

Pedal and Crank Kinetics in Uphill Cycling

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Alterations in kinetic patterns of pedal force and crank torque due to changes in surface grade (level vs. 8% uphill) and posture (seated vs. standing) were investigated during cycling on a computerized ergometer. Kinematic data from a planar cine analysis and force data from a pedal instrumented with piezoelectric crystals were recorded from multiple trials of 8 elite cyclists. These measures were used to calculate pedal force, pedal orientation, and crank torque profiles as a function of crank angle in three conditions: seated level, seated uphill, and standing uphill. The change in surface grade from level to 8% uphill resulted in a shift in pedal angle (toe up) and a moderately higher peak crank torque, due at least in part to a reduction in the cycling cadence. However, the overall patterns of pedal and crank kinetics were similar in the two seated conditions. In contrast, the alteration in posture from sitting to standing on the hill permitted the subjects to produce different patterns of pedal and crank kinetics, characterized by significantly higher peak pedal force and crank torque that occurred much later in the downstroke. These kinetic changes were associated with modified pedal orientation (toe down) throughout the crank cycle. Further, the kinetic changes were linked to altered nonmuscular (gravitational and inertial) contributions to the applied pedal force, caused by the removal of the saddle as a base of support.

Key words: pedal force, crank torque, posture, grade

Research on cyclists of different skill levels has answered many questions concerning biomechanical aspects of cycling performance (e.g., Coyle et al., 1991; Gregor, Broker, & Ryan, 1991). Undoubtedly, the most important technical development for cycling research has been the advent of instrumented pedals that measure forces applied at the foot/pedal interface. This technology has permitted researchers to study patterns of pedal force application under different cadence and workload conditions (Kautz, Feltner, Coyle, & Baylor, 1991; Redfield & Hull, 1986), has been used in the assessment of elite cyclists (Coyle et al., 1991), and has generated input for both inverse dynamics (Gregor, Cavanagh, & Lafortune, 1985; Redfield & Hull, 1986) and theoretical models of muscular output (Kautz & Hull, 1993).

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Because the vast majority of previous studies have focused on cycling on level surfaces, there is a lack of biomechanical information on cycling on graded surfaces. This is unfortunate because of the importance of hill-climbing in cycling road races. In both single-day and multistage international competitions, the winner is inevitably one who excels in the hill-climbing sections of the course. Uphill cycling performance is also of interest from a motor control perspective, because cyclists use various postural strategies to overcome the higher loads and subsequent fatigue. Some cyclists choose to remain seated while ascending a hill, while others elect a more upright standing position for at least part of the climb. Cycling on graded surfaces is therefore an excellent model for the study of neuromuscular adaptations associated with different environmental constraints (see also Brown, Kautz, & Dairaghi, 1996). However, only a few recent studies have reported pedal force profiles produced during uphill cycling (Alvarez & Vinyolas, 1996; Stone & Hull, 1993), and in these studies the number of subjects was very limited (only 4 riders in both papers combined). This lack of research is due in part to the difficulty of collecting data during actual on-road hill-climbing or simulating uphill conditions in the laboratory environment.

Therefore, the purpose of the present paper was to investigate pedal force profiles during uphill cycling using different climbing postures and to compare these profiles with those obtained during level cycling. As a first step we simulated the uphill conditions within our laboratory using a computerized cycling ergometer. It was hypothesized that both surface grade (level vs. uphill) and postural (seated vs. standing) differences between conditions would result in unique pedal kinetic profiles.

Methods

Eight elite (USCF category 1 or 2) male cyclists were recruited from local cycling clubs. Subjects were free of any neuromuscular disorders or orthopedic conditions that might preclude their participation in the study, and they signed informed consent documents after the experimental procedures were explained to them. Each subject rode a simulated course on his own bicycle mounted on a computerized Velodyne ergometer. The Velodyne provides an internal resistance that is calibrated to replicate the resistance associated with cycling at different intensities and grades. For the present study, subjects rode a 20-min "course" with the Velodyne set to provide constant power at a fixed workrate (Table 1) that corresponded to 80% of their predetermined $\dot{V}O_2$ max. The cycling course consisted of a 5-min level grade, followed by a 10-min simulated hill at 8% grade and a final 5-min level portion (see Figure 1). Each subject rode the simulated course four times. On the level sections the riders remained seated, while on the 8% grade they climbed either while seated or while standing. Although the Velodyne replicates hills by adjusting its internal resistance, the ergometer was secured to a standard exercise treadmill capable of attitude adjustments to match the actual geometric grade of each course section.

