Mechanical energy management in cycling: source relations and energy expenditure

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ABSTRACT

BROKER, J. P. and R. J. GREGOR. Mechanical energy management in cycling: source relations and energy expenditure. *Med. Sci. Sports Exerc.*, Vol. 26, No. 1, pp. 64–74, 1994. Conservation of energy suggests that during cycling the constrained lower extremity is capable of delivering energy to the bicycle without expending energy to move the limbs. The purpose of this study was to characterize the management of mechanical energy during cycling and, specifically, to evaluate the potential for system energetic conservatism. Mechanical energy contributions derived from lower extremity energy sources were computed for 12 experienced male cyclists riding at five combinations of cadence and power output. The knee joint dominated (>50%) in contributing to system energy and a moderate amount of energy was derived from hip joint reaction forces (>6%). Energy generations and dissipations at the sources were sensitive to power output and, within the range of conditions studied, insensitive to cadence. Two energy models estimated mechanical energy expenditure under hypothetical single-joint and multijoint muscle operating conditions. When multijoint muscles were incorporated into the energy management analysis, a significant reduction in mechanical work relative to the single-joint muscle operation occurred. Energy savings associated with multijoint muscle energy transfers were enhanced at higher bicycle power levels, suggesting that conservation of mechanical energy is plausible given appropriate actions of two-joint muscles.

MECHANICAL POWER, ENERGY TRANSFER, BIARTICULAR MUSCLE, WORK, BICYCLING

During cycling, the lower extremity is constrained to move in a predictable way. With each elevation of one leg, the other leg falls, and so on. If the two-legged lower extremity cycling system is modeled as two connected four-bar linkages (with fixed ankle joints and nonmobile hip joints), then the system has only one degree of freedom and, if set in motion without internal or external load, it will oscillate (in a circular fashion) forever. This follows from the law of conservation of energy. Several authors, however, suggest that it requires energy, or the mechanical work of muscles, to move the limbs through the circular pedalling motion (13,21,25,26). Is the constrained pedalling motion not energetically conservative? The answer to this question appears to depend on the method employed to study the energetics of the cycling task.

Energy analysis methods. In general, two scientific approaches have been used to study the energetics of movement. The first approach relies strictly on *kinematic* features and has traditionally been applied to the study of overground locomotion (walking and running) in which little energy is dissipated to the environment (5,11,19,29). The approach estimates mechanical work from absolute changes in the kinetic (KE) and potential (PE) energy of either the body center of mass (CM), the body segments relative to the CM, or both. Since *absolute* energy changes are equated with mechanical work, the approach allows investigators to avoid the "zero work paradox" associated with level walking and running in which over a complete cycle of movement the net work done (positive work minus negative work) equals zero.

The kinematic version has a sound theoretical basis with respect to the determination of mechanical energies within multisegment systems. This approach, however, produces ambiguous results when center of mass and segment energy changes are used to estimate mechanical work. The ambiguity lies in the possible energy exchanges within and between segments, and between the multisegment system and the environment.

In recent cycling studies, Morrisey et al. (21), Wells et al. (25), and Hull et al. (13) utilized a kinematic method presented by Winter (27) that allows energy transfers within and between segments, necessarily associating variations in total system energy (kinetic plus potential) with muscle actions and, consequently, mechanical work. These investigators estimated that approximately 42 J (21

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J per side) are required to accelerate and decelerate the limbs on a bicycle at 90 revolutions·min^{-1} (RPM), representing between 26 and 90% of the total work done per revolution (note: Morrisey et al. (21) and Wells et al. (25) included a near-zero load condition in their studies). Further, Luhtanen et al. (20) reported that 56 ± 12 J (28 J per side) are required for bilateral limb movements during pedalling at 60 RPM (20–38% of total work). More recently, Widrick et al. (26) reported that an additional 88 J (44 J per side) are required to move the limbs through the pedal cycle at 98 RPM. Widrick et al. (26), however, assumed that no energy transfer takes place between limbs via the cranks.

The second approach to studying the energetics of movement is based on *kinetics* and has been used to study both overground locomotion (6,9,22,24,28) and tasks like cycling that involve substantial energy dissipation to the environment (10,15,18,23). The approach involves the description of system energetics in terms of joint muscle powers (P_{MJ}) and joint force powers (P_{FJ}). P_{MJ}, the vector product of a joint's generalized muscle moment (GMM_J) and angular velocity $\dot{\varnothing}_J$), describes a muscular contribution of energy (positive or negative) to a multisegment system that can both increase (generate) or decrease (absorb) system energy (1). P_{FJ}, the vector product of joint reaction force ($\bar{F}_J$) and joint linear velocity ($\bar{V}_J$), describes the flow of energy between segments (resulting purely from joint reaction forces) and permits the separation of multisegment systems for energetic analysis (2,17).

The kinetic-based method is not without limitations. Assumptions regarding the rigidity of system links and fixed axes of rotation, for example, introduce errors into the computation of joint motions, joint moments, and consequently joint powers. The hypothetical nature of joint powers precludes the appropriate assignment of these powers, positive or negative, to the effects of active and passive elements of muscle, nonmuscular elastic structures, and joint friction. Further, the energetic loss associated with antagonists doing work in opposition to their agonists at a given joint is not accounted for in the determination of joint powers. Finally, the role biarticular muscles play in transporting and transferring energy between joints, although not affecting the net or summed joint powers, further complicates the distribution of joint powers among the potential muscular sources. Despite these limitations, however, the kinetic method permits a more detailed and descriptive accounting of the distribution and flow of energy within and through link segment systems.

Ericson et al. (10), Sirin et al. (23), and Ingen Schenau et al. (15), for example, used the kinetic approach and reported that due to limited negative (eccentric) source actions, most of the mechanical energy generated in the musculature during cycling may be delivered to the environment (see Table 3 for joule equivalents). In these studies, however, the various source contributions to system energy were not fully characterized and the effect of different operating conditions, i.e., cadence and power output, on system energetics were not addressed.

In a related study, Kautz and Hull (18) applied the kinematic and kinetic methods to evaluate the effects of various chainring shapes on internal work and mechanical energy expenditure, respectively. Although these researchers clearly exposed significant differences in calculated energy "cost" using the separate methods, their small sample size and substantial between-subject variability preclude adequate comparisons with similar studies. Furthermore, Kautz and Hull (18) reported only one condition of bicycle power and cadence, and employed a simplified linked segment model, which assumes the hips to be fixed and the feet to be rigid relative to the pedals.

