

The Pedaling Technique of Elite Endurance Cyclists: Changes With Increasing Workload at Constant Cadence

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A pedal dynamometer recorded changes in pedaling technique (normal and tangential components of the applied force, crank orientation, and pedal orientation) of 14 elite male 40-km time trialists who rode at constant cadence as the workload increased from similar to an easy training ride to similar to a 40-km competition. There were two techniques for adapting to increased workload. Seven subjects showed no changes in pedal orientation, and predominantly increased the vertical component of the applied force during the downstroke as the workload increased. In addition to increasing the vertical component during the downstroke, the other subjects also increased the toe up relation of the pedal throughout the downstroke and increased the horizontal component between 0° and 90°. A second finding was that negative torque about the bottom bracket during the upstroke usually became positive (propulsive) torque at the high workload. However, while torque during the upstroke did reduce the total positive work required during the downstroke, it did not contribute significantly to the external work done because 98.6% and 96.3% of the total work done at the low and high workloads, respectively, was done during the downstroke.

At present there is great interest in improving the performance of cyclists. The literature contains numerous examples of feedback devices that allow a cyclist to improve pedaling effectiveness (Bergmaier, Hediger, & Marki, 1989; Briggs Fedel, Woolley, & Foulke, 1989; McLean & Lafortune, 1988). There also are many training aids designed to help aspiring cyclists improve their pedaling technique. However, despite all of the attention focused on improving pedaling effectiveness, no studies have identified the pedaling technique of elite endurance cyclists under conditions similar to competition. Therefore this paper characterizes:

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Cavanagh (1988), who found that pedaling effectiveness decreased as pedaling cadence increased. The other studies in Table 1 examined the pedaling technique of endurance cyclists. McLean and LaFortune (1988) investigated competitive cyclists, but the power output of 235 W was significantly less than the power output experienced under competitive conditions (340 W, Hamilton, Beltz, Montain, & Coyle, 1989). Davis and Hull (1981) presented pedal force data collected at a power output similar to competition, but data were only presented for one subject.

It is clear from Table 1 that there is a lack of information on the pedaling technique of elite endurance cyclists during conditions similar to those experienced in a 40-km time trial. Of the studies in Table 1, four investigated changes in pedaling technique as the workload increased. All of these studies found that pedaling effectiveness increased as the workload increased. This was usually quantified by calculating the percent of the applied force that created a torque about the center of the crank (e.g., LaFortune & Cavanagh, 1983). However, none of these studies investigated changes in pedaling technique at conditions seen in competition. The study by Kunstlinger, Ludwig, and Stegemann (1985) approached competitive power outputs, but the cadence was only 60 rpm, and they did not actually investigate pedaling technique as defined in this paper (only the peak force applied to the pedal was measured). However, Kunstlinger et al. showed that at a given workload, experienced cyclists made smaller peak forces than inexperienced cyclists. In addition, the experienced cyclists had significantly lower oxygen consumption at all workloads.

In a physiological study, Coyle, Coggan, Hemmert, and Walters (1988) found that differences in performance between competitive 40-km time-trial cyclists were not due entirely to changes in a vast array of physiological parameters. The measures included maximal oxygen consumption ($\dot{V}O_{2max}$), blood lactate threshold, muscle glycogen utilization, fiber type composition, and numerous muscle enzyme measures. From their findings, Coyle et al. (1988) hypothesized that a cyclist's performance ability might be due in part to biomechanical factors related to individual pedaling technique. Thus differences in performance ability between subjects might be partially due to differences in pedaling technique. However, they did not collect the biomechanical data necessary to either confirm or deny this hypothesis. We are aware of no studies that have characterized the pedaling technique of elite performers in the detail necessary to make inferences about this hypothesis. Without data that describe the pedaling techniques used by an elite cyclist population, it is unclear whether pedaling technique could significantly contribute to performance ability differences.

The purpose of the present investigation was to examine the changes in pedaling technique of elite endurance cyclists as they rode at a constant cadence and while the workload was increased to a level that simulated the conditions experienced during a 40-km time-trial competition. The pedaling techniques of the elite endurance cyclists were compared at two workloads: one at approximately 60% of the $\dot{V}O_{2max}$ of each cyclist and the second at approximately 90% of the $\dot{V}O_{2max}$ of each cyclist. This allowed the changes in each cyclist's pedaling technique to be observed in response to the increased external demands (workload). As such, these changes served to accentuate the aspects of pedaling technique that are possibly more important in increasing the athlete's performance during competitive situations. Also, the variability between subjects served as an indicator as to whether pedaling technique could significantly contribute to differences in cycling performance.

the pedaling technique of elite 40-km time-trialists as their power output increases to a level that simulates competition, with the cadence held constant at an rpm value commonly observed in competition. In this paper, pedaling technique is defined as the time history of both the pedal orientation and the force applied to the pedal.

Knowledge of pedaling technique is a fundamental prerequisite for understanding the biomechanics of cycling. Because movement of the foot during cycling is constrained to a roughly circular path by its attachment to the pedal, the time history of the orientation of the pedal is the major factor in determining the kinematics of cycling (for example, Hull & Jorge, 1985, modeled the leg as a five-bar linkage that is kinematically determined by specifying the angle of the crank and the orientation of the pedal). The second component of pedaling technique, the time history of the force that the cyclist applies to the pedal, constitutes an integral portion of the dynamics of cycling.

Studies that have examined the pedaling technique of cyclists are summarized in Table 1. LaFortune, Cavanagh, Valliant, and Burke (1983) and Cavanagh and Sanderson (1986) have examined the pedaling technique of elite sprint (4,000-m) cyclists. Due to the different demands of the sprint event when compared to a 40-km time trial, such as the faster pedaling cadence required by sprint cyclists, comparisons of the pedaling techniques between sprint and endurance cyclists must be made carefully. This problem is further emphasized in Sanderson and

Table 1

Review of Literature Related to Pedaling Technique

Study	Subjects	Cadence (RPM)	Power output (Watts)
Davis & Hull (1981)**	5 competitive cyclists	80	180*
LaFortune & Cavanagh (1983)	20 students	60	155
LaFortune, Cavanagh, Valliant, & Burke (1983)	7 elite pursuit cyclists	103-126	331-449
Hull & Jorge (1985)	1 competitive, 2 recreational	63-97	150-250
Kunstlinger, Ludwig, & Stegemann (1985)**	6 competitive, 12 students	60	0-320
Cavanagh & Sanderson (1986)	7 elite pursuit cyclists	100	400
McLean & LaFortune (1988)	6 competitive cyclists	80	235
Ericsson & Nissel (1988)**	6 students	40-100	0-240
Sanderson & Cavanagh (1988)**	11 competitive cyclists	60-100	112-240

*Single leg power; ** Investigated changes as workload increased.

Methods

Subjects and Instrumentation

Informed consent was obtained from 14 elite (U.S. Cycling Federation Category 1 and 2) male cyclists who raced 40-km time trials. While the subjects did vary in ability, all had recently placed in state and/or national level competitions. These subjects were participating in a multidisciplinary study in which physiological data were collected in conjunction with biomechanical data to evaluate the determinants of endurance in cycling (Coyle et al., in press). The average recent time-trial result was 55.8 min \pm 2.9 min. To obtain information on the pedaling technique of each cyclist, an instrumented pedal dynamometer was used (described in Newmiller, Hull, & Zajac, 1988). The pedal dynamometer was equipped with a potentiometer that produced an analog signal that was directly related to the pedal orientation (β). Two additional analog signals indicated the magnitude of the components of the force that the cyclist applied to the pedal that were oriented normal (F_N) and tangential (F_T) to its superior surface. The pedal dynamometer was mounted on the right side of a bicycle ergometer, and it allowed each subject to use his normal racing shoes, whether cleated or clip-on.

To better simulate the geometry of each subject's bicycle, the ergometer was equipped with a racing style seat and drop handlebars. Both items were then adjusted to match the characteristics of each cyclist's bicycle. The crank length of the ergometer was 170 mm. The ergometer was equipped with a potentiometer that was attached to the crank and produced an analog signal directly related to the crank orientation (θ). The four analog signals described above were then converted to digital information, sampled at a rate of 500 hertz, and stored in the memory of an IBM PC-AT microcomputer while each cyclist rode on the ergometer.