During each cycling trial, the subject would begin with a 5-min warm-up at a self-selected pace. The simulated course was then begun with the rider at his 80% $\dot{V}O_2$ max workrate using a predetermined speed and self-selected gear ratio/cadence combination that was maintained throughout the initial level section. After 5 min, the Velodyne setting was adjusted to replicate the added resistance of the 8% grade, and the rider's speed, gear ratio, and cadence were adjusted to predetermined values to maintain the same constant power as on the level section. The treadmill attitude adjustment was used to orient the rider and bike to the 8% grade of the simulated hill. After 10 min on the hill, the Velodyne resistance, speed, gear ratio, cadence, and treadmill attitude were all returned to the initial

Table 1 Subject ($n = 8$), Workrate, and Cadence Characteristics

	Mean	SD
Age (years)	28	5
Mass (kg)	78.9	5.3
Height (cm)	185.4	6.0
Workrate (W)	294	17
Cadence (rpm)		
Level seated	82	15
Uphill seated	65	5
Uphill standing	64	5

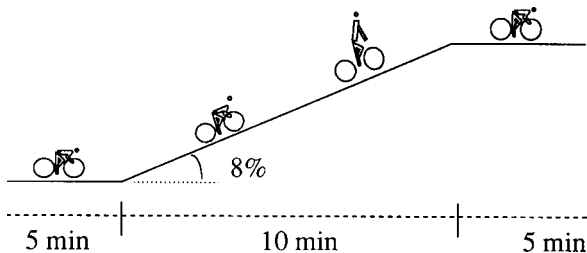


Figure 1 — Schematic representation of simulated cycling course. Cyclists rode for 5 min on the level, followed by a 10-min simulated hill of 8% grade, followed by another 5-min level section. Throughout the entire 20-min “course,” the subjects rode at a workrate equal to 80% of their maximal $\dot{V}O_2$.

values for the final 5-min level section of the course. This procedure was used to control for workrate, although the adjustments of speed and cadence led to increased variability in pedal force magnitudes. In the present paper we will contrast the pedal force profiles associated with three conditions: seated level grade, seated uphill grade, and standing uphill grade.

A high-speed (50 fps) cine camera was situated so that its optical axis was perpendicular to the sagittal plane of the cyclist on the ergometer. The camera permitted registration of the motion of reflective markers attached to the crank spindle, pedal spindle, and the back of a fin oriented to represent pedal angular position. Markers were also placed over appropriate body landmarks on the foot, ankle, knee, hip, and shoulder joints (Winter, 1990). A clip-in Look pedal instrumented with two piezoelectric load washers (Broker & Gregor, 1990) was attached to the subject’s bicycle on the side facing the camera, while a pedal of equal weight was used on the contralateral side. Film and force data were collected for 5 s at the 3rd minute of each level grade course section and at the 3rd and 7th minutes of the uphill climb. Force pedal data were collected at 100 samples per second using a 12-bit analog-to-digital (A/D) converter interfaced with a microcomputer. The force data were synchronized with the film data using a switch that illuminated a light in the field of view and provided a 3 V pulse to an additional channel on the force A/D

record. For each subject, four complete crank cycles of each of the three conditions were analyzed.

After appropriate bias adjustment and scaling to calibrated values, a recursive low-pass Butterworth filter was used to smooth the digitized film (4 Hz cutoff) and force (10 Hz cutoff) data. The pedal forces and marker kinematics were expressed as quintic splines (Dierkcx, 1975) and output at 1° increments of crank angle. These data were used to calculate crank and pedal kinematics and to describe crank and pedal kinetics in global, pedal, and crank reference systems (Figure 2). The pedal and crank kinetics were calculated using slight variations (due to differences in reference systems) of the equations reported in Coyle et al. (1991). The following equations were used to calculate crank torque and pedal forces in the global reference system, using the measured tangential (F_T) and normal (F_N) force components.

$$F_H = -F_T \times \cos \beta + F_N \times \sin \beta$$

$$F_V = -(F_T \times \sin \beta + F_N \times \cos \beta)$$

where F_H and F_V are the horizontal and vertical force components and β is the pedal orientation with respect to the horizontal. The crank torque (T_C) was calculated as

$$T_C = (F_H \times CrLen \times \cos \theta) - (F_V \times CrLen \times \sin \theta)$$

where CrLen is the crank arm length (crank spindle to pedal spindle) and θ is the crank angle with respect to top-dead-center (TDC).

