# HUMAN POWER

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# HUMAN POWER

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## IN THIS ISSUE

**The phantom trailer**

Andreas Könekamp tackles the problem of the occasional heavy demands that are made on family bicyclists and that could result in them giving up bicycling altogether. He applies the creative concept of designing a "smart" trailer containing a battery, motor and transmission, and controls that add motor torque only when needed.

**Measuring drive-train efficiency**

Angus Cameron wanted to find out what the efficiency of his bicycle transmission was, but realized that a full dynamic test involves very accurate instrumentation and expensive rig components. On the other hand, he saw that a static test would be within reach of most enterprising bicyclists, and virtually all high-school science labs. He shows data from his own experiments that are both believable and mind-opening.

**Predicting wheel dish from hubs**

One would think that wheel "dish" or lateral eccentricity would increase with increase in the number of chain cogs in the cluster. Vernon Forbes shows that while this is generally true, there are many exceptions. He produces graphs showing how a number he calls the "dish ratio" is related to other hub variables, and provides guidelines helpful in the design of new wheels.

**A bicycle with auxiliary hand power**

Many inventors in the past have produced bicycles that could be powered by hands and feet simultaneously. Duhane Lam and his co-authors believed that these predecessors all had fatal flaws. They have produced a bicycle with interesting and valuable characteristics. We'll be interested to learn the views of our readers.

### TECHNICAL NOTES

**Follow-ups to "Lower-extremity output in recumbent cycling"**

Authors R. F. Reiser and M. L. Peterson report an error made in their paper in the last issue of HP in their interpretation of data of Danny Too. Their paper stimulated much interest in Too's work, and Danny Too responded by reviewing many of his papers and answering questions of correspondents. He has kindly given us permission to publish all of these reviews and responses.

**Drag of two bodies in tandem and side-by-side**

Jim Papadopoulos and Mark Drela discuss, interpret and analyze drag data on the interference drag produced by two bodies (e.g., two vehicles or riders or frame tubes) close to one another and spaced laterally or in the line of travel, given in Hoerner's famous text on fluid-dynamic drag—a very erudite and informative note.

**IHPVA record wind rules: a participant's perspective**

Paul Buttemer, in the midst of setting some remarkable new long-distance HPV records, sent in these recommendations for changes in the rules for permissible wind speeds for records to be recognized.

### LETTERS

Wayne Estes comments on wind resistance as it relates to pedaling *vs.* coasting.

### EDITORIALS

**An appreciation of the life of Gunter Rochelt**

A note of appreciation is made for Gunter Rochelt, who accomplished amazing feats with the aid of his family and other team members, with the human-powered aircraft he designed and built. Sadly, he died in 1998.

**Human-Power numbering and indexing**

Volunteers are indexing Human Power, and we have taken the opportunity to change the often-irrational volume-plus-issue system by which past contributions were identified. We have gone to a simpler issue-number system. A conversion table is given.

### CONTRIBUTIONS TO *HUMAN POWER*

The editor and associate editors (you may choose with whom to correspond) welcome contributions to *Human Power*. They should be of long-term technical interest (notices and reports of meetings, results of races and record attempts, and articles in the style of "Building my HPV" should be sent to *HPV News*). Contributions should also be understandable by any English-speaker in any part of the world: units should be in S.I. (with local units optional), and the use of local expressions such as "two-by-fours" should be either avoided or explained. Ask the editor for the contributor's guide. Many contributions are sent out for review by specialists. Alas! We are poor and cannot pay for contributions. They are, however, extremely valuable for the growth of the human-power movement. Contributions include papers, articles, reviews and letters. We welcome all types of contributions, from IHPVA-affiliate members and nonmembers.

## CORRECTION

Correction to: Reiser, R. F. & Peterson, M. L. (1998). Lower-extremity power output in recumbent cycling: a literature review. *Human Power* 45, pp. 6–13.

While reviewing Too (1994), the authors noticed an error. In this study cyclists were tested for anaerobic power output in three different recumbent positions, all with a body configuration of 105°. The torso angles, as determined by the backrest angle, were at 60, 90, and 120° with the hip orientations at −15, 15, and 45°, respectively (fig. 6). This was reported correctly in the review article. However, the power-output results were switched between the 60 and 120° torso-angle positions. The results then indicated that power output was similar for the two positions with the hips elevated above the bottom bracket and significantly greater than the power output in the position with the hips located below the bottom bracket (table 2). This led Too to conclude that the effects of gravity do play a small role in anaerobic power output with these effects increasing when the hips are below the pedals. This low hip position results in gravity pulling the legs away from the pedals during the power stroke portion of the pedal cycle. Gravity then assists the legs during the recovery phase, opposite of the effects of gravity when the hips are above the bottom bracket. This could place slightly different loads on the working musculature, causing the differences in power output between the positions tested.