Biarticular muscle effects. An important advantage in the kinetic energy analysis method involves allowances for energy source intercompensations in the determination of mechanical energy expenditure. Intercompensations represent the transfer of mechanical energy via multijoint muscles from one joint at which energy is being absorbed (via negative source action) to an adjacent joint at which energy is being generated (via positive source action). Intercompensations functionally reduce mechanical energy expenditure by eliminating the duplication of effort associated with simultaneous energy absorption and generation at adjacent joints (1,2,14,16).

Ingen Schenau et al. (15) extended their examination of cycling energetics to qualitatively assess the possible mechanical energy savings associated with two-joint muscle actions. Although no detailed description of intercompensatory actions was attempted, they concluded that the power "lost" within the two-legged system (28 W at 340 W total bicycle power output) could be completely intercompensated by actions of two-joint muscles and, therefore, that "the power lost in changing the segmental energy in ergometer cycling . . . may even {be} negligible."

Purpose. The purpose of this study was to characterize the management of mechanical energy during cycling. Specifically, energy management was described in terms of joint muscle and joint force power profiles across a variety of operating conditions for a large group of experienced racing cyclists. These source powers were then used to estimate mechanical energy expenditure (MEE) under hypothetical conditions of single-joint muscle control (no intercompensations) and multijoint muscle control (full intercompensation). MEE sensitivity to intercompensation allowances across the various conditions were then used to suggest two-joint muscle intercompensation mechanisms and their effect on cycling energetic conservatism.

METHODS

Subjects. Twelve Junior National Team male cyclists participated in this study (mean age: 16.8 ± 0.4 yr). Written informed consent was obtained from each subject in accordance with the policies of the United States Olympic Training Center. Subjects had a minimum of 3 yr of competitive cycling experience and wore cycling shoes equipped with "clip-less" compatible pedal interfaces. Joint markers were placed on each subject's right hip, approximating the superior border of the greater trochanter, knee (lateral femoral epicondyle), ankle (inferior tip of the lateral malleolus), and 5th metatarsal-phalangeal joint (head of 5th metatarsal) axes. Anthropometric features (i.e., body weight and lower extremity segment lengths) describing each subject were measured.

Procedure. Subjects rode a test bicycle mounted to a fixed-fork Velodyne Trainer configured to modulate bicycle power output (watts) independent of bicycle wheel speed and pedalling cadence (RPM). To minimize the effects of unfamiliar frame geometry on pedalling mechanics, the height and fore/aft position of the test bicycle seat was adjusted to match the subject's "normal" seat position as measured on their own bicycle. After a 5-min accommodation period, subjects rode the test bicycle for a minimum of 1 min at each of the conditions listed in Table 1. Workloads and cadences were presented to the subjects in random order. Cadence, displayed digitally on the Velodyne Trainer, was voluntarily controlled by each subject.

The test bicycle was equipped with a dual piezoelectric force pedal system. This system measures normal (F_n) and tangential (F_t) components of the applied pedal load, the angle of the pedal with respect to the crank, and the angle of the crank with respect to the bicycle frame (3). Force and position data from the force pedal system were collected at 200 Hz during the final 15 s of each trial. Also during the final 15 s of each trial, joint marker displacements were recorded by a high-speed video camera (Vicon) positioned orthogonal to the plane of motion at a distance of approximately 3 m and operating at a 200 frames·s^{-1}.

Pedalling kinetics. Kinetic and kinematic data describing two consecutive pedal revolutions beginning and ending at top dead center (TDC) were isolated for analysis. The revolutions were selected from a series of several revolutions during which cadence was determined to be invariant. Coordinate data were then obtained by digitizing the video images (Peak Performance System) and smoothed at 4 Hz using a 4th order, zero-lag Butterworth filter. Segment inclination angles were computed from the smoothed coordinate data and derivatives obtained using finite difference techniques. Thigh, shank, and foot (ankle to pedal spindle) angles, angular velocities, and angular accelerations, as well as hip, knee, ankle, and pedal spindle linear velocities and accelerations were computed for each sample within the cycles analyzed.

Normal and tangential components of the load applied to each pedal were smoothed at 15 hz using a 4th order, zero-lag Butterworth filter, and then vectorally combined to describe the resultant load applied to the pedal ($\bar{F}_P$). The vector product of the resultant pedal load ($\bar{F}_P$) and pedal spindle velocity ($\bar{V}_P$) was integrated with respect to time to determine work performed (W_{pedal}) and average power (P_{pedal}) at the bicycle crank. Computationally:

$$W_{pedal} = \int_{t_i}^{t_f} (\bar{F}_P \cdot \bar{V}_P)\, dt \quad (1)$$

$$P_{pedal} = W_{pedal}/(t_f - t_i), \quad (2)$$

where t_i and t_f represent time at the beginning and end of the pedal cycle of interest, respectively.

Joint kinetics. The lower extremity was modeled as a planar, three-segment, rigid body system. Anthropometric data (segment masses, centers of mass, and moments of inertia) were obtained using regression equations developed by Dempster (8) and Clauser et al. (7). Axes of rotation were considered to be fixed at joint centers, internal joint friction was assumed negligible, and redistribution of mass within a segment due to muscular contractions was ignored. The linked segment model with all forces and moments acting upon the segments is presented in Figure 1. M_H, M_K, and M_A are generalized muscle moments (GMM) at the hip, knee, and ankle, respectively, representing the net effect of all muscles and periarticular structures acting about each joint. Equations of motion for the three segments were formulated using conventional Newtonian mechanics.

Source powers. A cycling energy model was formulated using the control system displayed in Figure 2. Mechanical energy functionally enters or exits the control system at the hip, knee, or ankle when control moments (GMM) accompany joint motions (angular velocities). These muscular energy sources were characterized by the net joint muscle powers (P_{MJ}) at each joint, and were computed as follows:

$$P_{MJ} = GMM_J \cdot \dot{\varnothing}_J, \quad (3)$$

where GMM_J and $\dot{\varnothing}_J$ are the generalized muscle moment and angular velocity of joint j, respectively.