Patterns of the pedal forces and crank torques were plotted for each trial as a function of crank angle from 0 to 360°, referenced to TDC in the global reference system. Discrete measures of interest from these kinetic patterns were the peak resultant pedal

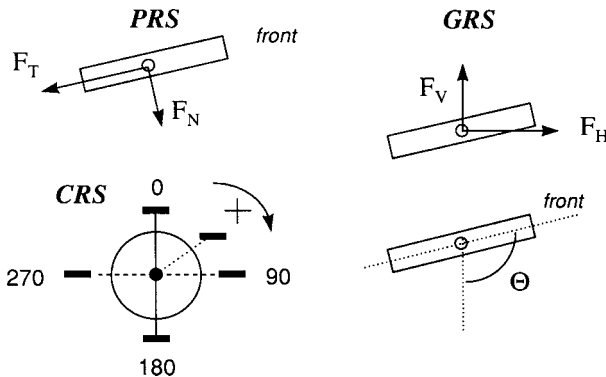


Figure 2 — Reference systems for pedal and crank kinetics. Forces were measured in the pedal reference system (PRS), with a positive normal force (F_N) directed downward and a positive tangential force (F_T) directed toward the back of the pedal. Together with the crank arm and pedal orientations, these measured force components were used to calculate torque about the crank spindle in the crank reference system (CRS), in which positive crank torques were those that applied propelling impulse to the bicycle. The measured forces were also expressed in a global reference system (GRS), with positive vertical force (F_V) directed upward and positive horizontal force (F_H) directed toward the front of the bicycle. The pedal angle Θ was measured with respect to the vertical. Note that the equations in the text use the pedal angle β , which is with respect to the horizontal ($\beta = \Theta - 90^\circ$).

force and peak crank torque and the crank angles at which these peaks occurred. An additional parameter of interest was the pattern of pedal orientation in space throughout the crank cycle, as this pedal angle is critical for determining the transformation from pedal force to crank torque. The peak pedal angle and the crank angle at which it occurred were also calculated. The individual trial patterns (8 subjects by 4 trials = 32 in each condition) were combined to form ensemble average curves and used to calculate the variability around these ensembles. The ensemble curves were used as the basis of a qualitative analysis among conditions, while the discrete measures were analyzed with a repeated-measures, within-subjects analysis of variance (ANOVA) to illustrate quantitative similarities and differences among conditions. For the ANOVA, the level of statistical significance was set at $p \leq .05$.

Results

Subject characteristics and cadences for each condition for the riders are given in Table 1. Despite the observed variability in subject mass, height, and cadence combinations, relatively stereotypical kinetic patterns were evident for each condition (Figure 3). Variability of pedal force and crank torque profiles across subjects and conditions was assessed through the coefficient of variation (CV), defined as the standard deviation expressed as a percentage of the range of the kinetic variable in question. CV values were low in all cases, ranging from 7.8% to 16.8%. Among the three cycling conditions, pedal force CVs were similar in the level seated (F_V 16.8%, F_H 12.8%), uphill seated (F_V 14.7%, F_H 12.9%), and uphill standing (F_V 9.3%, F_H 16.4%) conditions. Crank torque CV showed even less variation, being lowest in the uphill standing condition (7.8%) and only slightly higher in the uphill seated (9.9%) and level seated (10.3%) conditions. These variability data indicate that kinetic patterns were relatively stable across our subjects for all three conditions.

The components of the measured forces relative to the surface of the pedal are shown in Figure 4 for each condition. The patterns of normal forces for the level and uphill seated conditions were very similar, with a large positive (downward) force profile during the first 180° of the crank cycle, peaking just after 90°. The uphill standing condition demonstrated a much higher peak normal force, which occurred just prior to 180°. Tangential force profiles were also similar in the two seated conditions, although the uphill seated pattern had a shorter negative phase around 0° (TDC) and a higher positive peak near 90° of the crank cycle. The standing uphill condition displayed a much different pattern, with an extreme dip into negative values coinciding with the large peak normal force just prior to 180°.

Although Figure 4 illustrates the force application in relation to the pedal, the ability of these force components to generate crank torque in each condition is not clear. One important factor is the orientation of the pedal throughout the crank cycle, shown in Figure 5 as measured with respect to the vertical (90° indicates the pedal was horizontal). In all three conditions the pedal angle follows a sinusoidal path; however, these paths are offset in each condition. The uphill seated condition demonstrates the pedal orientation profile with the highest offset, indicating the toe was pointed upward more than in the other conditions. In contrast, in the standing uphill condition the pedal was angled more downward throughout the crank cycle. The differences in pedal orientation are quantified in measures of peak pedal angle, which was found to be statistically different between the level (112°), seated uphill (122°), and standing uphill (98°) conditions (Table 2). In addition, the crank angle at which the peak pedal orien-

