KINETIC CRANK ARM ANALYSIS DURING COMPETITIVE CYCLING

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While the major task facing coaches and athletes in competitive cycling is compliance to the specificity principle in training performance skills, physiological capacities and competitive strategies, there is a disappointing scarcity of objective information that quantifies the range, duration and combination of work intensities in either kinetic or physiological terms that must be met during the 3.5 to 4.5 hour events of road racing. This is not to say that there has been little research on cycling. On the contrary, the effects on crank forces and efficiency of bike design and structural materials, body position and the relationships of body segments, (Shennum, 1976; Faria, 1978; Nordeen-Snyder, 1977) pedaling frequency, (Seaburg, 1977; Jordan, 1979) and environmental conditions (diPrampero, 1979) have been studied extensively and the topic of specificity of cycle training relative to metabolic characteristics has received some attention (Bannister, 1967; Hagberg, 1975; Burke, 1979; Conconi, 1982). However, the detached nature of road racing compared to track events together with a widely varying terrain has precluded any extensive analysis of the mechanical or physiological characteristics of performance outside of the laboratory. This is particularly unfortunate as the principles of training currently employed in preparing for competition are designed to take advantage of an understanding of the interaction of forces, relative exercise intensities and time characteristics which are unique to a given event.

Therefore, the purpose of this project which has been funded for the last two years by Sport Canada with the support of the Canadian Cycling Association, was to develop technology which would permit quantification and qualification of the kinetic and physiological characteristics associated with competitive performances during road racing events. This involved two primary objectives: (1) identification of the principal variables; and (2) selection and construction of the data collection process.

If one ignores for the present the almost infinite number of variations which can be made in a bicycle through adjusting frame, wheel, seat, stem and crank dimensions and assumes that an experienced rider has constructed an optimum vehicle, then the most important variables from a practical point of view are probably bicycle velocity and acceleration. However, by themselves these variables give very little information about the degree of effort expended in their production. On the other hand, the most complete information would incorporate simultaneous determinations of physiological energy release together with measurements of force and the direction of its application to the pedals as well as the delivery of this force as torque at the hub of the rear wheel. While such data collection may be attempted in the laboratory it is impractical to consider applying the equipment which would be required to field studies, let alone competitive circumstances. Consequently, a level of compromise was required which would permit some form of movement-energy-force comparison for extended time periods without unduly encroaching on a rider's ability to compete favourably in regularly scheduled events. Moreover, rather than attempting a complete technological design at the outset, it was felt to be prudent that the most difficult problems be solved first and the process be used as a pilot study to the design of subsequent information channels.

Velocity and linear acceleration proved to be easily measurable with commercially available, miniaturized technology constructed either specifically for the bicycle in the case of velocity (Cateye Solar Inc.) or easily adaptable in the case of accelerometers (Entran Devices Inc.). Similarly, while direct measurement of metabolic energy expenditure in the form of ventilation and oxygen data was out of the question on the basis of the volume and mass of equipment required, the recent appearance and wide distribution of subject centered heart rate monitoring and data storage equipment with event markers (Polar Electro Ltd.) presented an excellent indirect method of evaluating aerobic energy expenditure which could be calibrated for a given rider with respect to work rate and blood lactate concentration while riding in the laboratory. Conceptually, measurement of forces proved to be deceptively easy through the standardized employment of foil strain gauges (M and M Inc.) as active elements in a Wheatstone Bridge. However from a practical point of view, this proved to be the most difficult task, part of the solution for which was also applicable to the storage phase of data on other variables.

The first question requiring attention in force data collection was "where to collect the data?" Ideally, multiplanar strain gauging of the pedals as has been previously described (Hoes, et al., 1968; Sjogaard, 1978; Soden, 1979; Cavanagh and Nordeen, 1979, among others) would maximize the information but introduce a minimum of six information channels that must be transmitted directly from the pedals. This would prove to be an impossible feat in the untethered bicycle without significant introduction of telemetry module mass to the pedal or encumbering wire connections attached to the riders leg because slip ring connectors from the pedal to crank and subsequently from crank to bicycle frame are so subject to vibration and road grime related interference. One alternative to instrumenting the pedals was to accept that torque generated in the crank arms is related to bicycle velocity and thus the most important resultant of forces applied to the pedal. This has the advantages of requiring only uniaxial strain-gauging and reducing the mathematical treatment required to separate rotational force normal to the crank arm from those in the other two planes while minimizing the technical difficulty of transmitting data. It has since been suggested that an alternative site to apply this rationale would be the spokes on the front chain ring in order to measure simultaneously from one location the combined forces from both cranks. Such an approach would avoid some wiring problems but not allow separate considerations of forces in each crank; a process which is important to skill development. On the negative side of the ledger through instrumenting only the crank arms is the loss of ability to assess the efficiency of rider skill in translating limb forces to the crank-arm. As this latter objective could be accomplished by the more conventional electronic tethering of pedals in