There were two main limitations in the experimental apparatus that must be considered when analyzing the data. The first was that an ergometer was used instead of the subject's bike—in part because it made the collection of physiological data much simpler for the multidisciplinary study. The ergometer was used in the constant force mode, where a belt provided a constant resisting force on the flywheel during the data collection. Fregly and Zajac (1989) showed that the equivalent inertia of such an ergometer is lower than both cycling on rollers in the lab and cycling on the road. Therefore the effects of pedaling a lower inertial system are discussed below when there are implications for data being interpreted. The second limitation was that forces were recorded for only one pedal, due to limited instrumentation.

Cavanagh and Sanderson (1986) showed that there were asymmetries in force application by elite pursuit riders. However, since the present study compared the same leg at all times, we felt that the changes in the cyclist's pedaling technique with the measured leg provided the necessary data to describe the changes as the workload increased. This was because the workload was always computed from the forces applied to the dynamometer. Therefore, while the importance of asymmetry between the two legs cannot be assessed by the data collected, the use of a single dynamometer did not affect our ability to investigate the changes in the applied forces to the pedal as the workload (single leg) increased.

Testing Protocol

The four signals described above (θ , β , F_N , F_T) were collected for 10 consecutive crank revolutions while each subject was riding at four to six different levels of power output. The cyclists were instructed to maintain a cadence of 90 rpm at all times. Oxygen consumption ($\dot{V}O_2$) of the cyclists was measured while they were riding at each power level (for details, see Coyle et al., 1988). In a separate session, the $\dot{V}O_{2\max}$ of each cyclist was also determined and this allowed each subject's power output, or workload, to be expressed as a percentage of his $\dot{V}O_{2\max}$. The workloads experienced by each cyclist approximated 60, 70, 80, 90, and 100% of his respective $\dot{V}O_{2\max}$. In this manner, the cyclists could be compared at power output levels that required approximately the same relative physiological demands.

Data Reduction

For each of the 10 crank revolutions sampled at each workload, the data from the crank potentiometer were used to compute the orientation of the crank (θ) relative to a vertical axis, and the data from both the crank and pedal potentiometers were used to calculate the orientation of the pedal (β) relative to a horizontal axis (see Figure 1a). However, for each revolution there were separate regions where each potentiometer reset, and spurious values occurred in these transition zones (Newmiller et al., 1988). To correct the transition zones for the crank data, each individual's time per revolution (t_{rev}) was determined from the known sampling rate (550 Hz) and the θ values that were not in the transition zone. The values of t_{rev} were then used to compute an average angular velocity of the crank for each revolution (ω_i , where i indicates the revolution number). It was assumed that ω_i remained constant during each revolution (Newmiller et al., 1988; Redfield & Hull, 1986), and thus the crank orientation (θ) during each transition zone was simply calculated from the average angular velocity.

To compute the pedal orientation during the transition zone of the potentiometer attached to the pedal dynamometer, the values for the pedal orientation (β) from the portion of each revolution that was free from the effects of the transition zone were used to establish a least-squares fit for the following function:

$$\beta = A \sin t + B \cos t + C \sin t^2 + D \cos t^2 + E \sin t + F \cos t + G \quad (1)$$

where t indicates the elapsed time from the beginning of each revolution, and the terms A through G represent constants.

The values of the force data (F_N and F_T) were filtered using a third-order zero-phase Butterworth low-pass filter. A cutoff frequency of 30 Hz was used to remove high frequency noise from the data. The data were inspected and the 30-Hz cutoff was felt to most accurately represent the data.

To better compare the data from each individual revolution, the data describing the crank arm and pedal orientation (θ and β , respectively) and the normal and tangential components of the net force applied to the pedal (F_N and F_T , respectively) were linearly interpolated at instants that corresponded to discrete 1° increments from top dead center (TDC, $\theta = 0^\circ$ or 360°), the start of each revolution, until the following instant when the crank arm again passed through

Top Dead Center

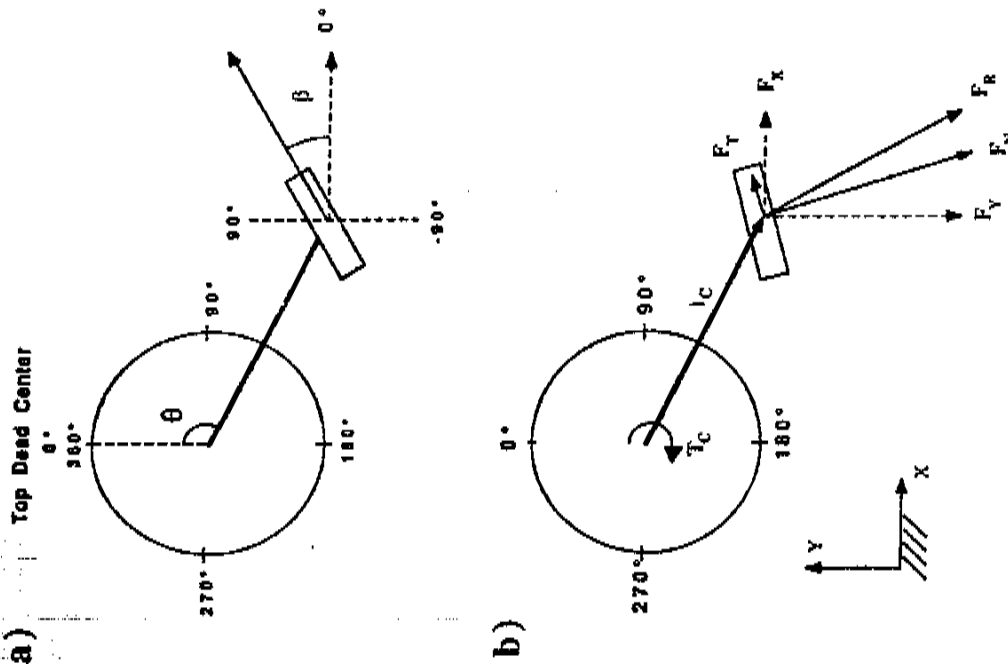


Figure 1 — Definition of (a) the crank (θ) and pedal (β) angles, and (b) the components of the force applied to the pedal (F_N , F_T , F_x , F_y , F_R), the torque created about the center of the crank (T_C), and the crank length vector (l_c).

a position of 0° or 360°. Thus at the completion of the data reduction, each of the values of β , F_N , and F_T were obtained at discrete 1° increments of θ from the start of each crank revolution. To make better comparisons among the subjects, the five consecutive crank revolutions where the angular velocity of the crank was nearest to 90 rpm were averaged. The data reduction resulted in a data file for each subject that best represented the characteristics of the cyclist's pedaling technique at each workload.

Calculations

To help interpret the force data, the values of β , F_N , and F_T (because an orientation is implicit in the definition of F_N and F_T , the processed values are henceforth considered to be the vectors F_N and F_T) were used to compute the horizontal (F_x) and vertical (F_y) components of the net force applied to the pedal (F_R) (Figure 1b):

$$F_x = F_T \cos(\beta) - F_N \sin(\beta) \quad (2)$$

$$F_y = F_T \sin(\beta) + F_N \cos(\beta) \quad (3)$$

The magnitude of F_R ($|F_R|$) was also calculated and is a scalar quantity.

The net torque created about the center of the crank (T_C) by F_R was computed by the following vector product:

$$T_C = l_c \times F_R \quad (4)$$

where l_c is a vector pointing from the center of the crank to the center of the pedal (Figure 1b).

The amount of external work (single leg work, W_{SL}) done by the cyclist at the pedal during one crank revolution was computed using the following expression:

$$W_{SL} = \int_{\theta=0}^{2\pi} T_C(\theta) d(\theta) \quad (5)$$

In addition to W_{SL} , the amounts of positive and negative work performed during a revolution were also calculated to better understand how the cyclist was creating W_{SL} . Therefore, when the integration to calculate W_{SL} was performed, separate totals were kept for the positive ($+W_{SL}$) and negative work ($-W_{SL}$) as well as the net work (W_{SL}). The average single leg power (P_{SL}) for one complete crank revolution (Davis & Hull, 1981) was computed simply as,

$$P_{SL} = \frac{W_{SL}}{t_{rev}} \quad (6)$$

where t_{rev} is the time required for the revolution. Because the forces applied by the cyclist are measured at the pedal (and for only one leg), care must be used when comparing P_{SL} and W_{SL} with their corresponding values in studies where power output and work were measured directly at the ergometer flywheel.