Mechanical energy can also enter or exit the control system at the hip joint and the foot/pedal interface when reaction forces (between the pelvis and hip and between the foot and pedal) accompany joint motions (linear velocities). Energy transfers occur within the system (be-

TABLE 1. Test conditions.

Condition	Cadence (RPM)	Power Output (W)
1	90	250
2	100	200
3	100	250
4	100	300
5	110	250

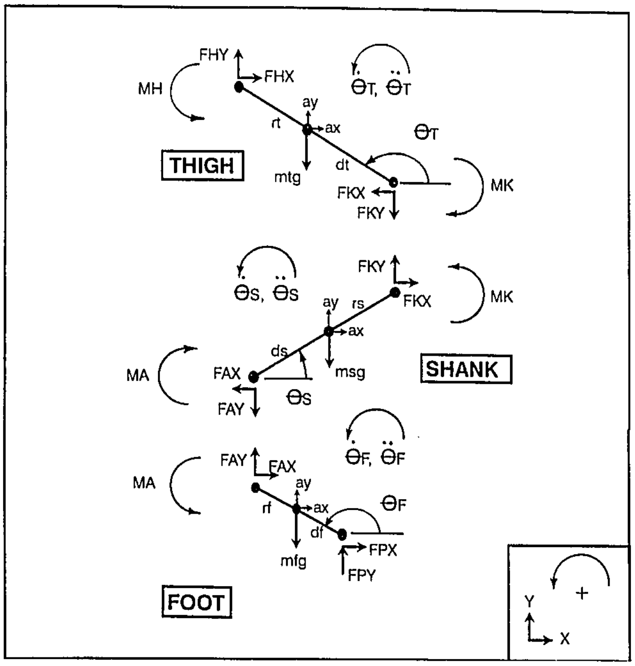

Figure 1—Linked segment model of the lower extremity during cycling. External reaction forces (FPx and FPy) act at the pedal spindle.

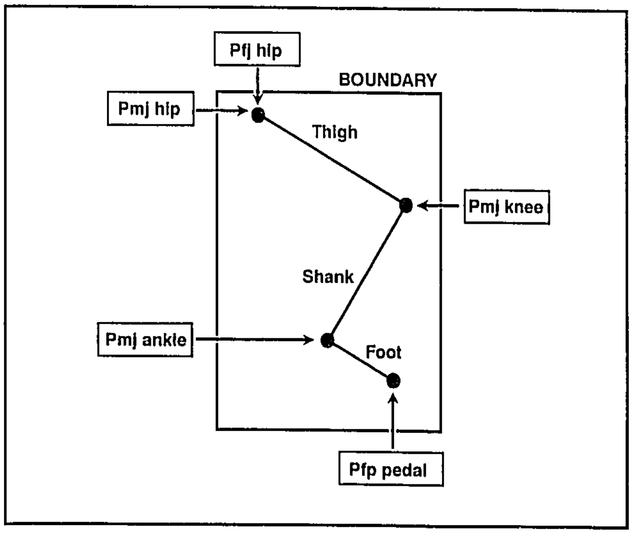

Figure 2—Control system describing energy flow into and out of the linked segment model. The three joint muscle powers (Pmj) and the joint force power (P_{FJ}) at the hip represent the energy sources to the system. P_{FP} at the pedal represents the energy destination.

tween segments) when intersegmental reaction forces (at the knee and ankle) accompany joint linear velocities. Transfers into, out of, or within the control system associated with these reaction forces are generally described by the joint force powers (P_{FJ}), which were computed as follows:

$$P_{FJ} = \bar{F}_J \cdot \bar{V}_J, \quad (4)$$

where $\bar{F}_J$ and $\bar{V}_J$ are the reaction force and linear velocity of joint j, respectively.

In the cycling energy model, Pmj at the hip, knee, and ankle, and the P_{FJ} at the hip characterize *sources* of mechanical energy to the control system. These powers were integrated with respect to time to describe both positive and negative work done by the muscular sources (in joules) during pedalling. Functionally, concentric and eccentric single-joint muscle actions are represented by positive and negative P_{MJ}, respectively. The joint force power at the pedal, hereafter referred to as pedal power (P_{FP}), represents the single mechanical energy "sink," or destination, in the cycling energy model. Initial and final system potential and kinetic energies were computed at the beginning and end of each pedal revolution analyzed to account for any change in control system energy (dEsys). Source contributions to system energy were checked against net energy delivered to the bicycle using the following control system energy balance relation:

$$\int_{ti}^{tf} (P_{MJhip} + P_{MJknee} + P_{MJank} + P_{FJhip})\, dt = \int_{ti}^{tf} P_{FP}\, dt + dEsys. \quad (5)$$

Mechanical energy expenditure. Two energy models were developed to estimate mechanical energy expenditure for the cycling control system. Both models represented theoretical multisegment systems powered by muscles acting at the hip, knee, and ankle, plus a joint force power input (P_{FJ}) at the hip.

The first energy model (MEEC) assigned all energy generated or absorbed at the muscular sources to active single-joint muscles. Consequently, muscular sources were assumed to be fully compensated, i.e., no energy saving, multijoint muscle intercompensations (between source energy transfer) could occur, and passive contributions to net joint power and recuperation of absorbed energy—via the storage and subsequent release of energy absorbed in elastic (and viscoelastic) structures—were disallowed. Additionally, energy transfer at the hip associated with hip reaction forces (P_{FJhip}) was assumed to be conservative, i.e., energy absorbed at one instant in the pedal cycle could be returned to the system later in the cycle.

The second energy model (MEEFIC) describes a hypothetical multisegment system in which energy transfers (intercompensations) can occur between joints within the system. Similar to the MEEC model, passive and recuperative contributions to Pmj were assumed to be zero in the MEEFIC model, and energy transfer at the hip associated with hip reaction forces (P_{FJhip}) was assumed to be conservative. Finally, energy transfers (intercompensations) between joints within the MEEFIC energy model were assumed to occur instantaneously.