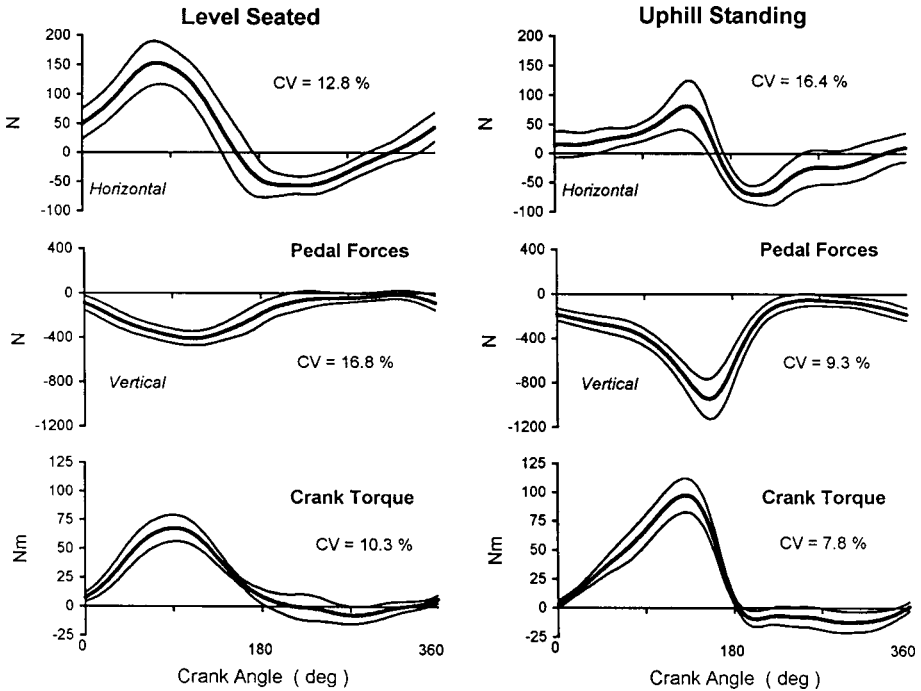


Figure 3—Pedal forces and crank torque from the level seated (left panels) and uphill standing (right panels) conditions, expressed as a function of crank angle. In each panel the thick central line represents the mean ensemble average for all subjects, while the thinner lines above and below the mean represent ± 1 SD. The coefficient of variation (see text for details) for each variable is indicated by CV. The top and middle panels illustrate horizontal and vertical force components, respectively. The bottom panels illustrate the torque generated about the crank spindle from the force on one pedal. The seated uphill condition is very similar to the seated level condition and is omitted for clarity.

tation occurred was significantly lower in the seated uphill condition (91°) compared to both the seated level (98°) and standing uphill (102°) conditions. The 8% alteration in grade accounts for approximately 4.6° of the crank and pedal angle changes between the level and uphill conditions because these angles were measured in the global reference system.

Further evidence of kinetic differences between conditions is found in Figure 6, which illustrates the horizontal and vertical components of the pedal forces, after transformation from the pedal reference system to the global reference system. The basic pattern of force application is similar in the level and uphill seated conditions, although the magnitude of the forward horizontal force component in the downstroke is greater for the uphill condition. The standing uphill condition displays a much different pattern for both vector components. The peak forces occur later in the cycle for both components, with the horizontal force displaying a much reduced peak and the vertical component a much increased peak.

Measurements of peak resultant pedal force (Table 2) support the impression formed from Figures 4 and 6. The mean peak resultant force was significantly higher in the uphill

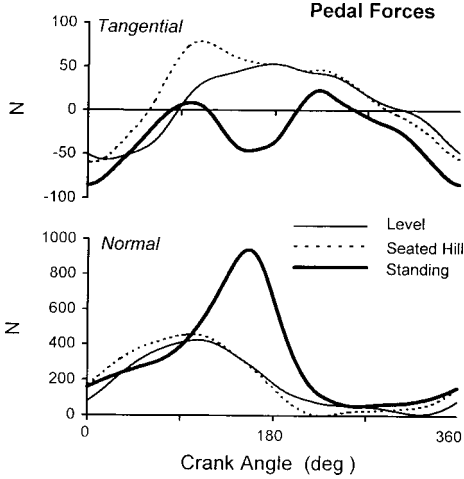


Figure 4 — Tangential (top panel) and normal (bottom panel) components of the measured forces relative to the surface of the pedal, expressed as a function of crank angle. Each line represents the mean ensemble curve for all subjects in each condition: thin solid line = level seated, broken thin line = uphill seated, thick solid line = uphill standing.

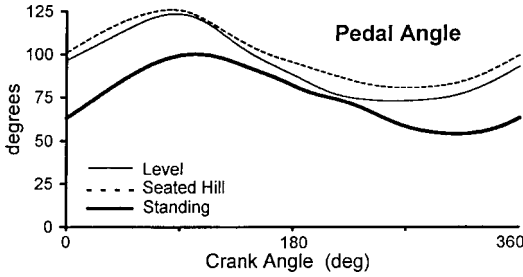


Figure 5 — Profile of the pedal angle Θ (with respect to the vertical) expressed as a function of crank angle. Each line is from a representative trial in each condition from one subject: thin solid line = level seated, broken thin line = uphill seated, thick solid line = uphill standing.

standing condition (965 N) than in either the seated level (438 N) or uphill (480 N) conditions. The timing of the peak force within the crank cycle was also significantly different, occurring at a crank angle of 155° in the standing uphill condition as compared to 107° and 101° in the seated level and uphill conditions, respectively.