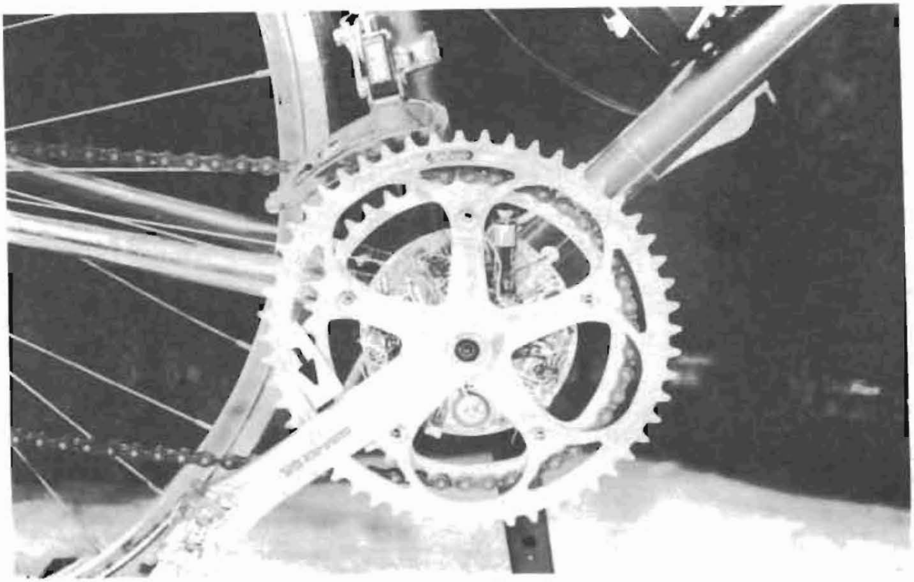


Figure 1. Instrumented crank and chain ring with one foil strain-gauge indicated by an arrow.

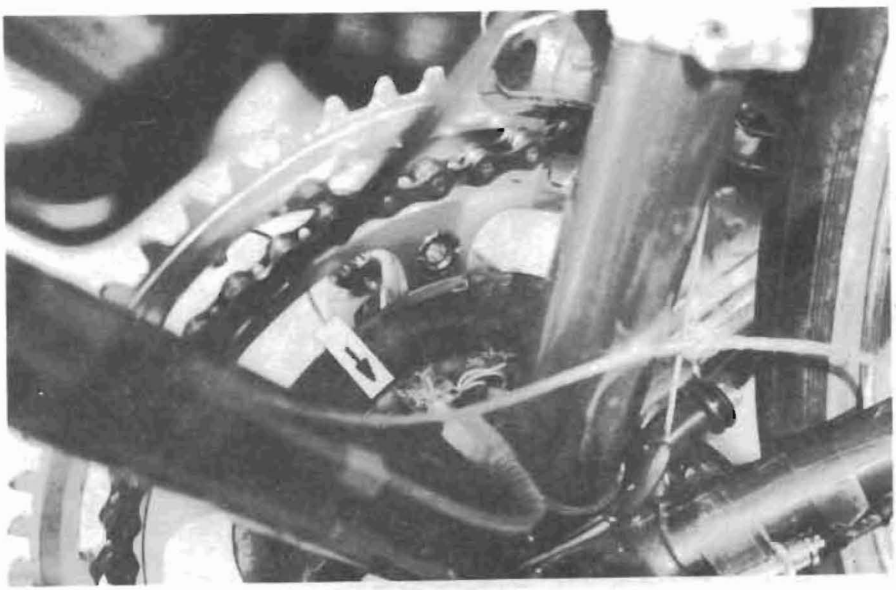


Figure 2. Frame mounted antenna (indicated by arrow) separated from chain ring electronics by a 4 mm gap.

the laboratory, and because losses in force transmission from the crank to the rear wheel are largely equipment related rather than subject related, the crank arm was selected as the site for force data collection. Interpretation of these data from both crank arms required an additional information channel with which to indicate crank position and, together with force data, were the first variables to be the objects of instrumentation.

DATA COLLECTION

Having selected force and crank position for instrumentation left the problem of how to record the resulting data. The extensive effort already expended in developing a strain-gauge, analog to frequency conversion, FM transmission, demodulation, microcomputer treatment and storage system for application to paddling events as will be described later at this conference made the prospect of applying the same technology to the bicycle very attractive. However, while this system might be tenable for track or short course events, our experience with the combination of the demodulator's requirement for clean signals with the effects of radio interference provided by the varied and obstructed terrain associated with road racing precluded the selection of telemetry technology. The remaining alternative involved recording apparatus to be carried on-board the bicycle and this approach was pursued.