The MEEC and MEEFIC energy model mechanical energy expenditure relations are as follows:

$$MEEC = \int_{ti}^{tf} (|P_{MJhip}| + |P_{MJknee}| + |P_{MJank}| + P_{FJhip})\, dt \quad (6)$$

$$\text{MEEFIC} = \int_{t_i}^{t_f} (|P_{MJhip} + P_{MJknee} + P_{MJank}| + P_{FJhip})\, dt. \qquad (7)$$

Statistical analysis. Means ± 1 standard deviation were computed for all continuous variables associated with the energy analysis at the each of the five test conditions. These variables include pedal kinetic and kinematic data (forces and angles), segment kinematics (angles, angular velocities, and angular accelerations), joint kinetics (joint GMM and reaction forces), and energy transfer data (joint muscle powers and joint force powers). The effects of cadence and bicycle power output on joint muscle and joint force power profiles were evaluated by comparing the mean profiles (±1 standard deviation) across test conditions.

Multiple linear regression analyses on repeated measures were performed on the various source contributions and the mechanical energy expenditure estimates (MEEC and MEEFIC models) using all data collected at the test conditions studied. This approach was used because between subject loading system power fluctuations and right vs left leg asymmetries created a situation in which subjects did not all pedal at the exact same conditions of cadence and power output. Independent variables included in the regression analysis were subject, power, cadence, and energy model. Interactions evaluated included cadence × power, cadence × energy model, and power × energy model. All significance was evaluated at the $P \leq 0.05$ level.

RESULTS

Pedal kinetics. Mean cadences for each of the five test conditions (1 through 5) were 89.4 ± 0.7, 99.3 ± 1.5, 99.4 ± 1.3, 98.7 ± 2.0, and 108.6 ± 2.0 RPM, respectively (see Table 1). Individual pedalling asymmetries, moderate cycle to cycle variations in pedal power, and loading system inaccuracies introduced moderate between and within subject variations in right-side pedal power. The mean right pedal powers at 90 and 100 RPM (test conditions 1 and 3) were 126.0 ± 16.8 and 124.4 ± 18.0 W, respectively, close to one-half the 250-W total that was set on the Velodyne loading system. The mean right pedal power at 110 RPM (test condition 5), however, was only 100.5 ± 19.5 W, somewhat below the set loading condition. The mean power levels for test conditions 2 and 4 (at 100 RPM) were 86.1 ± 24.1 and 133.3 ± 16.9 W, respectively. Right vs left pedalling power describing the multiple cycles was completely symmetric when all 12 subjects at each test condition were averaged together. Test condition 3 (100 RPM/250 W total) will hereafter be referred to as the "standard" test condition.

Joint muscle powers. All three joints generated energy throughout the first half of the pedal cycle (Fig. 3A–C). Peak power at the knee (250 W) was more than twice that observed at the hip and ankle (100–110 W).

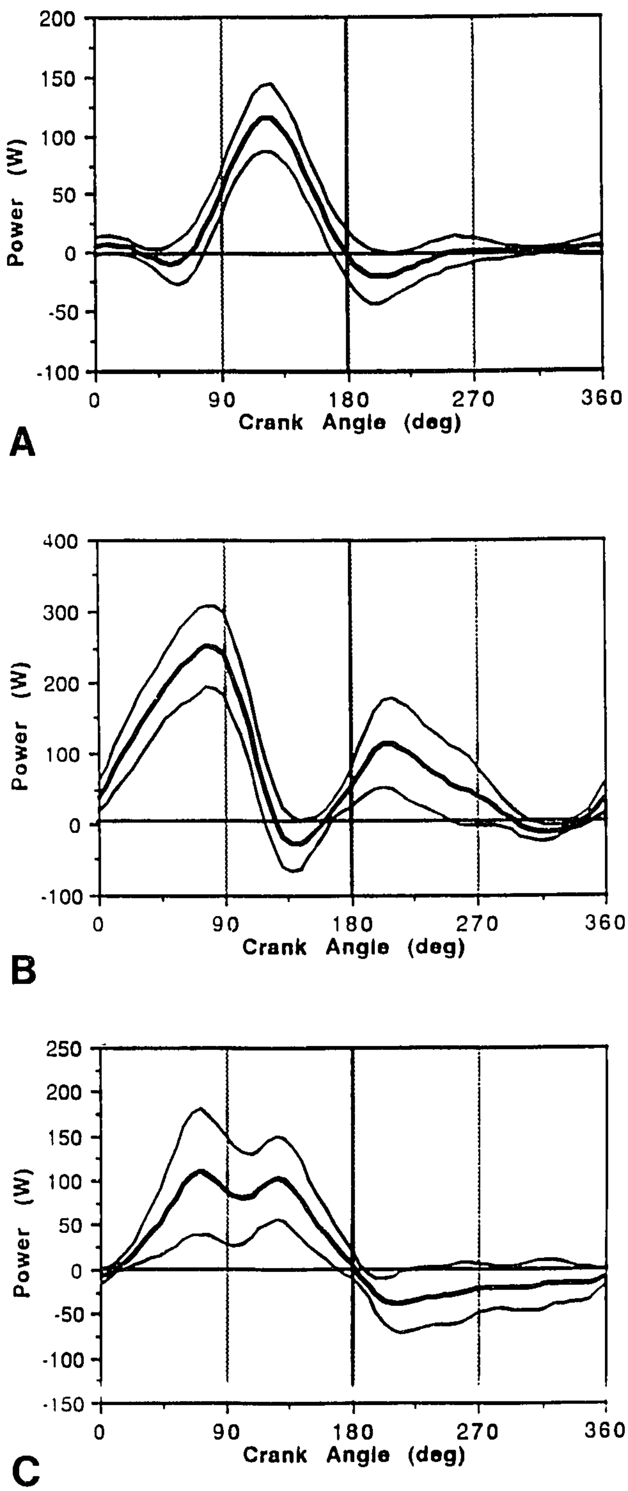

Figure 3—Mean joint muscle power (P_{MJ}) profiles (±1 SD) at the ankle (A), knee (B), and hip (C) for the standard (100 RPM/250 W) test condition.

Additionally, the knee generated sizable power during a large portion of the recovery phase (180–360°). Energy absorption associated with the Pmj occurred at the ankle during a brief period early in the pedal cycle (40–65° after TDC) and another beginning at BDC and continuing to 270° after TDC (Fig. 3A). Energy absorption at the knee was generally limited to a small region from 125–160° after TDC (Fig. 3B). In addition, energy was absorbed throughout the recovery phase at the hip (Fig. 3C).

