments were mechanical energy sources for the leg if they developed power during the movement (Aleshinsky, 1986b). The term 'source' is used regardless of whether energy was produced (meaning that if the source were acting alone, the total energy of the leg, $E_l$, would increase) or absorbed (if the source were acting alone, $E_l$, would decrease). The power, $P_p$, associated with the reaction force at the pedal was

$$P_p = \mathbf{F}_p \cdot \mathbf{V}_p. \tag{1}$$

The power, $P_{hf}$, associated with the hip joint reaction force was

$$P_{hf} = \mathbf{F}_{hf} \cdot \mathbf{V}_{hf} \tag{2}$$

and the power associated with the $j$th joint torque, $T_j$, was

$$P_j = T_j \omega_j, \tag{3}$$

where $\omega_j$ was the angular velocity of the $j$th joint. Since the power of the single leg system, $P_l$, was equal to the

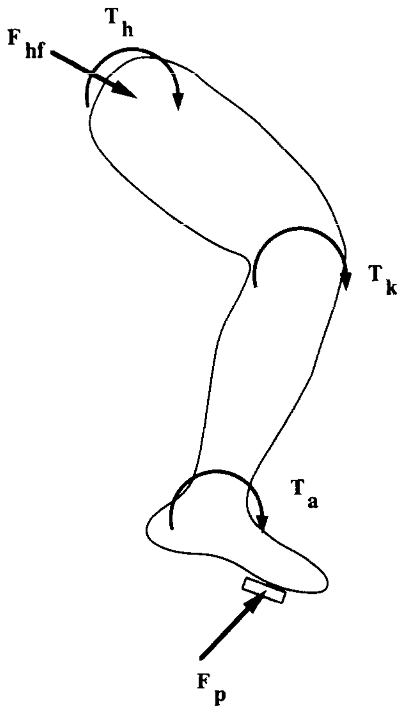


Fig. 1. Diagram showing the external forces and moments applied to the leg of the cyclists. Notice that the joint moments are considered external moments because they act upon the rigid bodies comprising the leg. Weight forces are included in the potential energy term of the total mechanical energy.

sum of the powers of the individual sources, the instantaneous power equation (modified from van Ingen Schenau et al., 1990) specific to single leg seated cycling was

$$P_l = \frac{dE_l}{dt} = \sum_{j=1}^{3} P_j + \mathbf{F}_p \cdot \mathbf{V}_p + \mathbf{F}_{hf} \cdot \mathbf{V}_{hf}, \quad (4)$$

where $P_j$ represents the joint powers. The instantaneous power of the second leg (180° out of phase) was added to equation (4) and the subsequent expression was integrated (over one crank revolution) to yield an expression for the change in total mechanical energy ($\Delta E = 0$ for a cyclical activity):

$$\Delta E = \sum_{j=1}^{6} W_j + W_{hf} - W_E = 0, \quad (5)$$

where the $W_j$'s are the net works done by the hip, knee and ankle joints of the two legs for one revolution, $W_{hf}$ is the net work done by the two hip joint forces for one revolution, and $W_E$ is the external work done by the legs on the pedals for one revolution. The negative sign appears because $W_E$ is equal and opposite to the work done on the legs by the two pedal reaction forces, $\mathbf{F}_p$. Thus, the net work done by the joint torques and the hip joint forces can be seen to be equal to the external work for steady-state cycling. Equation (5) represents an energy balance equation and can be used to assess partially the quality of the experimental data. Thus, an energy balance index was defined to measure the difference between the net work done by the power sources associated with the net joint torques and the net joint force at the hip, and the net work done on the environment:

$$E_B = \sum_{j=1}^{6} W_j + W_{hf} - W_E. \quad (6)$$

A new quantity, called $W_{extra}$, was defined to quantify the muscular mechanical energy expenditure (MMEE) beyond the external work. Additionally, the MMEE was calculated in two different ways to assess the potential impact of source intercompensation. The first method followed Aleshinsky (1986b) and allowed no intercompensation. $\mathrm{MMEE_N}$ represented the sum of the absolute values of the work done by the individual joint torques:

$$\mathrm{MMEE_N} = \int_{t_0}^{t_f} \sum_{j=1}^{6} |P_j| dt + W_{hf}. \quad (7)$$