It is not surprising that the calculated crank torques reflect the differences in pedal force patterns and measured variables between conditions (Figure 7 and Table 2). The highest peak torque was demonstrated in the standing condition ($101 \text{ N} \cdot \text{m}$), with the uphill seated peak torque at $78 \text{ N} \cdot \text{m}$ and the level condition at $68 \text{ N} \cdot \text{m}$. As with the resultant pedal forces, the peak crank torque occurred at a greater crank angle in the standing condition (131°) than in the seated uphill (86°) and level (94°) conditions. For both peak crank torque magnitude and angle of occurrence, the condition group means were significantly different from each other.

Table 2 Pedal and Crank Kinetic and Kinematic Data

	Level seated		Uphill seated		Uphill standing	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Peak resultant force (N)	438 ^b	68	480 ^b	73	965 ^a	190
Crank angle (°)	107 ^b	13	101 ^b	9	155 ^a	9
Peak crank torque (N · m)	68 ^c	12	77 ^b	11	101 ^a	13
Crank angle (°)	94 ^b	7	86 ^c	7	131 ^a	9
Peak pedal angle (°)	112 ^b	8	122 ^a	9	98 ^c	6
Crank angle (°)	98 ^a	9	91 ^b	9	102 ^a	9

Peak values (mean ± 1 *SD*) are provided for selected variables, along with the crank angle at which the peak occurred. Condition means with the same superscript letter are statistically identical, with ^a representing the highest condition mean and ^b and ^c representing successively lower condition means.

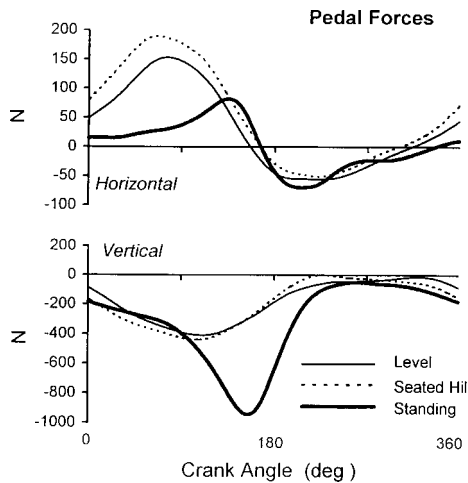


Figure 6 — Horizontal (top panel) and vertical (bottom panel) components of the pedal forces in the global reference system, expressed as a function of crank angle. Each line represents the mean ensemble curve for all subjects in each condition: thin solid line = level seated, broken thin line = uphill seated, thick solid line = uphill standing.

Discussion

In the present study, it was hypothesized that differences in surface grade and posture would result in unique pedal kinetic profiles. The results indicated that surface grade by itself did not drastically alter the patterns of pedal force or crank torque but that the postural adjustment from sitting to standing while hill-climbing had a profound effect on

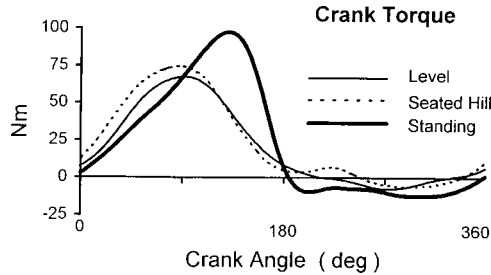


Figure 7 — Crank torque from forces applied to one pedal, expressed as a function of crank angle. Each line represents the mean ensemble curve for all subjects in each condition: thin solid line = level seated, broken thin line = uphill seated, thick solid line = uphill standing.

pedal kinetics. Further, pedal orientation throughout the crank cycle was altered with both grade and posture. Pedal force profiles were reflected in the crank torque calculations, with the two seated conditions demonstrating similar patterns with peak torque at approximately 90° of crank angle. In contrast, the uphill standing condition exhibited a peak torque of greater magnitude later in the crank cycle near 130° .

The pedal kinetic data from the level condition correspond with data from many studies found in the literature. The measured force components normal and tangential to the pedal surface are similar in both pattern and magnitude to those reported by others if differences in reference directions are taken into account (Fregly & Zajac, 1996; Gregor, Cavanagh, & Lafortune, 1985; Hull & Davis, 1981; Hull, Gonzalez, & Redfield, 1988; Hull & Jorge, 1985; Kautz, Feltner, Coyle, & Baylor, 1991; Newmiller, Hull, & Zajac, 1988; Redfield & Hull, 1986). There are discrepancies among these studies in regard to the tangential component pattern, likely due to variability in cadence, workload, foot/pedal interface, and/or rider skill level. When resolved into horizontal and vertical components, our pedal force data agree with other studies in both pattern and magnitude (Coyle et al., 1991; Kautz & Hull, 1993; Kautz et al., 1991). Finally, the calculated crank torque profiles from the level condition are similar in both shape and magnitude to other published data (Coyle et al., 1991; Hull & Jorge, 1985; Kautz et al., 1991; Newmiller et al., 1988).