The final value calculated was an index of the relative importance of the downstroke for doing positive work (W_{180}). It was computed as,

$$W_{180} = \frac{\int_{\theta=0}^{\pi} +T_C(\theta) d(\theta)}{\int_{\theta=0}^{2\pi} +T_C(\theta) d(\theta) + W_{SL}} \times 100.0\% \quad (7)$$

and expressed the amount of positive work done during the downstroke as a percentage of the total positive work done during the entire revolution.

Table 2b

Pedalling Data for the Cyclists at the High Workload

Subj.	VO ₂ (%)	Cad. (rpm)	P _{SL} (W)	Peak F _R (N)	Peak F _R (°)	Peak T _C (Nm)	Peak T _C (°)	+W _{SL} (J)	-W _{SL} (J)
NA*	93	89.9	244	558	113	88	98	163	0
CB*	88	90.1	191	342	81	57	79	127	0
MB*	91	90.3	160	385	113	60	97	107	1
CL*	83	89.7	167	508	97	83	89	135	10
BM*	93	89.8	180	390	88	62	85	120	0
SM*	96	93.3	176	401	95	66	86	115	2
NR*	87	90.7	174	439	79	74	77	121	6
DB	92	90.4	205	543	95	90	89	142	6
ME	100	90.6	211	502	98	84	88	143	3
SG	94	90.2	183	422	97	69	90	125	3
TL	89	91.0	211	528	88	88	81	141	2
NS	85	89.5	160	450	98	74	81	127	5
SS	91	90.7	194	410	84	69	80	129	1
NT	95	89.5	200	497	102	81	92	136	3
M	92.3	90.3	192.6	454.6	95.6	74.6	86.6	130.8	3.0
SD	3.9	1.1	20.9	69.0	10.2	11.1	6.5	14.0	2.9

*Member of anklng group.

Two main findings were revealed by the changes that occurred in response to the increased workload. First, at the high workload the pedal was maintained in a position of increased toe-up (positive) rotation during the downstroke (θ values from 0° to 180°). The second finding was related to the torque produced during the upstroke portion (θ values from 180° to 360°) of the revolution. As expected due to the increased external demands, the cyclists exerted a significantly larger propulsive (positive) torque during the downstroke at the high workload; however, the resistive (negative) torque produced by the cyclists during the upstroke at the low workload was absent at the high workload. The resistive torques were replaced by either a small propulsive torque or a region of negligible torque (near zero values). The positive torque produced in the upstroke did not contribute significantly to the total work done by the cyclist (W₁₈₀ calculated from the data in Figure 2b was 98.6% at the low workload and 96.3% at the high workload), and the significance of this finding will be discussed below.

Changes in Pedal Orientation

When the data for the individual cyclists were analyzed, the changes in pedal orientation exhibited in the curves of Figure 2a at the low and high workloads were not evident in the data for all subjects. However, inspection of the data for the individual cyclists revealed the use of two varied strategies for adapting to

Subject Comparisons

To compare the cyclists and better understand how they responded to changes in workload, the data files for all subjects were averaged at the lowest relative workload for each subject (60.9 ± 3.4% of VO₂max) and at the highest relative workload for each subject not exceeding his VO₂max (92.3 ± 3.9% of VO₂max). These will be referred to subsequently as the low and high workloads, respectively.

Results and Discussion

Tables 2a and 2b present the data for the individual subjects at the low and high workloads, respectively. The data presented are (a) cadence; (b) workload expressed both in terms of percent of VO₂max and average single leg power (VO₂ and P_{SL}, respectively); (c) peak magnitudes of both the resultant force applied to the pedal (F_R) and the torque created about the center of the crank (T_C), and the crank angles where each value occurred; and (d) the amount of positive and negative work performed during a complete revolution of the crank (+W_{SL} and -W_{SL}, respectively). Table 2a also includes the cyclists' best recent time for a 10-km time trial (T_{10km}). Figures 2a and 2b present the plots of pedal orientation (β), and the net torque exerted about the center of the crank (T_C) at the low workload and high workload, respectively.

Table 2a

Pedalling Data for the Cyclists at the Low Workload

Subj.	VO ₂ (%)	Cad. (rpm)	P _{SL} (W)	Peak F _R (N)	Peak F _R (°)	Peak T _C (Nm)	Peak T _C (°)	+W _{SL} (J)	-W _{SL} (J)	T _{10km} (Min)
A*	66	89.4	159	487	106	78	97	120	13	51.0
B*	60	90.3	137	245	100	40	92	91	0	59.0
B*	59	90.3	114	286	106	46	98	80	4	61.0
L*	56	91.9	118	390	100	63	92	102	25	54.0
M*	60	91.5	107	228	97	37	89	71	1	59.0
M*	59	89.8	100	326	89	55	84	88	21	55.5
IR*	57	89.3	104	319	97	53	84	86	18	52.5
B	64	90.5	136	401	100	65	89	106	16	54.0
E	68	89.7	119	370	102	59	92	93	14	55.5
G	63	90.4	118	310	95	51	86	88	10	59.0
L	63	92.2	144	414	92	68	86	98	4	57.0
S	57	90.0	129	343	95	56	85	92	6	52.5
S	62	90.1	119	254	88	43	81	80	1	54.0
IT	59	89.6	112	342	95	57	89	92	17	57.0
f	60.9	90.4	122.6	336.8	97.2	55.1	88.9	91.9	10.7	55.8
D	3.4	0.9	16.6	72.1	5.5	11.4	5.0	12.1	8.1	3.0

Member of anklng group.

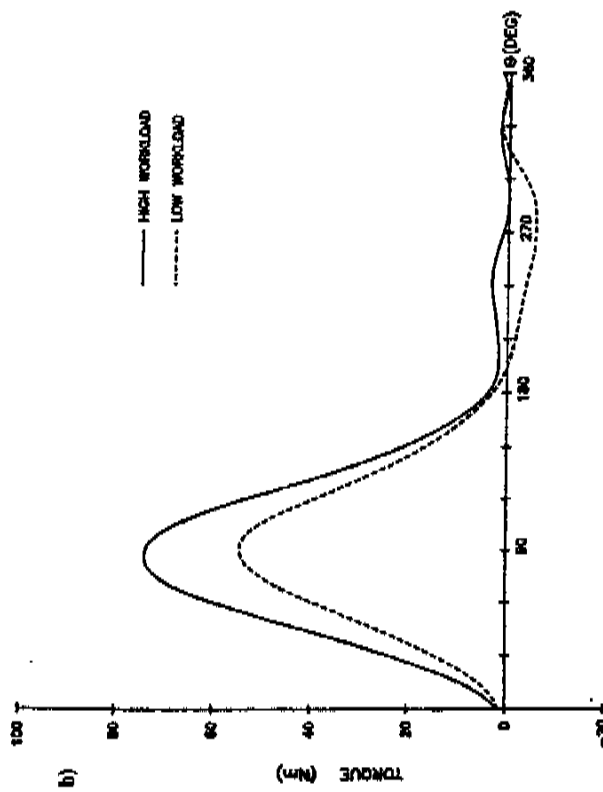
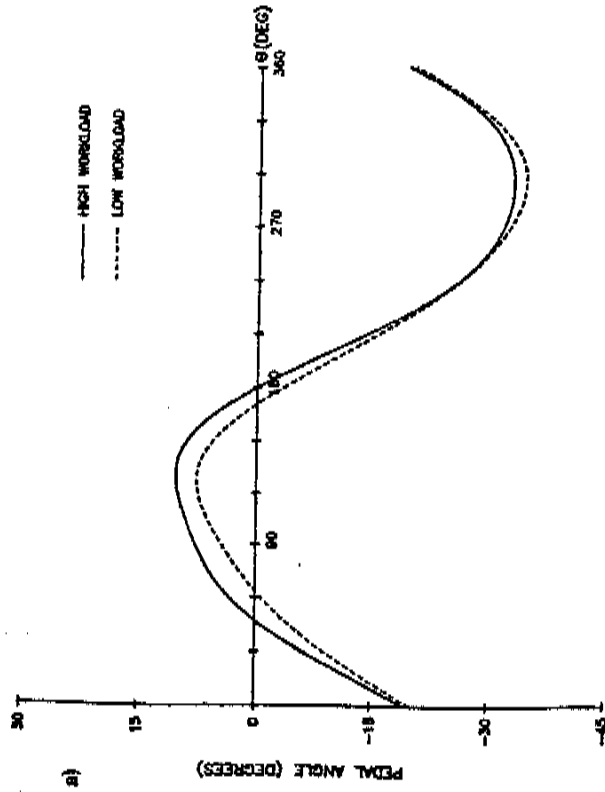