Note that $\mathrm{MMEE_N}$ was modified for cycling to include the net work done by the hip joint reaction force ($W_{hf}$). Using $\mathrm{MMEE_N}$, $W_{extra_N}$ was defined as

$$W_{extra_N} = \mathrm{MMEE_N} - W_E. \quad (8)$$

A second MMEE measure allowed reductions due to the source intercompensation allowed by biarticular muscles of the lower extremity. $\mathrm{MMEE_I}$ estimated an upper limit for work savings by allowing complete intercompensations between hip and knee moments (due to the biarticular muscles of the hamstrings group, the sartorius and the rectus femoris) and ankle plantarflexors and knee flexors (due to the gastrocnemius). Based on the net joint torques at each joint, the algorithm calculated the appropriate total joint power assuming complete intercompensation between joints that were crossed by biarticular muscles. Table 1 lists the decision criteria of the $\mathrm{MMEE_I}$ algorithm, as well as the corresponding equation used to calculate the intercompensated total joint power for each leg ($P_I$). When $W_{extra_I}$ was calculated as

$$W_{extra_I} = \mathrm{MMEE_I} - W_E$$
$$= \int_{t_0}^{t_f} \sum_{l=1}^{2} (P_{I_l}) dt + W_{hf} - W_E. \quad (9)$$

The statistical analysis consisted of two steps. First, the correlation between internal work ($W_I$) and each measure of $W_{extra}$ was tested using simple linear regression models. $W_I$ was calculated as the absolute sum of the changes in the total mechanical energy of the two legs (Winter, 1979; Pierrynowski et al., 1980):

$$W_I = \sum_{i=1}^{360} |E_i - E_{i-1}|. \quad (10)$$

Second, to test for differences between chainrings, the experimental model was randomized complete block design. The means of $W_I$, $W_{extra_N}$, $W_{extra_I}$, $W_{hf}$, $W_E$, $W_B$ and cadence were calculated for five revolutions within each of the four randomly selected data collection periods to provide a mean for each subject-chainring combination. The results from the chainrings were blocked by subject, and a one way ANOVA tested for significant differences between the means of the chainrings ($p < 0.05$). When significant differences were evident, Duncan's multiple range test was used to determine which means were significantly different while controlling the type I comparisonwise error rate.

Average time histories of the instantaneous power associated with the pedal reaction force ($P_P$) were calculated for each chainring by averaging the individual curves for each subject ($n = 10$). Individual curves were created with each subject–chainring combination from the 20 revolutions of data collected. Then the instantaneous external power ($P_E$) curves—sum of both $P_P$ (assuming symmetry)—were calcu-

Table 1. Decision criteria and formulas used in algorithm to calculate intercompensated $W_{extra}$

| Joint torque combination (ankle-knee-hip) | Intercompensated power ($P_I$) |
|---|---|
| Dorsiflexor–flexor–flexor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |
| Dorsiflexor–flexor–extensor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |
| Dorsiflexor–extensor–flexor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |
| Dorsiflexor–extensor–extensor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |
| Plantarflexor–flexor–flexor | $\lvert P_a + P_k + P_h\rvert$ |
| Plantarflexor–flexor–extensor | $\lvert P_a + P_k + P_h\rvert$ |
| Plantarflexor–extensor–flexor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |
| Plantarflexor–extensor–extensor | $\lvert P_a\rvert + \lvert P_k + P_h\rvert$ |

lated for each chainring from the individual $P_P$ curves. To test for statistical differences between the chainrings, the maximum and minimum values from the $P_P$ and $P_E$ curves were found for each subject–chainring combination. Again, the means for each subject–chainring combination were blocked by subject, and a one-way ANOVA tested for significant differences between the means of the chainrings ($p<0.05$) with Duncan's multiple range test used to determine post-hoc which means were significantly different.