Our data from the uphill conditions are also similar to those found in the literature, although there are far fewer studies with which to compare. Of particular interest is the recent study by Alvarez and Vinyolas (1996), who collected data from a single cyclist outdoors on an instrumented bicycle under natural hill-climbing conditions. Normal and tangential pedal forces from their subject climbing in a seated posture agree in shape and magnitude with the patterns from our subjects shown in Figure 4. Our data also agree with those of Alvarez and Vinyolas (1996) in the uphill standing condition. This agreement is important because their subjects were free to move their bicycles in the medial/lateral direction, as has been reported to occur in the standing situation (Hull et al., 1990; Stone & Hull, 1993). Our subjects were constrained to relatively little side-to-side movement by the rigid attachment of the bicycle to the Velodyne. The normal force profiles both from the subject studied by Alvarez and Vinyolas (1996) and from another subject climbing while on a treadmill (Stone & Hull, 1993) are similar to our data. The tangential force component for uphill standing from Alvarez and Vinyolas (1996) also agrees in general shape with our data, although they reported a continuously backward pull on the pedal during the middle portion of the crank cycle (90° to 270°). In contrast, Stone and Hull

(1993) reported a continuously forward push throughout the entire crank cycle and reported that the tangential force component had the highest variability among the three subjects tested. As with the level condition, the tangential force component may differ for several reasons. One important reason in this instance is the foot/pedal interface, as Stone and Hull (1993) used standard pedals with toe-clips, while we in the present study as well as Alvarez and Vinyolas (1996) used the more rigid attachment afforded by step-in “clipless” pedals.

Effect of Grade: Level Versus Uphill Seated

The effect of a change in grade from level to 8% uphill on pedal and crank kinetics was relatively small. Initial inspection of the crank torque profiles shows that cyclists adapted to the hill by increasing the propelling torque during the first 120° of the crank cycle. A second increase in torque production was seen at the first half of the upstroke between 180° and 270° crank angle. These torque increases are largely explained by the change in cadence from the level (82 rpm) to uphill (65 rpm) condition. Because the workrate was kept constant at a level equivalent to 80% $\dot{V}O_{2\max}$, the external work per crank revolution was increased by approximately 26% due to the change in crank cycle time (level, 0.73 s; uphill, 0.92 s). This work increase can only be effected by increasing the area under the crank torque–crank angle profile (Figure 7). Inspection of the pedal kinematic and kinetic profiles indicates that the increase in external work was accomplished by a combination of greater force magnitude and different direction of force application. On the hill the normal force component was increased in magnitude during the first 120° of the crank cycle and then reduced during the start of the upstroke. The tangential force changed from forward to backward earlier in the downstroke (near 70° crank angle) and then reached a higher backward magnitude for the remainder of the downstroke. When these applied force changes are combined with the alteration in pedal orientation to a more “toe-up” position, the horizontal force component is higher during the downstroke, while the vertical force component is closer to zero during the initial portion of the upstroke. These pedal force changes are directly associated with the observed crank torque changes, and the alteration in pedal orientation is an important aspect of these modifications.

Effect of Posture: Uphill Seated Versus Uphill Standing

Unlike the relatively small effect of changing grade from level to 8% uphill, the alteration in posture from seated to standing on the graded surface had profound effects. The normal and tangential pedal force components both illustrated patterning differences when compared to the seated conditions, particularly in the second portion of the downstroke from 90° and 180° crank angle. During this phase the tangential force was directed toward the front of the pedal, rather than toward the heel as in the seated trials. At the same time, the force component normal to the pedal surface had a much greater magnitude in the standing condition, reaching a peak averaging over 900 N. These altered force components are associated with a distinctly different pedal angle, with the front of the pedal shifted downward compared to both the level and seated uphill conditions. Together these alterations result in different horizontal and vertical force components. The horizontal force during the initial part of the downstroke was sharply reduced from the seated conditions, but after reaching its lower peak near 135° crank angle it followed a similar pattern during the rest of the crank cycle. The vertical force also showed similarities with the seated trials, specifically in early (0° to 90°) and late (200° to 360°) portions of the crank cycle. However, in the late downstroke and early recovery phases (90° to 200°), the pedal force demon-

strated a large downward vertical component, peaking near 170° at over 900 N. Together with the downward angled pedal, these force components produced torque about the crank spindle that was much higher than in seated cycling during the late downstroke phase. Thus, a combination of differences in applied pedal force *and* pedal orientation altered both timing and magnitude of peak crank torque in the standing condition.