Figure 2 — Plots of (a) the average pedal angle (β) and (b) torque (T_c) versus θ for all subjects at the high and low workloads.

the high workload. Seven subjects (NA, CB, MB, CL, BM, SM, NR) responded by significantly changing the orientation of the pedal (β) during the downstroke as the workload increased ($p < 0.05$ for an increased maximum positive value of the pedal angle using Student's t test), while the other seven cyclists (DB, ME, SG, TL, NS, SS, NT) demonstrated no changes in β ($p > 0.3$). Therefore, to better understand how the subjects responded to the changes in workload by altering the pedal orientation, they were divided into two groups: the anking and non-anking groups, respectively. In this context, anking refers to changes in pedal orientation and not to the actual kinematics at the ankle joint.

Figures 3a-3g present the plots of the pedal orientation (β), net torque exerted about the center of the crank (T_c), tangential force applied to pedal (F_T), normal force applied to pedal (F_N), horizontal force applied to pedal (F_x), vertical force applied to pedal (F_y), and the magnitude of the resultant force applied to the pedal ($|F_R|$) versus crank angle (θ) at the high and low workloads for the anking group. The same plots are presented for the nonanking group in Figures 4a-4g. These data indicate that during the downstroke the anking group not only increased the toe-up orientation of the pedal (Figure 3a) but also changed the pattern of tangential force (F_T) applied to the pedal (Figure 3c). The peak positive value of F_T came earlier in the downstroke ($\theta = 42^\circ$ vs. $\theta = 65^\circ$ for the high and low workloads, respectively), and there was an earlier transition from pushing forward to pulling back (a negative value for F_T) along the pedal face at the high workload ($\theta = 120^\circ$ vs. $\theta = 175^\circ$, respectively).

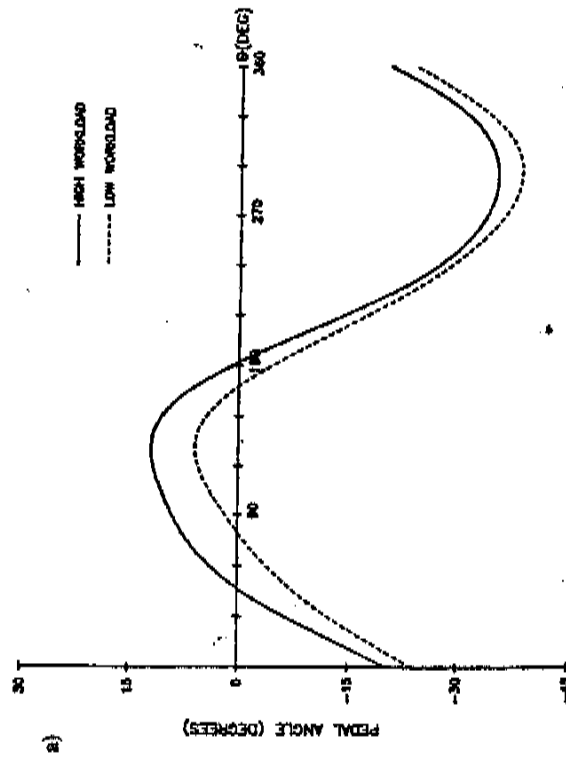


Figure 3 — Average plots of (a) pedal angle (β), (b) torque created about the center of the crank (T_c), (c) tangential force (F_T), (d) normal force (F_N), (e) horizontal force (F_x), (f) vertical force (F_y), and (g) the magnitude of the resultant force (F_R), versus the crank orientation (θ) for the subjects of the anking group at the high and low workloads. (cont.)

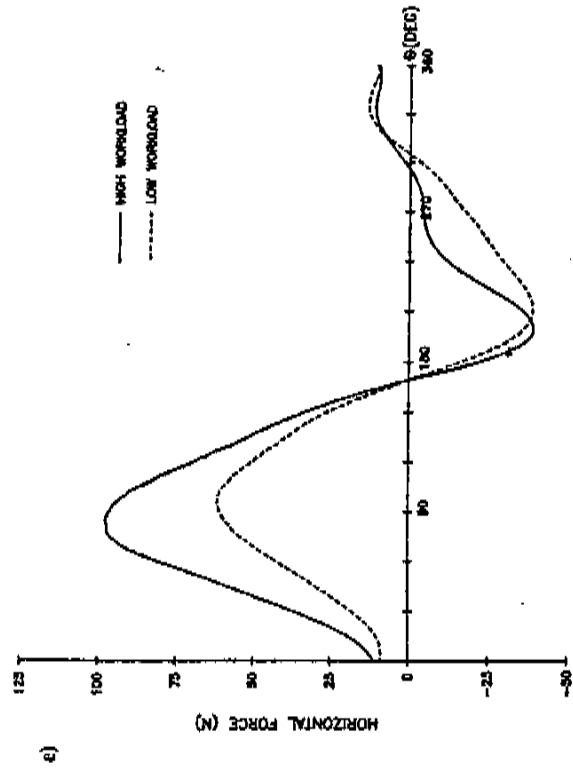
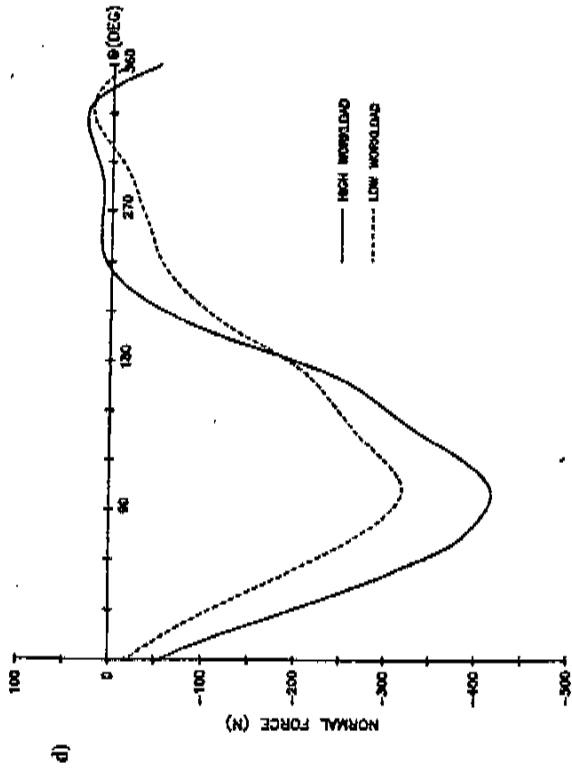


Figure 3 — (cont.)