## RESULTS

Cadence and workload were sufficiently well controlled during the experimental trials to allow comparisons between chainrings. The average cadence was $87.8 \pm 0.7$ rpm and the average workload ($W_E$) was calculated as $157.4 \pm 14.7$ J (assuming symmetry). The constant workload setting of the Velodyne should have yielded an average power of 163.3 J at this cadence. This small discrepancy should not affect the results because there were no significant differences ($p>0.05$) in workload (or cadence) between chainrings (Table 2).

The calculated work input to the mechanical system by the individual power sources accounted for nearly all of the measured work done by the system. The average sum of the work done by the joint powers and the hip joint force was $154.5 \pm 12.5$ J which was only 1.8% lower than the average external work of 157.4 $\pm 14.7$ J with no significant differences in $E_B$ ($E_B = -2.9 \pm 5.3$ J) between chainrings (Table 2). Also, the work done by the net hip joint forces was not significantly different between the chainrings ($7.8 \pm 2.9$ J).

The hypothesis that reduced internal work in cycling would correlate with reduced MMEE (as measured by either $W_{extra}$) was not valid. Linear regression comparisons of the mean values for each subject–chainring combination ($n=30$) revealed that internal work was uncorrelated with either $W_{extra_N}$ ($r=0.12$, $p=0.52$) or $W_{extra_I}$ ($r=-0.16$, $p=0.41$).

Furthermore, RIW and IIW successfully reduced and increased internal work compared to CIR, while: (1) $W_{extra_N}$ showed a trend (but not significant at the 0.05 level) to increase for both RIW and IIW compared to CIR and (2) $W_{extra_I}$ was significantly increased for RIW relative to both CIR and IIW.

Group average time histories of the instantaneous power associated with the force applied to the pedal ($P_P$) calculated for each chainring revealed an interaction between chainring and $P_P$ (Fig. 2). During the downstroke, the magnitudes of the peak negative value of $P_P$ were significantly different for all chainrings (increased negative power indicates increased energy flow from leg to crank) with RIW ($-520.6 \pm 40.1$ W) increased and IIW ($-448.7$ $\pm 24.7$ W) decreased relative to CIR ($-486.2 \pm 43.9$). During the upstroke, the magnitude of the peak position value of $P_P$ (positive values indicate that the pedal delivered power to the leg) was significantly increased for IIW ($147.3 \pm 27.9$ W) relative to both CIR ($104.1 \pm 30.1$ W) and RIW ($91.5 \pm 19.1$ W). In addition to increasing the energy of the leg, some of the power delivered to the leg during the upstroke was dissipated as negative work since even the sum of the intercompensated instantaneous joint powers was sometimes negative in this region.

When symmetry was assumed and $P_P$ was added to a phase-shifted version of itself, there were striking differences between the chainrings with respect to the group average curves of instantaneous external power ($P_E$, net power dissapated by the environment due to the reaction forces acting at the two pedals) (Fig. 3). Note that the integral of this curve with respect to time gives the negative of $W_E$, the external work done during one complete revolution, because the force applied by the pedal on the foot is equal and opposite to the force applied by the foot on the pedal. The CIR curve was intermediate at nearly all crank angles, with RIW increased and IIW decreased when the cranks were nearly horizontal (60 to 120° and 240 to 300°) and IIW decreased and RIW decreased elsewhere. The differences observable in the peak values of the group average curves were statistically significant for all chainrings with the peak magnitude of the negative $P_E$ increased for RIW ($-448.5 \pm 46.8$ W) and decreased for IIW ($-345.3 \pm 17.8$) compared to CIR ($-391.3$ $\pm 43.5$ W) and the minimum magnitude of $P_E$ decreased for RIW ($-51.8 \pm 35.8$ W) and increased for