The effects of bicycle power on the net ankle, knee, and hip muscle power profiles were directly related to the changes in joint GMM profiles. Higher bicycle powers resulted in higher positive joint muscle powers, and the effects of cadence and bicycle power on joint muscle power absorption were greatest at the hip, where high cadences and low bicycle powers were associated with higher energy absorption during recovery.

Joint force powers. During the power phase of the pedal cycle (0–180° after TDC), energy flowed proximal to distal, i.e., energy was transferred from (a) the pelvis to the thigh, (b) the thigh to the shank, (c) the shank to the foot, and (d) the foot to the pedal (Fig. 4). During recovery, energy usually flowed distal to proximal, i.e., energy was transferred from (a) the pedal to the foot, (b) the foot to the shank, and (c) the shank to the thigh. Energy at the hip during recovery, however, continued to flow distally (pelvis to the thigh). These power and recovery phase joint force power relationships were consistent across all subjects and across all five test conditions.

Joint force power increased at all joints during the power phase of the pedal cycle in response to higher bicycle power and/or cadence. During recovery, larger negative joint force powers were observed at the knee, ankle, and pedal at the high cadence and low output power conditions.

Energy balance. Multiple regression analysis on the net, positive, and negative energy contributions for each source indicated that the effects of cadence and cadence by power interactions on source contributions to system energy were not significant. The effect of bicycle power on each source contribution, however, was significant. Net, positive, and negative source contributions to total system energy, plus the summed energies from the sources (net, positive, and negative) derived from the linear regressions at low and high powers (at 100 RPM) are presented in Table 2. Regression r^2 values describing the effect of bicycle power on net, positive, and negative source contributions to lower extremity energy ranged from 0.65–0.92.

Most of the energy delivered to the system was associated with the knee P_{MJ} source. As power levels increased (175 to 275 W), the knee P_{MJ} source contributed more to the total system energy (49.7 to 59.5 J), but less when expressed as a percentage of the total system energy (87 to 72%). The ankle P_{MJ} and hip P_{FJ} source contributions to total system energy, when expressed in joules or as a percentage of the total system energy, varied little as power levels changed. Combined, the ankle P_{MJ} source and the hip P_{FJ} source contributed approximately 20% of the total energy derived from all the sources. Finally, the hip P_{MJ} source absorbed more energy at low power levels than it generated. As power levels increased, the energy derived from the hip increased dramatically, and at high total power levels (275 W) the hip P_{MJ} source contributed 8.7% of the total energy generated by the system. The additional energy derived from the hip P_{MJ} source at higher power levels resulted from the combined effect of decreased energy absorption (11.0 J to 9.2 J) and increased energy generation (7.5 J to 16.4 J).

Mechanical energy expenditure. Regions of the pedal cycle associated with energy expenditure *in excess* of that required to drive the bicycle were exposed when the instantaneous summed powers from the sources associated with the mechanical energy expenditure models (terms inside the brackets in equations 6 and 7) were graphically displayed versus crank angle along with the net instantaneous power (Fig. 5). Excess energy expenditure for the single-joint energy model (MEEC) occurs

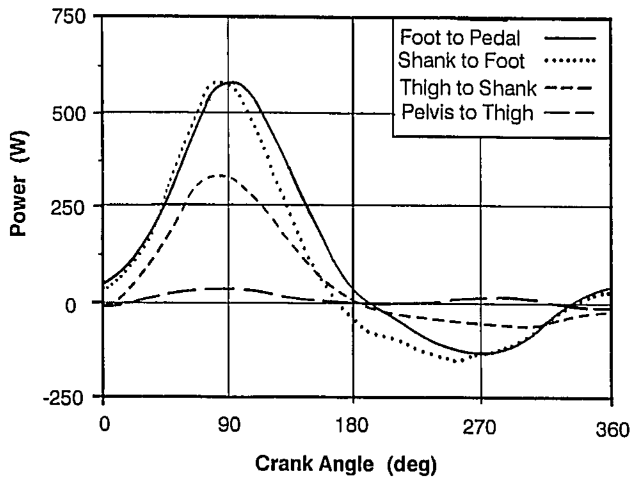

Figure 4—Mean joint reaction force powers (P_{FJ}) describing energy flow between the pelvis and thigh, the thigh and shank, the shank and foot, and the foot and bicycle pedal. Positive and negative reaction force powers describe distally and proximally directed flow of energy between adjacent segments, respectively.

TABLE 2. Single-limb source contributions to system energy derived from regression analysis results.

Source	Energy at 175 W (% Total)	Energy at 275 W (% Total)
P_{MJ} hip (net)	−3.5J(−6.4)	7.2J(8.7)
P_{MJ} hip (pos)	7.5J	16.4J
P_{MJ} hip (neg)	11.0J	9.2J
P_{MJ} knee (net)	45.7J(87.0)	59.5J(72.1)
P_{MJ} knee (pos)	47.8J	61.3J
P_{MJ} knee (neg)	2.1J	1.8J
P_{MJ} ankle (net)	7.1J(13.5)	10.1J(12.3)
P_{MJ} ankle (pos)	12.0J	15.6J
P_{MJ} ankle (neg)	4.9J	5.5J
P_{FJ} hip (net)	3.0J(5.8)	5.7J(6.9)
P_{FJ} hip (pos)	5.2J	7.7J
P_{FJ} hip (neg)	2.2J	2.0J
Total (net)	52.3J	82.6J
Total (pos)	72.5J	101.0J
Total (neg)	20.2J	18.5J

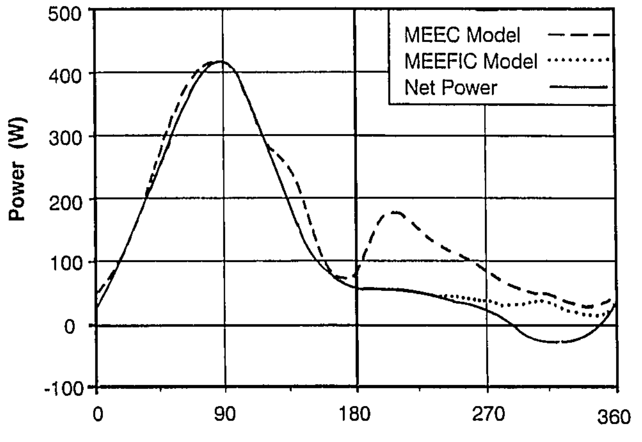

Figure 5—Mean instantaneous net and summed source powers for the MEEC and MEEFIC energy models at the standard test condition.