It was at this point that our appreciation for the extent of sophistication to which the construction of cycling equipment has advanced became intensified. Up to this time we had been working in grams of weight addition in the form of strain-gauges, integrated circuits and high density storage batteries which could be added to the main crank and chain ring; an exotic alloy assembly on which many hundreds of dollars are spent to reduce the rotational forces required and the weight added to that of the bicycle to give totals considerably less than 8 to 10 Kg. Equally sophisticated data recorders may, complete with batteries, themselves add a Kg or more and thus not be readily acceptable to competitive riders whose racing status must be maintained throughout many events in a season. This was a perplexing problem given the alternative of employing the inadequacy of slip-ring technology to conduct the signals to a frame mounted, but heavy recorder. The solution lay in combining telemetry technology with rapidly increasing sophistication of personal "walkman" type stereo systems through the initiative and ingenuity of a radio frequency engineer who became interested in our project.

The approach finally adopted was to use the voltage output of two opposing crank mounted strain-gauges energized by electronics housed on the main chain ring (figure 1) to modulate a precision voltage to frequency converter which generates a pulse train for transmission across a 4 mm distance from the chain ring to an antenna mounted on the bottom bracket (figure 2). The pulse train is registered as a triangular wave at about 80 kHz (figure 3). This method reduces harmonic contamination which could interfere with the 16.5 kHz timing track recorded from the frame mounted electronics and facilitates frequency multiplexing of additional channels. The signal is then divided by a factor of 10 to 8 kHz which allows a wide deviation in frequency for adequate resolution of force and accommodates the band width of the recorder. The 8 kHz wave is truncated to approximate a sine wave for FM recording on the frame mounted recorder, minimizing harmonics, intermodulation and cross-modulation products. The

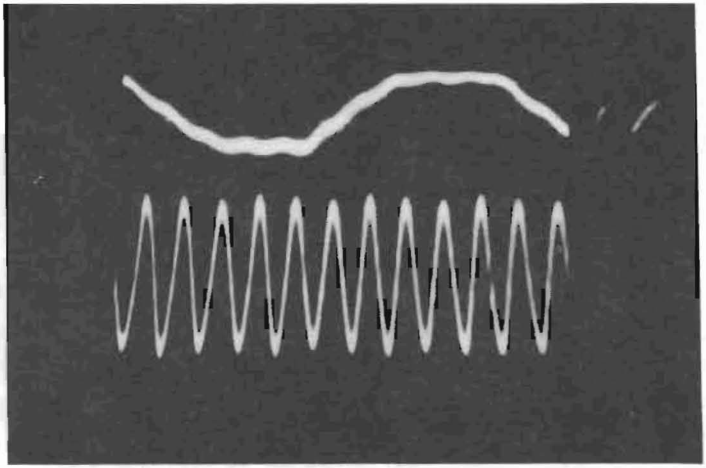
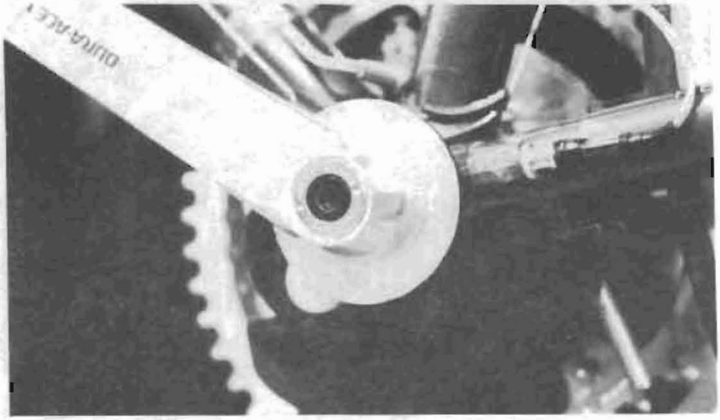
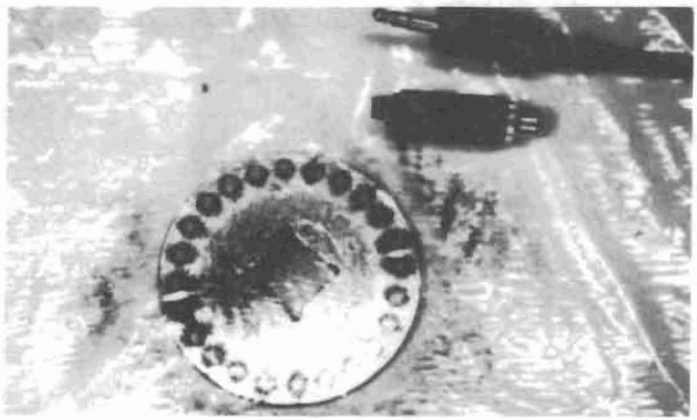


Figure 3. Oscilloscope recording of the 80 Hz triangular wave (lower curve) which is transmitted as an FM multiplex signal and the 8 kHz truncated sine wave which is recorded (upper wave).