Table 2. Mean values ($\pm$SD) of energetic variables and cadence. While internal work was significantly different with all three chainrings. $W_{extra}$ measures showed no correlation with internal work

| Chainring | CIR | RIW | IIW |
|---|---|---|---|
| Cadence (rpm) | $88.1 \pm 0.5$ | $87.9 \pm 0.5$ | $87.6 \pm 0.9$ |
| $W_E$ (J) | $157.3 \pm 14.6$ | $156.5 \pm 15.6$ | $158.4 \pm 15.2$ |
| $W_{hi}$ (J) | $7.7 \pm 3.0$ | $7.9 \pm 3.0$ | $7.7 \pm 2.7$ |
| $E_B$ (J) | $-3.9 \pm 4.8$ | $-1.8 \pm 5.5$ | $-3.0 \pm 5.9$ |
| $W_{extra_N}$ (J) | $34.6 \pm 10.6$ | $39.1 \pm 12.2$ | $39.5 \pm 10.2$ |
| $W_{extra_I}$ (J) | $6.0 \pm 6.9$ | $9.6 \pm 7.5$* | $5.3 \pm 8.5$ |
| $W_I$ (J) | $39.1 \pm 5.1$* | $31.2 \pm 5.0$* | $49.2 \pm 4.5$* |

* Significantly different ($p<0.05$).

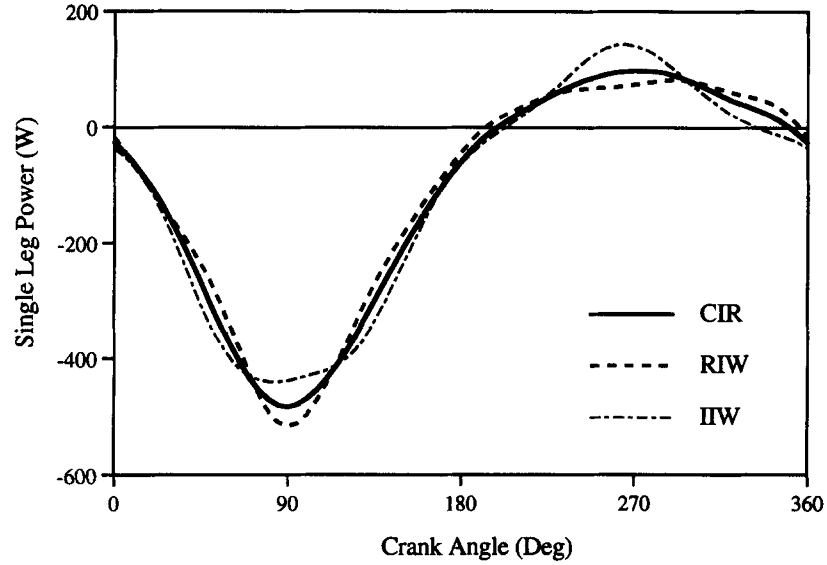


Fig. 2. Power associated with pedal reaction force (external power) of one leg using CIR, RIW and IIW. Around 90° during the downstroke, the elliptical chainrings exhibited differences with RIW increasing and IIW decreasing external power relative to CIR. During the upstroke, the large positive values of external power indicate that power is being absorbed by the leg.