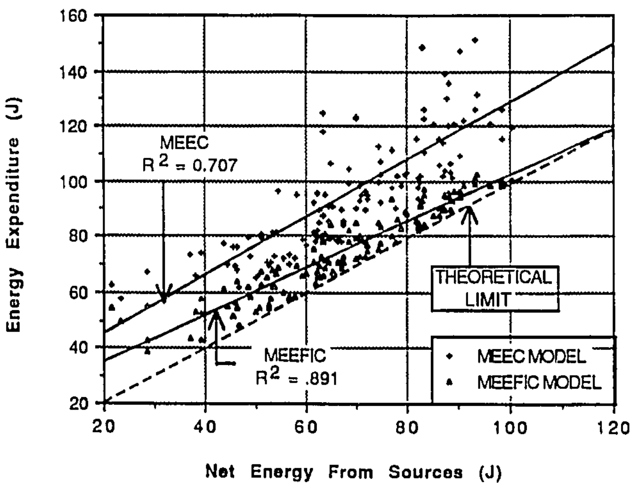

Figure 6—Mechanical energy expenditures for the MEEC and MEEFIC energy models expressed as a function of net energy from the sources. Note that the MEEFIC model estimate converges toward the theoretical limit where energy expenditure equals net energy generated.

whenever energy is absorbed at the sources within the system and was evident during brief periods in the first and second quadrants of the pedal cycle (0–180° after TDC) and throughout recovery. Excess energy expenditure for the multijoint, fully intercompensated energy model (MEEFIC) generally occurs when the algebraic sum of the P_{MJ} sources within the system is negative. Such a condition was only evident during mid to late recovery (Fig. 5).

Mechanical energy expenditure totals computed using equations 6 and 7 are displayed as a function of the net energy from the sources in Figure 6. Also included in Figure 6 is a line with a slope of unity that represents the theoretical limit at which mechanical energy expenditure equals the net energy delivered to the bicycle. Mechanical energy expenditure in excess of the net for the MEEC model was relatively constant across the workloads (net source energy levels) employed in this study (slope = 1.04). An additional 27 J (above that delivered to the environment) were required to drive the system using single-joint muscles alone. When multijoint muscle intercompensations were allowed to occur, mechanical energy expenditure (MEEFIC model) was dramatically lower and, in fact, approached the theoretical limit (where excess energy equals zero) as workload increased.

DISCUSSION

Power from the sources. Despite significant differences in cadence and bicycle power output, net joint muscle power (P_{MJ}) profiles derived in this study are generally supported by those previously reported (10,16,23). Energy was generated at the hip, knee, and ankle during most of the power phase, as all three joints extended (ankle plantarflexes) in conjunction with extensor GMM (ankle plantarflexor GMM). The small regions of energy absorption at the ankle (45–90°) and knee (125–160°) involved ankle dorsiflexion in conjunction with an ankle plantarflexor GMM, and knee extension in conjunction with a knee flexor GMM, respectively. The energy absorption at the knee during the first half of the pedal cycle is more pronounced in this study and in data presented by Ingen Schenau et al. (15) and is virtually absent in the lower cadence studies conducted by Ericson et al. (10) and Sirin et al. (23).

During early recovery, the ankle acted as an energy absorber as an ankle plantarflexor GMM accompanied ankle dorsiflexion. At the knee, energy was generated during the recovery phase as a knee flexor GMM accompanied knee flexion. The recovery phase hip muscle power profiles reported by Ericson et al. (10) and Sirin et al. (23) describe energy generation at the hip. The generation results from a hip flexor GMM accompanying relative hip flexion. Conversely, hip muscle power profiles observed in this study (Fig. 3C) and published by Ingen Schenau et al. (15) indicate that energy is generally absorbed at the hip during recovery (hip extensor GMM during hip flexion). The differences are directly related to the GMM pattern differences between studies, which in turn appear to be associated with subject and test condition differences. Ericson et al. (10) and Sirin et al. (23), for example, tested recreational subjects on cycle ergometers at 60 RPM with imposed loads of 120 W and 160 W, respectively. Ingen Schenau et al. (15) tested experienced cyclists on an ergometer at 90 RPM and 340 W. In this study, experienced racing cyclists where tested at five different conditions representing a range of cadences (90–110 RPM) and bicycle powers (178–267 W).

Between subject variability in joint muscle powers was high, particularly at the hip. The variability was directly related to between subject variability in joint moment patterns (GMM). Between subject joint moment pattern variability in cycling is well documented (12).

Reaction force powers internal to the cycling system, i.e., P_{FJ} at the knee and ankle (see Fig. 4), are conceptually equivalent to the F-sources defined by Aleshinsky (1,2) and participate in the redistribution of energy within the system without altering total system energy. Reaction force powers at the borders of the cycling system, i.e., P_{FJ}s at the hip and pedal, represent sources and destinations of mechanical energy, respectively.

The reaction force profiles derived in this study indicate a distal flow of energy during the first half of the pedal cycle and a proximal flow of energy during recovery. Only Ingen Schenau et al. (15) calculated the energy input to the lower extremity associated with the P_{FJ} source at the hip. Their results are in complete agreement with the hip reaction force powers derived in this study (Fig. 4). The hip joint appears to provide energy to the lower extremity during both the power and recovery phases of the pedal cycle. Hip joint reaction force contribution to lower extremity energy, however, should be viewed with caution as the precise determination of hip joint motion during cycling is difficult.

A balanced energy state. Over one complete pedal cycle at constant cadence, the net work done by the sources should equal the energy delivered to the pedal. For comparison, mechanical work (positive, negative, and net) performed by the sources and the work performed at the pedal in this study (at high output power) and in the studies reported by Ericson et al. (10), Sirin et al. (23), and Ingen Schenau et al. (15) are presented in Table 3.