Undoubtedly, these kinetic and kinematic changes are associated with the riders' altered body position on the bike in the standing trials. In the seated position, the hip joint was positioned posterior to the crank spindle due to the bike geometry, and the hip moved relatively little throughout the crank cycle (Neptune & Hull, 1995). This configuration can be modeled as a rather constrained five-bar linkage system, one with only two degrees of freedom (Hull & Jorge, 1985). We observed this constraint in stereotypical leg segment kinematic patterns, with differences among seated riders usually seen only in their ankle patterns. Switching to a standing position releases the cyclist from this constrained system, as the hip joint moves forward toward the handlebars (Figure 8). This alters the angular kinematics at all three lower extremity joints and allows much greater motion of the hip joint, particularly in the vertical direction. One significant change that this body positioning permits is the more rotated orientation of the foot and pedal throughout the crank cycle. The downward pedal attitude and lower toe position are associated with the more forward positioning of the knee and hip joints afforded by moving the pelvis off the saddle.

An interesting aspect of this change in body positioning is the possibility that there is a change in the relative contribution of muscular and nonmuscular sources to the measured pedal force. Kautz and Hull (1993) demonstrated the inertial, gravitational, and muscular components of the pedal force during seated cycling, using a three-link model of

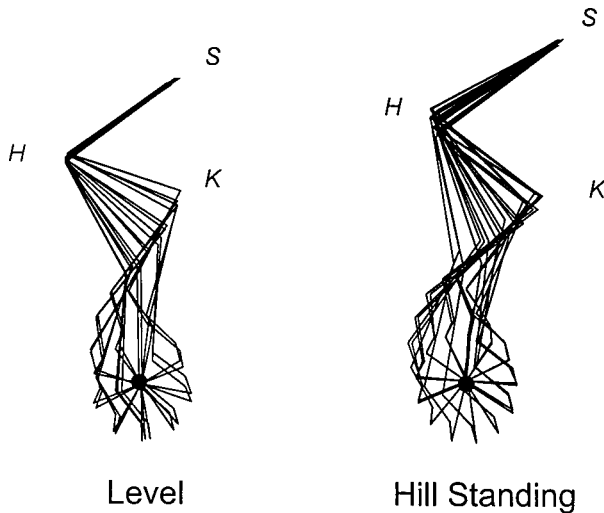


Figure 8 — Stick-figure representation of segmental motion in the level seated and uphill standing conditions for two crank cycles. Segments of each stick figure represent trunk, thigh, leg, foot, and crank arm positions, with the crank spindle designated by the large filled circle. Letters *S*, *H*, and *K* represent approximate positions of shoulder, hip, and knee joints, respectively. Note the forward and upward shift of the trunk and thigh in relation to the crank spindle in the uphill standing condition.

the lower extremity. Their results indicated that the relative contribution of the mechanical sources to the pedal force varies throughout the crank cycle. Also, these contribution patterns are altered with changes in cadence; therefore, a modification of the relative contribution of nonmuscular and muscular components may be involved in the pedal force differences between level (82 rpm) and uphill (65 rpm) seated conditions. These alterations with cadence occur even though the physical support for the body in relation to the pedal does not change. In seated cycling, the body mass is supported in five locations: the two feet on the pedals, the two hands on the handlebars, and the pelvis on the saddle. The nature of the three-link model of Kautz and Hull (1993) dictates that the weight of each lower limb is supported at both the pedal and at the hip/saddle. The weight of the rest of the body is shared by the saddle and handlebars, with much of the weight of the trunk supported by the saddle.

In standing cycling, the support of body mass changes dramatically when the saddle is removed as a base of support. The role of the saddle must be replaced by additional weight support at the handlebars and pedals. The actual distribution of weight to the remaining four support points will be influenced by the amount of forward horizontal shift of the total body CM during the crank cycle. Muscular contributions to pedal force will also change, because the greater hip motion while standing permits work to be done on the torso by handlebar forces and moments (Stone & Hull, 1993) and energy to be transferred through the pelvis to the lower extremity and pedal. When applied to our seated trials, the pedal force decomposition technique gives results (not shown) very similar to those reported by Kautz and Hull (1993). However, in the absence of measured handlebar forces and without constructing a whole body linked-segment model, we have no quantitative pedal force decomposition data from the standing trials.

However, it is clear that removing the saddle as a base of support alters the nonmuscular (gravitational and probably inertial) contribution to the pedal force, and these changes are likely the dominant contributor to the increased peak crank torque that occurs later in the downstroke during the uphill standing condition. Certainly, the gravitational component of the pedal force in standing cycling will be greater than in the seated conditions. This statement is supported by measurements of static pedal forces (unpublished observations) that indicate an increase up to as much as 240% of seated values with a shift from seated to standing posture. During actual cycling, the weight distribution will be biased much more heavily toward the downstroke leg, as the upstroke pedal is supporting roughly the same vertical force as in the seated conditions (Figure 6). Further, Stone and Hull (1993) reported peak vertical handlebar forces of roughly 110 N during the downstroke and -175 N during the upstroke. Assuming symmetry, the biphasic pattern of their handlebar force profile from one brake hood will be effectively canceled by the force from the other brake hood. This leaves the downstroke pedal as the major point of support for the gravitational load of the whole body. In addition, the vertical hip motion evident in the standing condition (Figure 8) indicates that the inertial contribution to pedal force will also likely increase over that seen while seated.