Figure 4. Frame mounted electronics housed in a standard water bottle and the FM recorder; total weight = 620 gms.



(a)



(b)

Figure 5. (a) Position indicator and sensor mounted on the alternate crank.

(b) Magnets mounted in the position indicator identified by dusting with iron filings.

recorded signal can deviate over a 3 kHz range which is well within the 16 kHz expanded range of the "walkman" recorder chosen (Sony Corp.). The entire data collection package of about 620 gms (figure 4) is about equal in weight to the full water bottle which is replaced by the housing for frame mounted electronics.

Another circuit similar to that employed for generating the recorded signal serves to convert the signals back to an analog format for direct data access during laboratory centered riding where the bike is operated in series with a Monark ergometer for control of resistance loading. Position of the crank arm is recorded on a second FM channel as pulses generated in a frame mounted switch by 24 magnets mounted radially at 15^0 intervals on the alternate crank (figure 5).

The net result of this instrumentation in its current form is that up to one hour of force and crank position data from one crank can be recorded during competition. Pilot work is currently being carried out to assess the efficacy of this system and to provide the data on which to base modification of the computer treatment programs which are described in the context of the paper on our system for measuring paddling performance. In brief, the recorded signal is sampled at 100 to 200 kHz, digitized and entered into the expanded RAM of an Apple IIe microcomputer for floppy diskette, hard disk or mainframe storage and subsequent generation of rate of change in force (df/dt), time to peak force, peak force, duration and impulse ($\int_0^t \Sigma f_x dt$) values as well as intercrank comparisons. The multiplexing characteristic of the radio frequency data link will allow the addition of force values from the second crank for intercrank comparison as well as velocity, accelerometer and heart rate information when the major data collection and treatment problems have been solved. Current recordings are limited to 60 min. but the recorder is modifiable to one-half speed with auto-reversing to give a 4 hour total recording time.

The data specifications include a linearity of better than 0.01% with force discrimination intervals of 100 gms from peak to peak modulation of ±6 mV and signal resolution of 7 bits (128 data points). This provides a total work rate discrimination of from 5 watts at a pedaling frequency of 50 rpm to 11.5 watts at 120 rpm which is well below increments of work rate that are employed in the laboratory. Figure 6 shows the nature of the force curves in analog form as recorded directly from pre-recorder circuitry on a strip chart.

As will be described in our subsequent papers, analog to digital conversion and high and low pass filtration combined with five point averaging allows an effective sampling rate of 1msec or 1000 Hz. This rate is more than adequate for measurement employing the compliance characteristics of human powered rigid systems like the bicycle.

In summary, the purpose of this project was to develop technology which would allow untethered field collection of motion, force and physiological data for the quantification and qualification of competitive road cycling events. Completion of the first phase employs a strain-gauge voltage output from one crank to modulate a voltage to frequency converter for generation of a pulse train which is registered as a triangular wave and transmitted at 80 Hz, divided by 8 Hz, truncated to a sine wave and recorded on a wide band FM recorder. Conventional microcomputer centered analog

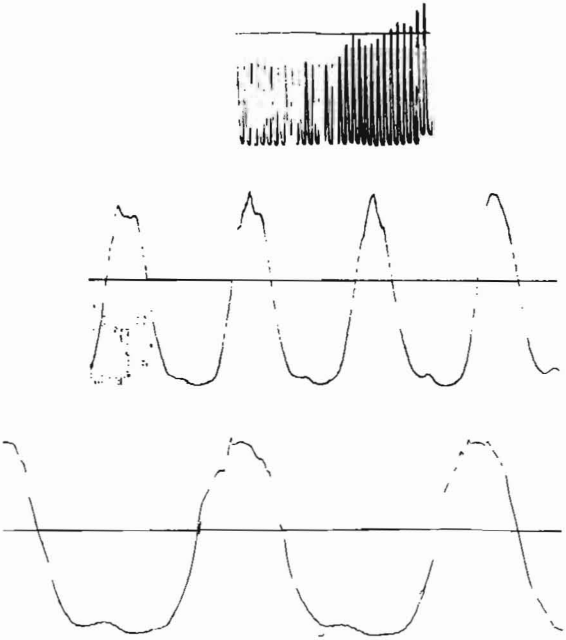


Figure 6. Crank-force traces recorded at 0.25,5 and 10 cm sec^{-1}.

to digital conversion and treatment provides force and position curves from which crank arm kinetics and work rates can be calculated. The second phase of this project will involve the addition of data from the second crank as well as velocity, acceleration, and heart-rate signals.

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± Technical work by T. Mousseau, R. Fournier, A. Gadouas.

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