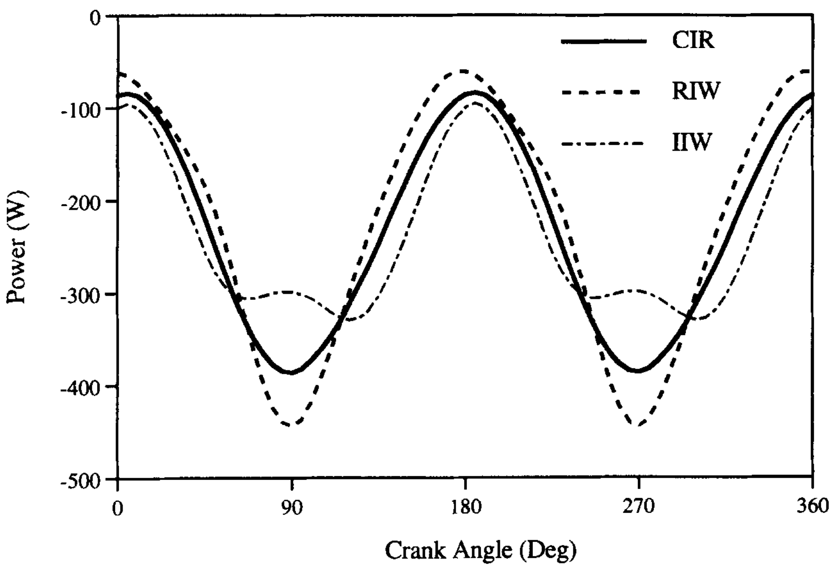


Fig. 3. Power associated with pedal reaction force (external power) for both legs using CIR, RIW and IIW. For RIW and IIW, intervals of increased crank angular velocity relative to CIR are associated with decreased amounts of external power. Thus, the pedal reaction forces were dramatically affected by the changed crank kinematics.

IIW ($-93.5 \pm 43.9$ W) compared to CIR ($-77.1 \pm 38.3$ W). Also, note that the periods of increased external power for each elliptical chainring occurred during the periods when crank angular velocity was decreased relative to CIR. Therefore, the amount of work done during these intervals would be increased even more than is apparent from the power plots because the integration would occur over a longer time interval.

## DISCUSSION

The primary purpose of this study was to determine whether reducing internal work during cycling would result in decreased total mechanical work for a given external workload, and hence, increased efficiency. To this end, the quantity $W_{extra}$ was introduced to quantify the mechanical work per revolution done in addition to the external work. Thus, the hypothesis that reduced internal work during cycling was correlated with reduced $W_{extra}$ was tested using an energy analysis of cycling.

Two potential sources of error were inherent in the calculations of MMEE. Ideally, the mechanical work done would be calculated at the level of the individual muscles (the actuators doing the work). But the mechanical work done by individual muscles cannot be assessed using inverse dynamics analysis because the muscles forces composing the net joint moment cannot be uniquely partitioned. As a result, net joint moments were used as the basis for the mechanical work calculation, and intercompensation between the net joint torque sources existed due to two-joint muscles. Thus, two values of $W_{extra}$ were calculated. $W_{extra_N}$ did not allow intercompensation and as a result overestimated the mechanical work when two-joint muscles redistributed energy by allowing negative work at one joint to do simultaneous positive work at another (van Ingen Schenau *et al.*, 1990). $W_{extra_I}$ allowed total intercompensation at joints crossed by biarticular muscles thereby estimating the savings possible due to total intercompensation by biarticular muscles. Although not presented in this paper, an even more conservative estimate of $W_{extra}$ was calculated by allowing total intercompensation at all joints, and the all statistical results were consistent with the results of $W_{extra_I}$. The actual intercompensation of the net joint powers at each joint crossed by the biarticular muscle will depend on the activity of the muscle and its moment arms at each joint crossed, and the actual $W_{extra}$ calculated if all intercompensations were known is bounded by the two measures. The second potential source of error when calculating $W_{extra}$ was that the mechanical work was overestimated if elastic energy storage in muscle–tendon complexes during a stretch-shorten cycle resulted in the recuperation of negative work during a later portion of the crank cycle. Possible stretch-shorten cycles during cycling have been noted in the triceps surae muscle group by Gregor *et al.* (1991) and in several muscles within the thigh by Hull and Hawkins (1990).