In the study by Ericson et al. (10), pedal work was remarkably close to the work performed by the sources. These researchers, however, computed pedal work by simply halving the total ergometer load setting, i.e., symmetry was assumed and energy transfer at the pedal was not verified (e.g., by computing pedal power and integrating with respect to time). Consequently, the energy balance indicated in the Ericson et al. (10) study may be exaggerated. Also, in the studies by Ericson et al. (10) and Sirin et al. (23), the energy contribution at the hip associated with the hip joint reaction force was not included. Hip joint reaction force contributions would most likely improve the balance between source work and pedal work in the Sirin et al. (23) study.

In the data reported by Ericson et al. (10) and Sirin et al. (23), approximately 53% of the total system energy

TABLE 3. Energy balance: source work vs pedal work.

	Positive Work	Negative Work	Net Source Work	Pedal Work
Ericson et al. (10)	66.8J	6.0J	60.8J	60.0J
Sirin et al. (23)—right	68.0J	6.4J	61.6J	66.0J
—left	82.0J	9.0J	73.0J	77.0J
Ingen Schenau et al. (15)	116.6J	9.6J	107.0J	112.0J
This study (high power)	96.9J	14.3J	82.6J	85.3J

was generated at the knee, 30% at the hip, and 17% at the ankle. Our data suggest that source contributions to system energy are sensitive to bicycle power output (Table 2). Specifically, changes in bicycle output power (from 175 to 275 W) were associated with large changes in generated energy at the hip P_{MJ} and the knee P_{MJ} sources. The increased energy contribution from the hip P_{MJ} source at higher bicycle power output was traceable to higher energy generation at the hip during the first half of the pedal cycle, and lower energy absorption at the hip during recovery (Fig. 3C).

Morrisey et al. (21), Wells et al. (25), Luhtanen et al. (20), and Widrick et al. (26) applied the kinematic method presented by Winter (27) to determine the "energy required" to accelerate and decelerate the leg segments during cycling. Hull et al. (13) also used Winter's method to calculate the mechanical work associated with limb movements in an attempt to identify an energetic advantage associated with elliptical chainrings. As described, Winter's (27) method defines "internal work" as that required to produce the changes in segmental energies observed during movement. Internal work is added to the work performed on the environment to estimate total mechanical work.

According to equation 5, changes in system energy (dEsys) result from combined source actions, listed on the left side of equation 5, and energy transfers between the system and the environment (P_{FP}). During pedalling, decreases in total system energy (negative dEsys), which are by definition associated with additional or "internal" work by Winter's (27) method, occur whenever energy transfer to the pedal exceeds the net energy derived from the sources—regardless of whether the net energy from the sources is positive or negative. Fluctuations in system energy cannot be associated with source actions alone and thus cannot be directly related to the mechanical work of muscles.

The interplay between source actions, energy transfers between the foot and pedal, and total segmental energies illustrate how seemingly erroneous relationships between segmental energy variations and mechanical work can emerge. Most of the energy absorbed at the sources within the system was absorbed at the hip joint during the recovery phase of the pedal cycle—when single-limb segmental energy was increasing. The segmental energy increase occurred because the negative energy transfer from the foot to the pedal during recovery exceeded the net energy absorbed by the sources, and not because additional muscle actions accelerated and lifted the legs. During the power phase, energy transfer to the pedal exceeded that derived from the sources and single-limb segmental energy decreased. This decrease, however, benefited the transfer of energy to the pedal and to the contralateral limb (via the bicycle cranks), and did not involve energy absorbing muscle actions. Kautz and Hull (18) similarly associated the interplay between source actions, energy transfers, and segmental energies with the lack of correlation between internal work (kinematic method) and kinetic based estimates of mechanical energy cost.

Mechanical energy expenditure. The single-joint muscle energy model (MEEC) exhibited mechanical energy expenditure in excess of the net whenever energy was absorbed at the P_{MJ} sources within the system. Conceptually, MEEC model energy is absorbed by eccentric actions of single-joint muscles, degraded to heat, and cannot be recovered. Excess energy expenditure was exhibited by the single-joint muscle energy models during isolated regions of the first half of the pedal cycle and throughout recovery (Fig. 5). The excess energy expenditure could be traced to negative P_{MJ} source powers at the ankle during the first quadrant (30–70°), at the knee during the second quadrant (125–160°), again at the ankle during the third quadrant (180–270°), and at the hip throughout recovery.

The hip P_{FJ} source absorbed between 3.5 and 5.7 J during the pedal cycle. In general, energy absorbed at the hip by the P_{FJ} source that (a) serves to increase the energy (potential and/or kinetic) of the pelvis and trunk, or (b) is transferable to the opposite limb through the pelvis, may be recoverable and, consequently, might not involve additional mechanical energy expenditure. Conversely, energy absorbed (degraded to heat) in pelvic and trunk muscles and passive tissues is nonrecoverable and should not be associated with increased energy expenditure. Because the precise destinations of energy absorbed at the hip P_{FJ} source are not determinable, the extent to which the absorbed energy can be recovered is unknown. The single-joint muscle energy model (MEEC) represented the extreme condition, i.e., all the energy was recoverable.

The multijoint muscle energy model (MEEFIC), permitting full intercompensation of the P_{MJ} sources, exhibited mechanical energy expenditure in excess of the net whenever energy absorbed at the muscular P_{MJ} sources could not be immediately transferred to other P_{MJ} sources by multijoint muscles. Functionally, excess energy expenditure was exhibited by the MEEFIC model only when the summed energy absorptions at the P_{MJ} sources exceeded the summed energy generations. When full muscular intercompensations were permitted (MEEFIC model), for example, the two regions of excess energy expenditure in the first half of the pedal cycle—associated with energy absorptions at the ankle and knee in the MEEC models—were eliminated. These results can be explained by referring to the net muscle power (P_{MJ}) profiles shown in Figure 3. Energy absorbed at the ankle (30–70°) was fully transferable to the knee and hip where considerable energy generation was occurring. Later in the cycle, energy absorbed at the knee (125–160°) was fully transferable to the hip and ankle.

Early in recovery (180–270°), energy absorbed at the ankle and hip was mostly transferable to the knee—where energy was being generated. A small portion of the absorbed energy was not transferable during this phase of the pedal cycle because the summed energy absorptions at the hip and ankle slightly exceeded the energy generated at the knee. Later in recovery (270–360°), substantial energy absorption at the hip occurred in conjunction with minimal energy generation at the ankle and knee. Consequently, full muscular intercompensations were unable to markedly attenuate the associated excess energy expenditure during this phase of the pedal cycle.