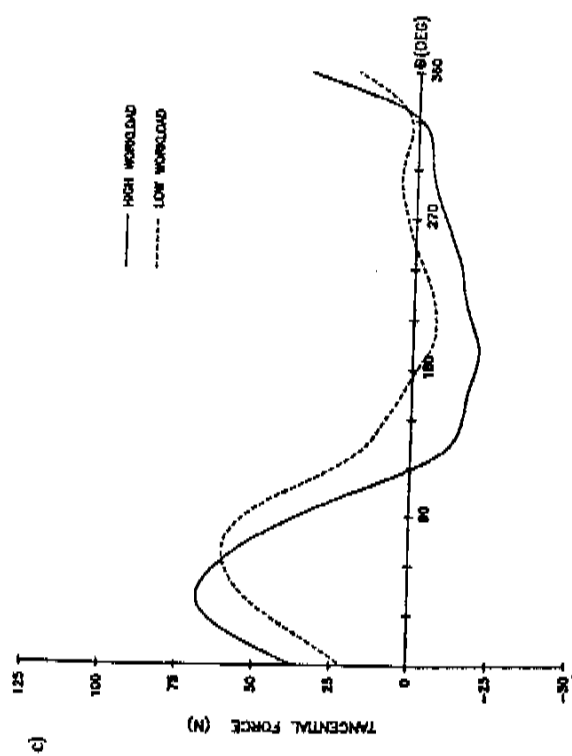
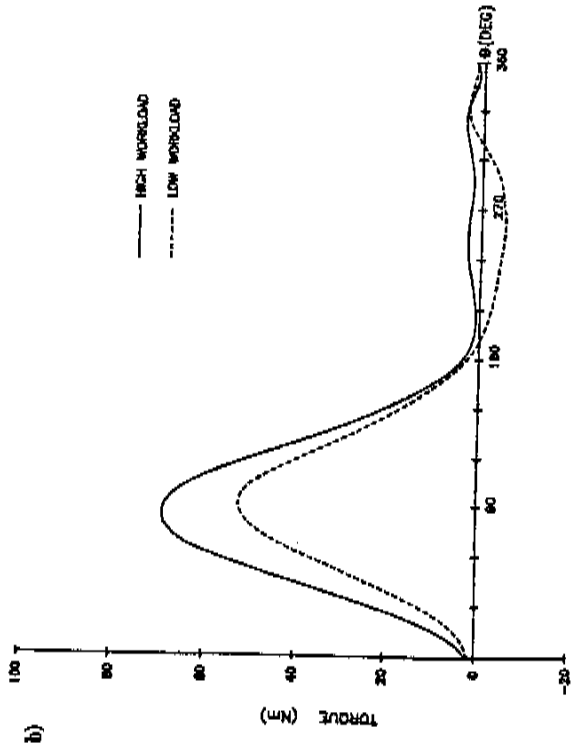


Figure 3 — (cont.)

The pedal orientation and the pattern of the tangential force applied to the pedal remained relatively unchanged for the cyclists in the nonankling group at the low and high workloads, with the exception of a slight increase in the magnitude of F_T at the high workload (Figure 4c). As workload increased, both groups demonstrated similar changes in the pattern of the normal force applied to the pedal (F_N). Both groups increased the magnitude of F_N during the downstroke and decreased the magnitude of F_N during the upstroke at the high workload (Figures 3d and 4d, respectively).

The changes in the values of β and F_T shown by the cyclists in the ankling group as workload increased were also associated with changes in the horizontal (F_X) and vertical (F_Y) components of F_R . These changes revealed that the two groups responded to the increased workload differently. The nonankling group adapted to the increased workload primarily by increasing the magnitude of F_Y during the downstroke (Figure 4f) while the magnitude of F_X increased only slightly (Figure 4e). Also, the patterns of both F_X and F_Y remained essentially unchanged as the workload increased. The ankling group responded to the increased workload by increasing the magnitude of F_X during the downstroke to a much greater extent than the nonankling subjects (Figure 3e). Most of the increase in F_X preceded a crank angle of 90° . Consequently, the position of the peak magnitude of F_R (Figure 3g) shifted only slightly (from $\Theta = 101^\circ$ to $\Theta = 97^\circ$) in

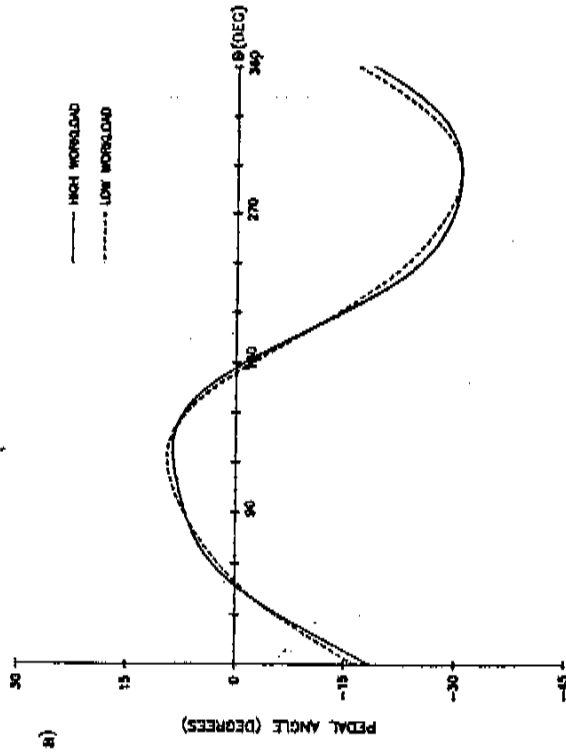
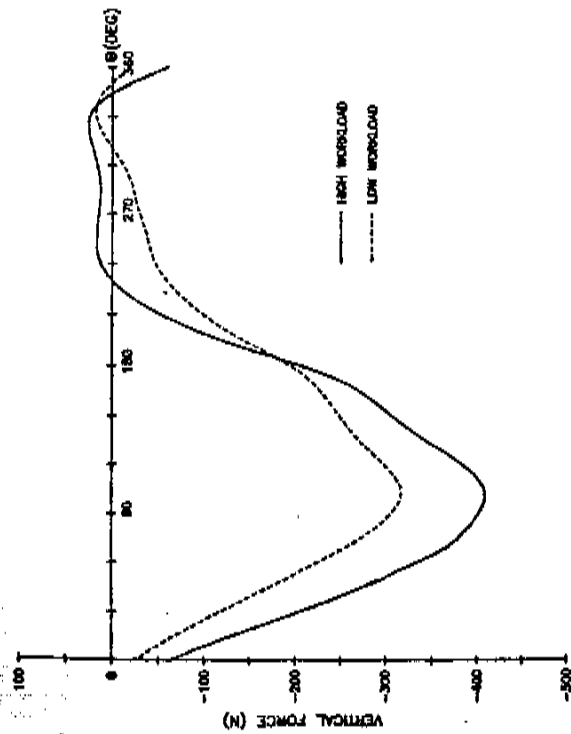


Figure 4 — Average plots of (a) pedal angle (β), (b) torque created about the center of the crank (T_c), (c) tangential force (F_T), (d) normal force (F_N), (e) horizontal force (F_X), (f) vertical force (F_Y), and (g) the magnitude of the resultant force (F_R) versus the crank orientation (Θ) for the subjects of the nonankling group at the high and low workloads. (cont.)

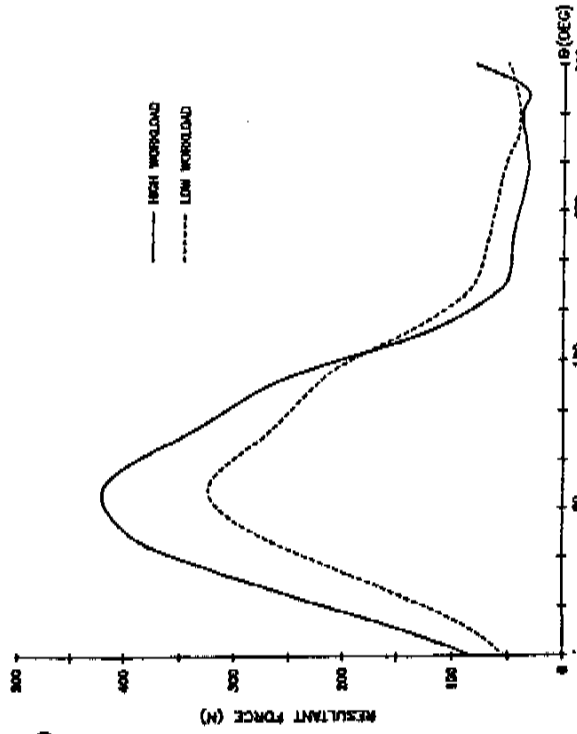


Figure 3 — (cont.)