The calculation of both measures of $W_{extra}$ included the net work associated with the hip joint reaction forces for one crank revolution ($W_{hf}$) to reflect power delivered to the limbs from the pelvis segment. Similar to van Ingen Schenau *et al.* (1990), this study found positive work associated with the hip reaction force indicating net power delivery to the thigh segment. The power associated with the hip joint force must have been developed by other sources since internal forces only redistribute power (Aleshinsky, 1986a), and the hip joint force is an internal force within the body of the cyclist. Potential sources of power which the hip joint force redistributed were upper body external forces, gravitational forces, and upper body joint torques. However, external forces applied to the upper body had no associated work in our experimental setup because the bicycle was fixed to the ground (like an ergometer) causing the interaction forces at the seat and handlebars (Bolourchi and Hull, 1985) to be applied at stationary points. Also, the net work done through the hip joint forces by conservative gravitational forces acting on the upper body must be zero for one cycle of steady-state pedaling since an additional implication of the applied external forces having no associated work was that the gravitational forces acting on the upper body could only do work on the legs through interaction forces acting at the two hips. Thus, while gravity could contribute to positive work done on the thigh segments by the pelvis segment over portions of the cycle, the only sources for the net positive work done over the entire cycle were net joint torques in the upper body. Accordingly, $W_{hf}$ was added to the work done by the net joint torques in the calculation of MMEE to reflect mechanical work done by net joint torques of the upper body (note that this assumes symmetry of the two hip joint reaction forces). However, including $W_{hf}$ within the MMEE was computationally the same as subtracting $W_{hf}$ from the external work ($W_E$) to reduce $W_E$ to that done by the net joint torques, and using the revised $W_E$ to calculate $W_{extra}$. The second alternative more closely follows the discussion in van Ingen Schenau *et al.* (1990).

For this experiment, there was a consistent bias for the net work done by the sources (net joint torques and not hip joint forces) to be less than the external work (work done on the environment) as reflected by the mean value for the energy balance ($E_B = -2.9 \pm 5.3$) despite the fact that the net work done by all sources during one revolution should equal zero if the total system energy returns to its initial level (equation 5). Thus some values of $W_{extra_I}$ calculated for the individual subjects were negative, implying that more work was done by the leg on the environment than was put into the leg. However, the systematic underestimate of the net work done by the sources in this study (an average of 1.8%) is similar to the underestimate of 4.4% reported by van Ingen Schenau *et al.* (1990) and the ANOVA showed no difference between the chainrings. Therefore, the results of this study should be largely unaffected by the bias towards underestimating the net work done on the environment.

The hypothesis that reduced internal work during cycling would correlate with decreased MMEE was found to be invalid. Statistical analysis revealed that internal work was not correlated with either $W_{extra_N}$ or $W_{extra_I}$. In fact, RIW significantly reduced internal work while significantly increasing $W_{extra_I}$ compared to CIR. And while RIW significantly decreased internal work by 18.0 J relative to IIW, $W_{extra_I}$ was significantly increased by 4.7 J relative to IIW, while $W_{extra_N}$ remained unchanged. Thus, internal work provides erroneous information about MMEE in cycling. The results of this study show quite dramatically how potentially misleading the evaluation of total work from the sum of internal and external work can be.

The values of $W_{extra_N}$ calculated for CIR in this study are comparable to existent literature on joint power in cycling (Ericson, 1988; Ericson *et al.*, 1986; van Ingen Schenau *et al.*, 1990). Although none of these studies explicitly calculated MMEE, the values of $W_{extra_N}$ were estimated as twice the negative work. At 60 rpm and 120 W, Ericson *et al.* (1986) reported $W_{extra_N}=25.6$ J for six recreational cyclists. Ericson (1988) investigated power output as a function of cadence and workload. The conditions most similar to this study were 60 rpm at 240 W, 85 rpm at 160 W and 100 rpm at 200 W. For these conditions, $W_{extra_N}$ was 28.0, 34.4 and 53.2 J, respectively (again using six recreational cyclists). The values at comparable cadence (85 and 100 rpm) tend to be somewhat higher for the recreational cyclists of Ericson (1988) than for the experienced cyclists of this study.

The study of van Ingen Schenau *et al.* (1990) used five 'well-trained' male cyclists pedalling 88 rpm at 340 W. Under these conditions $W_{extra_N}$ was 38.4 J. This value must be considered a minimum since van Ingen Schenau *et al.* (1990) only reported the negative work done at the hip. Thus, the average $W_{extra}=34.6$ J calculated for the 10 experienced subjects of this study pedalling 87.6 rpm at 225.5 W represents reasonable agreement with the literature, although the value is lower than that for either recreational cyclists, or experienced cyclists at a much higher workload.