Regression equations describing mechanical energy expenditure relations for the energy models displayed in Figure 6 were used to quantify the maximum possible mechanical energy savings resulting from multijoint muscle intercompensations. Single-limb mechanical energy expenditures for the MEEC and MEEFIC models at 100 RPM and 275 W, representing 82.5 J delivered to the bicycle, were 109.7 J and 87.7 J, respectively. MEEFIC intercompensations thus reduced nonrecoverable energy absorption considerably i.e., those associated with single-joint muscle function (MEEC model), thereby reducing the mechanical energy expenditure by 20%. These findings support assertions that multijoint muscle intercompensations can significantly reduce mechanical energy expenditure relative to that associated with single-joint muscle function. Furthermore, the regression slopes derived for the models (see Fig. 6) indicate that the kinetic characteristics of the lower extremity system, i.e., pedal force application and joint GMM patterns, appear to change at higher output power levels in such a way that the potential for energy saving transfers is enhanced.

The MEEFIC cycling energy model operated at lower total mechanical energy expenditure than that hypothetically achievable because multijoint muscles were considered in the model to cross all joints and be capable of completely transferring energy absorbed at one joint to *any* other joint. Specifically, two joints cannot always be served by a single multijoint muscle (e.g., a single muscle cannot produce an ankle dorsiflexion GMM and a knee extensor GMM). Also, two-joint muscle GMM contributions at adjacent joints are proportionally fixed by their respective moment arms and, consequently, a two-joint muscle's capability to generate or absorb energy at a joint may be limited.

Energy losses to friction and opposing muscle actions at a given joint generally increase mechanical energy expenditure relative to that computed in this study. Conversely, energy losses to elastic structures (both muscular and nonmuscular) were treated nonconservatively in the MEEC and MEEFIC models, and this energy can partially be recovered to reduce mechanical energy expenditure.

In another paper using the data presented herein, Broker and Gregor (4) impose realistic anatomical and operational constraints on two-joint muscles in the cycling lower extremity—and then assign joint muscle powers (Pmj) to specific single- and two-joint lower extremity

Appendix A

Nomenclature	
BDC	Bottom dead center: bicycle crank vertical and directed down.
dEsys	The change in energy of the system.
d_f, d_s, d_t	Distances from the distal joint to the center of mass of the foot, shank, and thigh, respectively.
F_J	Joint reaction force at joint *j* (*x* and *y* denote horizontal and vertical components, respectively).
F_n, F_t	Normal and tangential components of pedal loading, respectively.
F_{Px}, F_{Py}	Horizontal and vertical components of pedal loading, respectively.
g	Gravitational acceleration (9.81 ms^{-2})
GMM_J	Generalized muscle moment acting at joint *j*.
M_A, M_K, M_H	Generalized muscle moments (GMMs) acting at the ankle, knee, and hip, respectively.
MEE	Mechanical energy expenditure.
MEEC	General term for mechanical energy expenditure associated with totally compensated P_{MJ} sources and conservative energy exchange at the hip P_{FJ} source.
MEEFIC	Energy model defining mechanical energy expenditure associated with totally intercompensated P_{MJ} sources.
m_f, m_s, m_t	Mass of the foot, shank, and thigh, respectively.
P_{FJ}	Joint force power resulting from reaction force F_J acting at joint *j*.
P_{MJ}	Joint muscle power resulting from a generalized muscle moment (*GMM*) acting at joint *j*.
r_f, r_s, r_t	Distances from the proximal joint to the center of mass of the foot, shank, and thigh, respectively.
TDC	Top dead center: bicycle crank vertical and directed up.
t_i	Initial time.
t_f	Final time.
V_J	Linear velocity of joint *j*.
V_P	Linear velocity of the pedal spindle.
W_{pedal}	The mechanical work done at the bicycle pedal.
$\varnothing_f$, $\varnothing_s$, $\varnothing_t$	Foot, shank, and thigh angles measured from the right-horizontal.
$\dot{\varnothing}_f$, $\dot{\varnothing}_s$, $\dot{\varnothing}_t$	Foot, shank, and thigh angular velocities (*CCW+*).
$\ddot{\varnothing}_f$, $\ddot{\varnothing}_s$, $\ddot{\varnothing}_t$	Foot, shank, and thigh angular accelerations (*CCW+*).
$\dot{\varnothing}_J$	Angular velocity of joint *j*.

muscle groups in accordance with minimum energy expenditure criteria. In so doing, these researchers expose likely intercompensatory mechanisms related to two-joint muscle actions during cycling, compare and contrast these muscle actions with electromyographic recordings of representative single- and two-joint muscles, and address the probable role of passive contributions to joint moments, stretch-shorten cycle effects, and energy transport phenomena on cycling energetics.

CONCLUSIONS

Mechanical energy contributions were derived from lower extremity energy sources in 12 experienced male cyclists riding at five different conditions of cadences and workload. The knee was found to dominate in its contribution to total system energy, moderate power was derived from hip joint reaction forces, and energy generations and absorptions at the various sources were sensitive to bicycle power output.

Net energy generation at the sources occurred during the power phase—when total segmental energy levels decreased. Conversely, net energy absorption at the sources occurred during recovery—when total segmental energy levels increased. Net generation during segmental energy decline and net absorption during segmental energy rise uniquely benefited the transfer of power through the pedal to the environment and opposite leg. These energetics highlighted the ambiguity inherent in kinematic based mechanical work estimates (i.e., internal work method), which necessarily associate segmental energy fluctuations with muscle actions.

Two energy models estimated mechanical energy expenditure under hypothetical single-joint (no intercompensation) and multijoint (unlimited intercompensation) muscle operating conditions. Single-joint muscle control required an additional 21 J (above that delivered to the environment) to accomplish the task, independent of bicycle power output. When intercompensating multijoint muscles were incorporated into the energy management analysis, a marked reduction in mechanical work relative to single-joint muscle operation occurred—and the effect was enhanced at higher bicycle power levels. Relative energetic conservatism appears plausible given appropriate actions of two-joint muscles in the lower extremity during cycling.

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