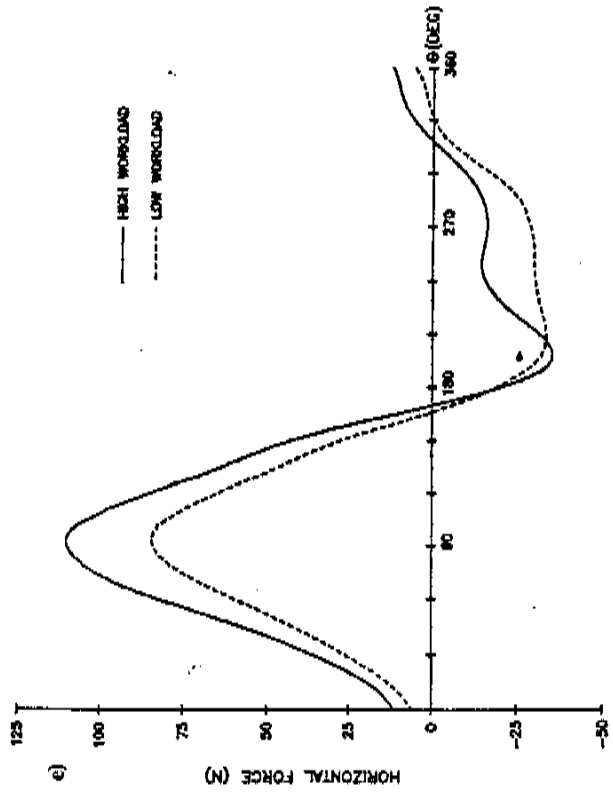
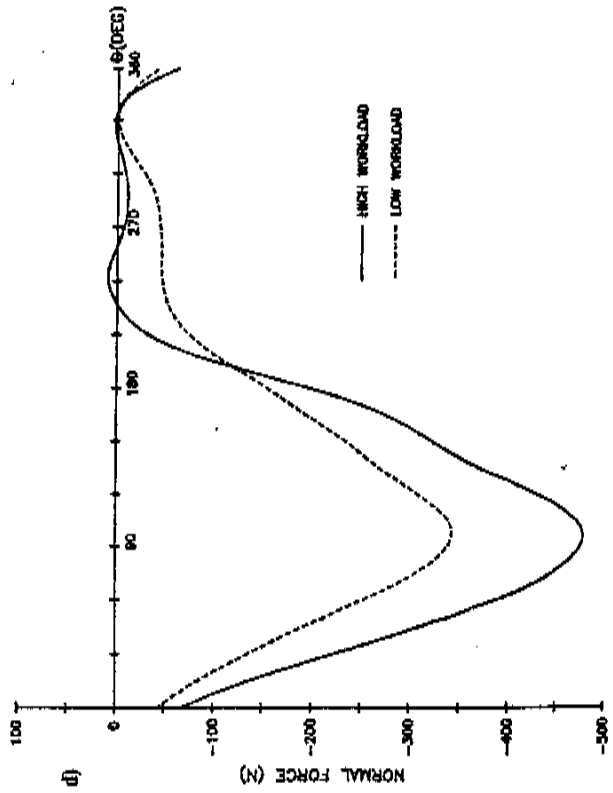


Figure 4 — (cont.)

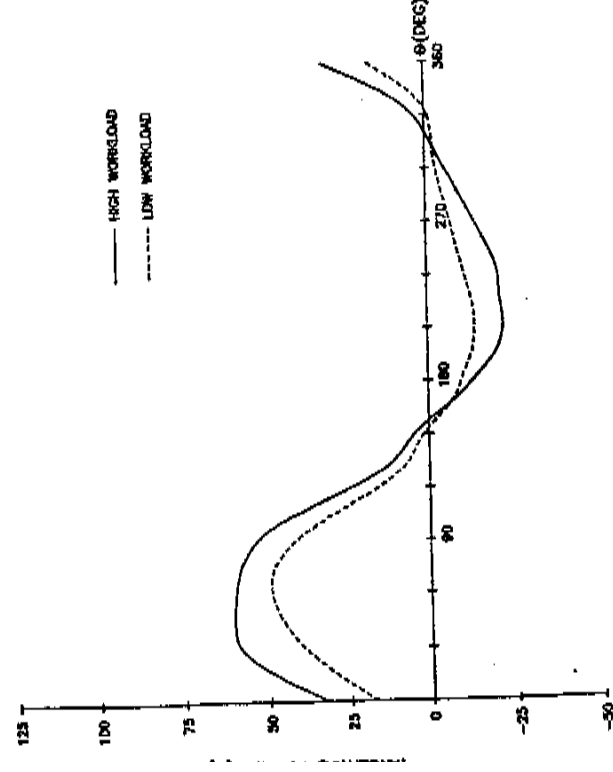
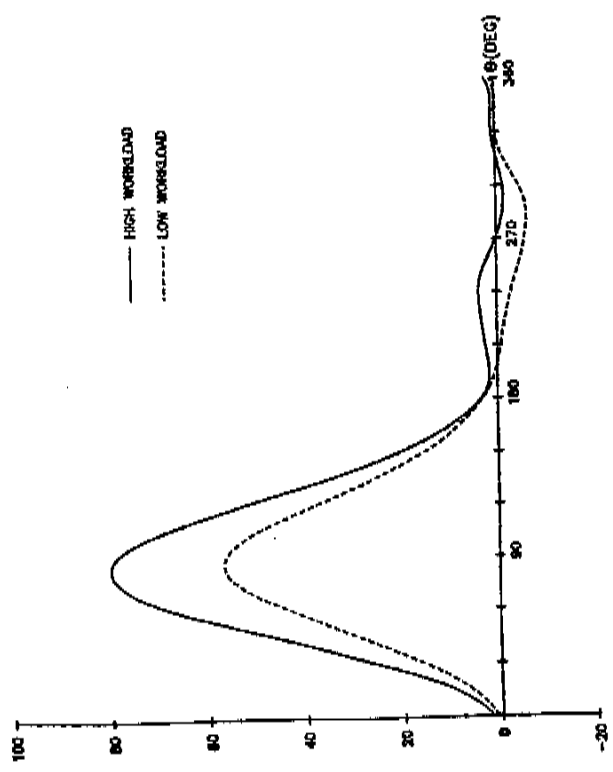


Figure 4 — (cont.)