Similar to this study, all of the previous studies measured only one leg. Because the work that was calculated for the system when symmetry was assumed and both legs included was consistent from subject to subject, and was consistent with the workload setting of the Velodyne, the magnitude of the workdone by the opposite leg was likely similar to that done by the measured leg. As a result, it is unlikely that asymmetries between legs would have a large systematic effect on the $W_{extra}$ calculations. Any asymmetries should be just as likely to cause $W_{extra}$ to be overestimated as underestimated, and the statistical significance determined should not be affected.

Having established that internal work is not correlated with $W_{extra}$ in cycling, it is instructive to determine what internal work represents. As is shown clearly in equation (4), the change in the total mechanical energy of the five bar linkage model of the cyclist at any given time is the instantaneous difference between the mechanical energy input to the legs by the net joint torques ($W_j$) and the output work done about the center of the crank ($W_E$). Therefore, internal work occurs during intervals when the joint torques are doing more work on the legs than the legs are doing on the pedals, as well as during the subsequent intervals when more work is done on the pedals than is being done by the joint torques. Thus internal work is a measure of the timing between work done on the legs and subsequent work done on the pedal. RIW decreased internal work relative to CIR because $W_E$ production more closely matched $W_j$ production, while IIW increased internal work relative to CIR because $W_E$ production was more out of phase with $W_j$ production.

The results of this study imply that future work in the design of non-circular chainrings must incorporate the dynamic effects of induced crank angular velocity ($\omega_c$) variations. For RIW and IIW, phases of increased external power (Fig. 3) were associated with periods where $\omega_c$ was decreased (45 to 135° and 225 to 335° for RIW, 335 to 45° and 135 to 225° for IIW). Increased amounts of power were also absorbed (negative work was done) during the periods of increased $\omega_c$. Therefore, the dynamics of the cycling motion appear to be an important component to consider when designing a chainring.

While this study shows that estimating the total mechanical work from the sum of the internal and external work is invalid for cycling, the definition of internal work does provide a valid measure of the fluctuation in the total energy in cycling, and the results of the elliptical chainring testing shed some interesting light on the idea in non-circular chainring design that kinetic energy fluctuations should be reduced (Harrison, 1970; Okajima, 1983). While the physiological cost of cycling was not tested in the current study, an earlier human performance study (Hull *et al.*, 1992) used the same chainrings, but different subjects, and found a trend of lower oxygen consumption with the circular chainring although the results were not statistically significant at the 0.05 level. Because a mechanical energy analysis was not performed in the earlier study, a correlation between $W_{extra}$ and physiological cost cannot be attempted. But the trend of CIR showing reduced oxygen consumption compared to RIW and IIW is similar to the result with $W_{extra_N}$ of this study, suggesting that an appropriately intercompensated measure of $W_{extra}$ is a potentially useful indicator of physiological energy expenditure. Given the results of this study and the previous human performance work (Hull *et al.*, 1992), it appears that designing non-circular chainrings to limit energy fluctuations is not a sound approach for realizing a chainring shape which improves cycling efficiency.

## CONCLUSIONS

The main conclusions of this study are:

(1) The hypothesis that internal work is correlated with muscular mechanical energy expenditure during cycling was found to be invalid. Reduced internal work in cycling does not correlate with reduced MMEE. Thus, estimating MMEE from internal work measurements is inappropriate in cycling. While others have shown the theoretical problems with the internal work hypothesis (Aleshinsky, 1986a,b; van Ingen Schenau *et al.*, 1990; Wells, 1988), the experimental manipulation of internal work in this study dramatically shows how potentially misleading

it can be to evaluate the total work from the sum of internal and external work.

(2) The dynamic effects of a non-circular chainring must be considered in the design process because the induced crank angular velocity variations can affect muscular mechanical energy expenditure.

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