Relevance to Cycling Performance: Why Stand?

Cyclists use different strategies while climbing hills during competitions, with some choosing to stand for sections of the uphill grade. This choice is made even though the higher frontal area increases the aerodynamic drag resisting forward motion. The present study offers at least one piece of evidence to explain why riders choose to stand. With the standing position they are able to produce higher peak forces on the pedal, resulting in greater peak torque application on the crank spindle. One might speculate that these higher pedal

and crank kinetics are produced using different muscles than in the seated condition. Support for this speculation comes from various sources, including the changes seen in segmental kinematics, the reorientation of the segments with respect to the pedal and crank, and the increased nonmuscular contributions to the pedal force. Even if the same muscles contribute to production of pedal force, some of these muscles will operate across different portions of their active force-length relations and likely will have differing contractile velocities than in the seated condition. These differences in contractile velocity are possible because of altered joint range of motion, even though the cadences in the two uphill conditions were almost identical. Further studies are needed to examine the issue of muscular changes, using both mechanical analyses of joint moment and power (e.g., Broker & Gregor, 1994; Gregor et al., 1985) and electrophysiological studies of muscle activity (e.g., Ryan & Gregor, 1992).

From a motor control perspective, the alteration in posture during the standing condition increases the number of degrees of freedom available to the rider. This less constrained position allows the cyclist to explore changes in segmental coordination with which to generate effective crank torque for forward propulsion. The removal of the saddle as a base of support is the key because it allows the mechanical linkage of handlebar and pedal forces through the trunk segment. This changes the situation from one in which the lower extremity alone is responsible for generating crank torque to one in which effective application of forces and torques on the handlebars can help produce the crank kinetics. Removing the saddle as a base of support allows the entire body weight to contribute to the pedal force vector. One could view using the entire body weight to generate propulsive torque as an effective use of nonmuscular forces to solve the movement problem.

One final question concerns the reason why the peak pedal force and crank torque are shifted to later in the crank cycle in the standing condition. For a variety of reasons, cyclists apply positive torque mainly during the downstroke on each side, resulting in a total crank torque (including force on both pedals) that is positive throughout the crank cycle (Figure 9). The magnitude of this positive crank torque varies throughout the cycle, and there is more variation (a greater range of values) in the standing condition. However, if the torque values in Figure 9 are averaged across the entire crank cycle, the mean torque levels for uphill seated (46 N · m) and standing (45 N · m) conditions are almost identical.

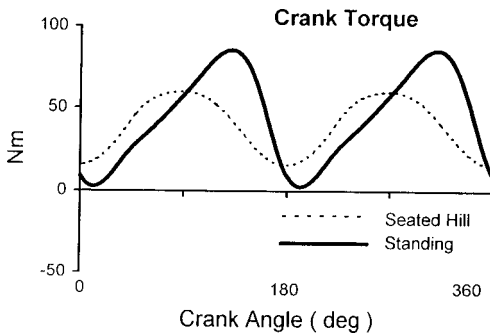


Figure 9 — Crank torque profiles considering forces from both right and left pedals, expressed as a function of crank angle. The contralateral crank torque was simulated by assuming symmetry of force application on each pedal. Each line represents the mean ensemble curve for all subjects in the two uphill conditions: broken thin line = uphill seated, thick solid line = uphill standing.

This is a mechanical necessity, a consequence of the set external workrate and the equivalent gear ratios and cadences used by the riders in the two uphill conditions. Therefore, from a mechanical viewpoint these torque profiles are equally effective in propelling the bicycle and rider. However, the torque profiles are much different in the two conditions. While standing, the riders produce two concentrated “bursts” of crank torque, peaking in the late downstroke on each side. In the seated condition the two torque peaks are less distinct, with a more rounded shape during the downstroke. We conclude that the pedal and crank kinetic profiles from the standing condition are a natural consequence of the new segmental positions, joint ranges of motion, and altered contribution from muscular and nonmuscular sources.

In summary, these data indicate that the change in surface grade from level to 8% uphill by itself does not significantly change the application of force on the pedal or torque about the crank spindle. In contrast, the alteration in posture from sitting to standing permits the rider to produce different patterns of pedal and crank kinetics, characterized by higher peak values that occur much later in the downstroke. These kinetic changes are associated with altered pedal orientation throughout the crank cycle, and they result predominantly from altered nonmuscular (gravitational and inertial) contributions to the applied pedal force associated with the removal of the saddle as a base of support.

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