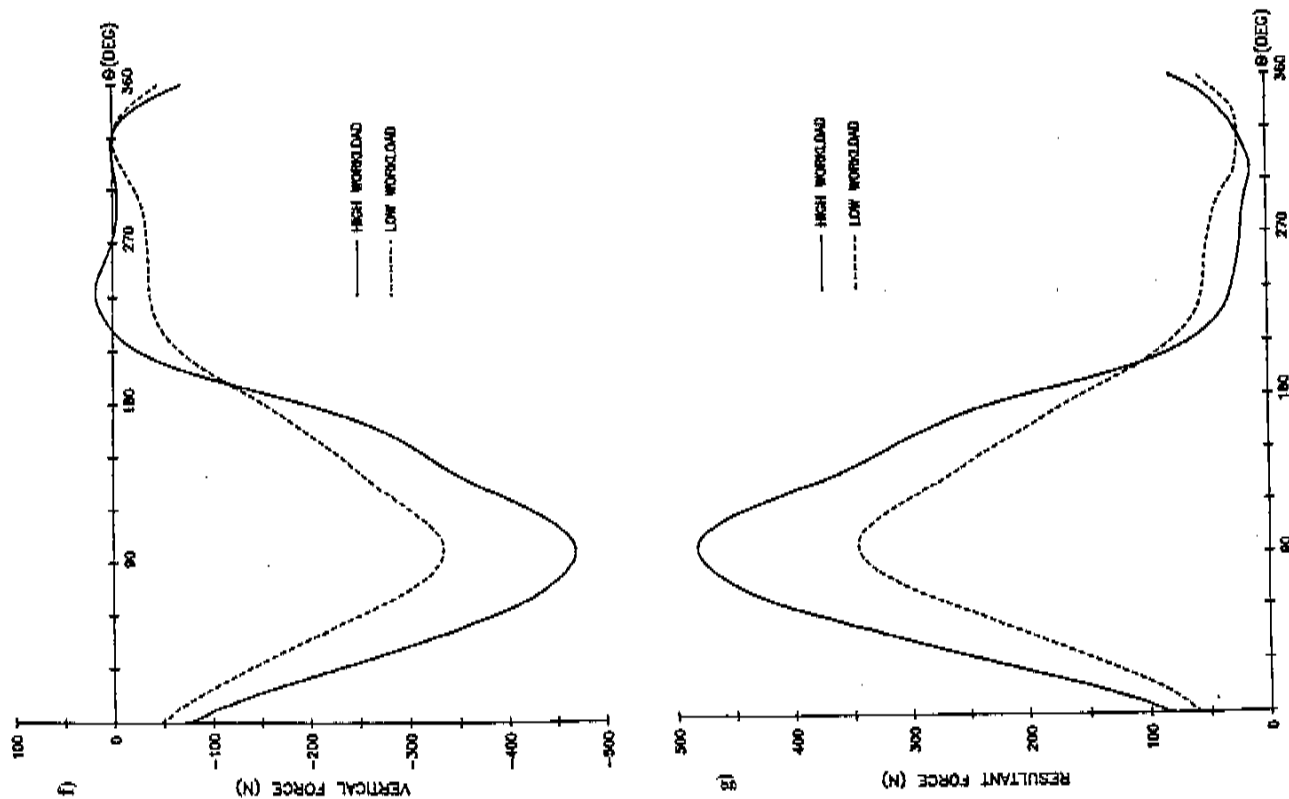


Figure 4 — (cont.)

the ankle group, but the position of peak torque (T_C) production (Figure 3b) shifted to much earlier in the downstroke (from $\theta = 92^\circ$ to $\theta = 85^\circ$). The non-ankling group exhibited no similar changes in F_R or T_C (Figures 4b and 4g). Therefore, as the workload increased, the nonankling group tended to maintain a similar pedal orientation pattern and they predominantly increased the magnitude of the vertical component (F_{y_1}) of the force applied to the pedal throughout the downstroke. The ankle group also increased F_{y_1} during the downstroke and also increased the pedal angle (β) throughout the downstroke. This change in pedal orientation was associated with an increased horizontal component (F_{x_1}) of force applied to the pedal between 0 and 90° in the downstroke.

Changes in Torque Production

To investigate the second major change that occurred in response to the increased workload—the lack of negative torque production and/or the slight propulsive torque production during the upstroke (Figure 2b)—the torque curves of the individual subjects were analyzed. The data presented in these plots revealed that during the upstroke there were two distinct regions of positive torque production by the cyclists: one between 180 and 270° and the other between 300 and 360°.

The two phases of positive torque production during the upstroke were due to changes in the applied forces. However, whether the normal or tangential component of the applied force was responsible for the two different phases of positive torque depended upon the orientation of the pedal (β) when the force was applied. In general, the pedal angle typically became negative near 180° and reached a maximum position of toe-down (negative) rotation near the crank position of 300°. The pedal then began to rotate positively and was near horizontal just after top dead center (approximately 40°). Therefore between 180 to 270° the pedal was oriented such that either a negative tangential force or a positive normal force applied to the pedal resulted in a positive or propulsive torque created about the center of the crank. Between 300 and 360°, only a positive normal force would create a positive torque about the center of the crank, as a tangential force would be directed along the crank arm.

Figure 5 shows the pattern of torque (T_C) production for three subjects (CB, SG, BM) and a graphical representation of their individual pedaling technique at the high workload. These subjects were chosen because they exhibit the different techniques for producing positive propulsive torque during the upstroke (however, note that they tended to produce more positive torque than average), one or more of which were used by all of the subjects who produced positive torque. The subjects could pull back (negative tangential component) and/or up (positive normal component) on the pedal between 180 and 270°, and/or they could pull up on the pedal between 270 and 360°.

Subject CB (Figure 5a and 5b) produced a large propulsive torque during the entire upstroke. The amount of positive torque produced during the upstroke was much more than for the other cyclists, but his data illustrate all of the techniques for producing positive torque. From 180 to 200° he produced the propulsive torque by primarily applying a negative tangential force to the pedal. But soon after 200°, the propulsive torque was almost entirely produced by an upward directed normal force applied to the pedal surface. Subject SG (Figure 5a and 5c) produced propulsive torque between 180 and 240° by relatively equal contributions from a negative tangential force and a positive normal force. Finally, Subject BM (Figure 5a and 5d) used a positive normal force to produce positive torque from 230 to 360°.

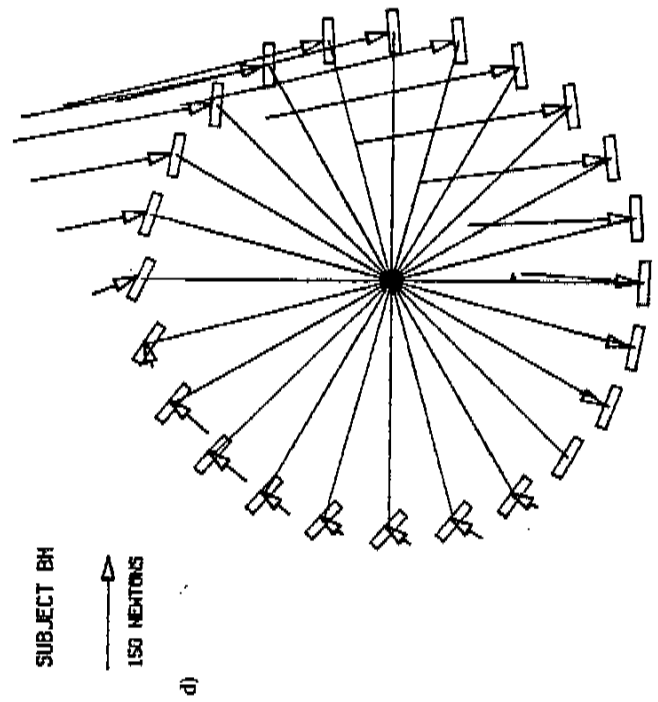
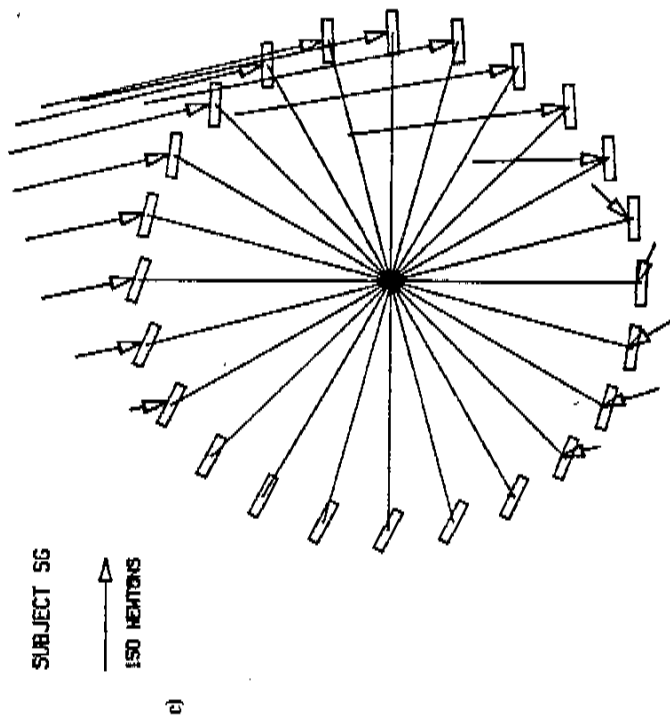
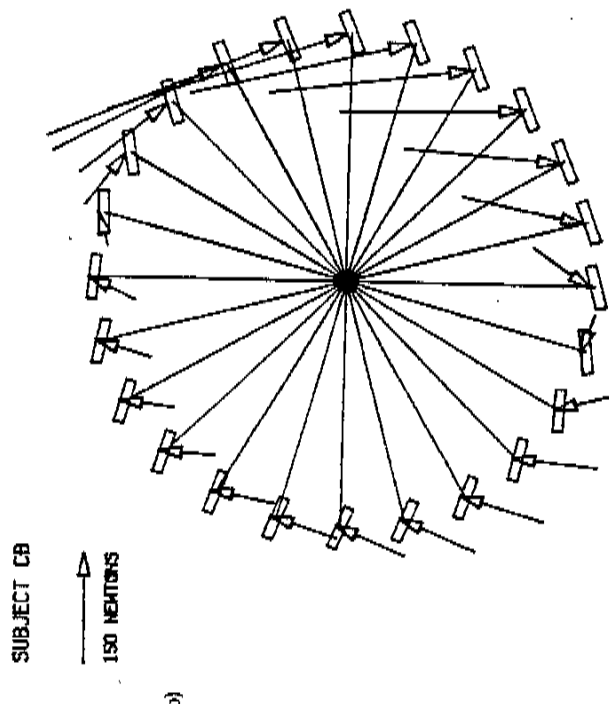
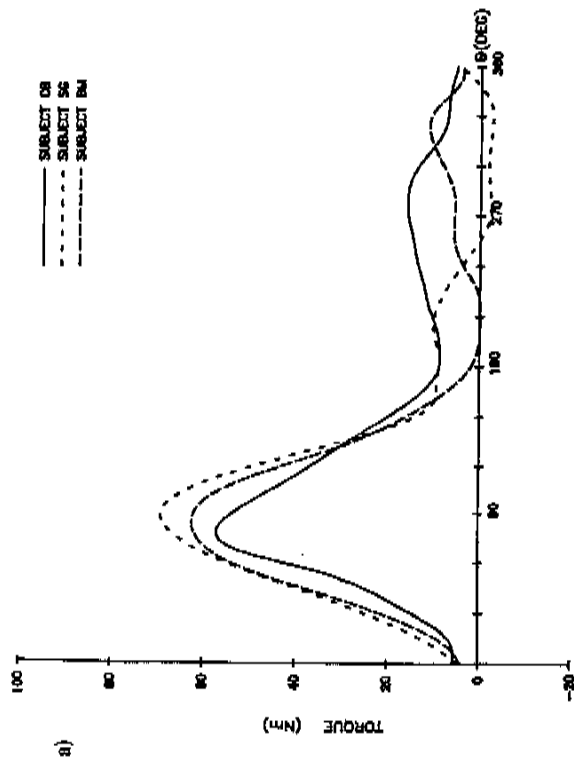


Figure 5 — (a) Plots of T_c versus θ at the high workload for three subjects, and plots of the pedaling technique of (b) Subject CB, (c) Subject SG, and (d) Subject BM. The vectors in 6b, 6c, and 6d represent F_g . Forces less than 30 N are not shown.

Figure 5 — (cont.)

As evidenced by the data of Figure 5, the individual subjects produced propulsive torque during the upstroke by increasing the applied force components differently. Each subject (including the 11 not shown) had a typical pattern of pulling back and/or pulling up on the pedal that was usually apparent at the low workload, and increasing the workload only further emphasized each subject's technique. The subjects who produced significant positive torque during the upstroke at the high workloads also did so at the low workloads, and the torque versus θ profiles appeared as individualized as fingerprints for each subject.

Conclusions

The elite subjects showed two different techniques for adapting to increasing workload. As the workload increased, half of the subjects increased the pedal angle (θ) throughout the downstroke and the horizontal component (F_x) of the applied force between 0 and 90°. The other half tended to keep the pedal orientation the same regardless of workload and predominantly increased the vertical component of the force applied to the pedal (F_y) throughout the downstroke in response to the increased workload.

A second finding of this study was that the negative torque (T_c) present during the upstroke at the low workload was either reduced to a negligible magnitude or reversed to a positive (propulsive) torque at the high workload. However, the magnitudes of the propulsive torques produced during the upstroke were significantly smaller than those produced during the downstroke.

There were two main phases of propulsive torque production during the upstroke, and the orientation of the pedal determined whether the normal or tangential component of the applied force produced the positive torque. The first phase was between 180 and 270°, where the pedal orientation was such that both a negative tangential force and a positive normal force could create propulsive torque. The second phase was between 300 and 360°, where the pedal orientation was such that propulsive torque was primarily due to positive normal forces. The first phase had been reported previously by Hull and Davis (1981), who noted that "during the upstroke positive torque is produced by inclining the pedal and pulling back, rather than pulling vertically up on the pedal" (p. 854).

Our finding of positive values of F_N over much of the upstroke (although not large enough to do significant work) represents a finding that differs from the consensus of the literature (Davis & Hull, 1981; LaFortune & Cavanagh, 1983; Soden & Adeyefa, 1979). In comparing our data with the literature, the conditions (90 rpm and 123 single-leg W) of our low workload were very similar to those (90 rpm and 235 W) of McLean and LaFortune (1988). In that study, McLean and LaFortune present torque versus crank angle data for competitive cyclists before and after real-time biomechanical feedback of the negative torque produced. Our data showed less negative torque than their data did before biofeedback, but more negative torque than their data did after the biofeedback. McLean and LaFortune (1988) did not measure the components of the applied forces, so it is unknown whether the positive torque they show between 180° and approximately 240° (see their Figure 2) was produced by a tangential or normal component of applied force. Therefore our low workload data are consistent with the published data collected under the most similar conditions.

Cavanagh and Sanderson (1986) collected pedaling technique data from elite pursuit cyclists at a workload similar to our high workload data (400 W vs. 193 single-leg W), but at 100 rpm instead of 90 rpm. The data (see their Figure 13) showed a subject who pulled up on the pedal between 270 and 360° in a very similar fashion to some of our subjects. However, Cavanagh and Sanderson remarked that most subjects did not pull up. One contributing factor to our subjects' increased pulling up could have been the lower inertia of pedaling on an ergometer compared to cycling on a bike. Cavanagh and Sanderson (1986) reported that during a low inertia pedaling experiment, in which the cycle stopped rapidly when pedaling stopped, there were significant amounts of pulling up. However, our ergometer had much more inertia than did the bike in the Cavanagh and Sanderson experiment.

Because of the similarity of our data and that from other studies collected under similar conditions, we feel that the character of the positive torque produced by our subjects does reflect their pedaling technique under conditions simulating competition. Our data show that while negative torque occurs at a low workload, positive normal forces appear for some subjects as the workload increases to a high level. Because positive normal forces appear mainly at the high workload, we feel that one reason many other studies failed to show them was in part because the studies did not collect data at a high enough workload. But it is quite possible that the magnitude of pulling up shown by some of our subjects was partially due to the lower inertia of the ergometer used for data collection.

Having noted the production of propulsive torque throughout much of the upstroke, we want to reemphasize the relative unimportance of the upstroke for doing work when compared to the downstroke. The importance of the upstroke at the high workload was that, by decreasing the negative torque, the cyclists effectively decreased the work that must be done during the downstroke of the other leg, thereby doing less positive work for the same power output. The positive work done during the downstroke was 98.6% at the low workload and 96.3% at the high workload. Although elite subjects were able to reduce the work requirements of one leg during the downstroke by eliminating negative torque production or by producing some slight positive torque during the upstroke with the other leg, they did not use a strategy of producing significant positive work during the upstroke at the higher workload. Thus there is little evidence that feedback devices used to increase pulling up during the upstroke (e.g., Briggs et al., 1989) would help improve the performance of elite cyclists. Nevertheless, since the amount of negative torque produced during the upstroke by the elite subjects in our study appeared significantly less than the amount produced by less skilled subjects in other studies (LaFortune and Cavanagh, 1983; Ericson & Nissel, 1988), it is possible that less skilled cyclists might benefit from learning to reduce negative torque during the upstroke, without attempting to pull up significantly.

Further study is needed to determine the biomechanical techniques employed by elite cyclists. Given the variability shown in the pedaling technique data among the subjects in this study, it is not unreasonable to hypothesize that performance differences between elite subjects could in part be related to biomechanical differences. However, pedaling technique data alone cannot provide enough information to observe these performance differences. Since pedaling technique is merely the output of a complex biomechanical system, further investigations must integrate

pedalling technique data with the kinematics and dynamics of the lower extremities during cycling.

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