Since the gravitational effects on a cyclic activity sum to zero (what is gained in one phase of the activity from gravity is then lost in a different phase) and the peak-power output is measured when the working musculature is in a non-fatigued state (minimizing the effects of slightly altering the loads on the musculature), there may be other factors involved that produce these significant differences in power output. One possible interaction that might cause differences in power output between a position with the hips above the bottom bracket and one below is in the foot-to-pedal interface. Toe clips, as were used in this study, have been shown to be a relatively sloppy interface (see foot-to-pedal interface articles referenced in the review article). The problems with the toe clips could be increased when the hips are below the bottom bracket, placing the foot effectively underneath the pedal during the entire pedal stroke. With the foot underneath the pedal, the toe clip may not provide adequate support to the foot-to-pedal interface which would result in reduced power output.

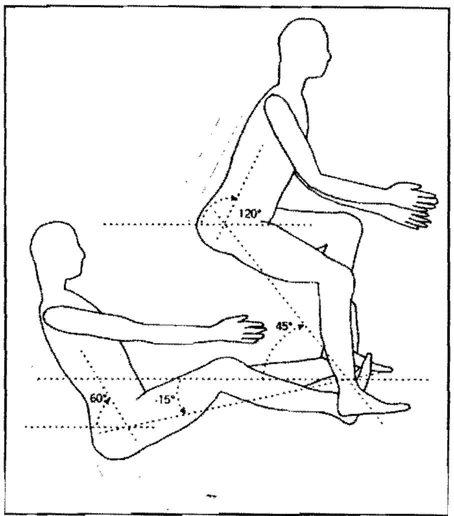


Figure 6. Range of test positions utilized by Too (1994): hip orientation of −15 to 45° in 30° increments. The torso angle was adjusted with hip orientation from 60 to 120° in order to maintain a 105° body configuration.

The numerous possibilities for why the cycling position with the hips below the bottom bracket are less powerful than the hips-above positions demonstrate how complex the system is that we are trying to understand. It also shows the need for more research in this area so that improvements may be made in the area of human-powered vehicles.

Additionally, hip orientation was referenced by Too based on seat-tube angle which is slightly different than the line between the hip joint and the bottom bracket. However, these two methods to determine hip-to-pedal orientation should be very similar (within a couple of degrees).

Also, since publication it has come to our attention that the speed record in the conventional riding position is above 50 mph. The current record of 51.29 mph was set by Jim Glover in a fully-faired Moulton AM7 at the 3rd IHPV Scientific Symposium in Vancouver [Expo 86 IHPSC] on 29 August 1986. Apologies to Jim and all the people who worked on that project.

**Table 2 (corrected)**

| | | | |
|---|---|---|---|
| **Hip orientation** (degrees) | −15 | 15 | 45 |
| **Torso angle** (degrees) | 60 | 90 | 120 |
| **Body configuration** (degrees) | 105 | 105 | 105 |
| **Peak power** (W/kg BM) | 11.68 | 12.29 | 12.14 |
| **Average power** (W/kg BM) | 8.73 | 9.27 | 9.00 |
| **Fatigue index** (%) | 46.1 | 44.3 | 46.0 |

## TECHNICAL NOTES

### SUMMARIES OF PAPERS
***by Danny Too***

*(Editor's note: These summaries were given by Danny Too on the hpv mailing list after Raoul Reiser and M. L. Peterson had discussed some of his papers in our last issue. He kindly agreed to these summaries being reproduced here. We are repeating figure 1 from the paper by Reiser and Peterson, p. 6, to illustrate the various angles that are referenced. —Dave Wilson)*

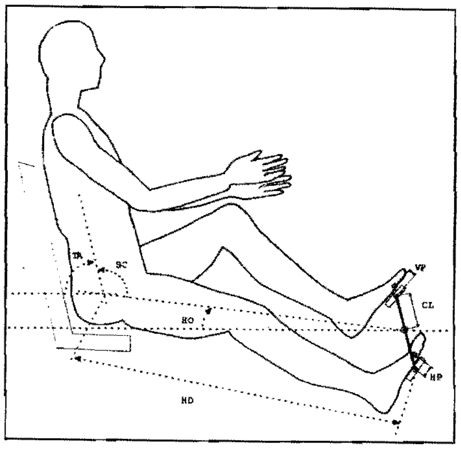


Figure 1. Geometrical variables which must be defined to completely describe the cycling position of the rider: hip orientation (HO), torso angle (TA), hip distance (HD), crank-arm length (CL), and horizontal (HP) and vertical (VP) foot position, as well as the foot-to-pedal interface (not shown). Body configuration (BC), which may be deduced from TA and HO is also included to help describe the cycling position.

**Too, D. (1990).** The effect of body configuration on cycling performance. In E. Kreighbaum & McNeill (eds.), *Biomechanics in Sports VI* (pp. 51–58). Montana State University, Bozeman, Montana.

This study examined the effects of changes in hip angle (while keeping the knee and ankle angles the same) on cycling duration and work output. Hip angles were manipulated by a systematic change in seat-tube angle (as determined from a vertical line passing through the crank spindle). Five seat-tube angles were examined: 0, 25, 50, 75, and 100 degrees. For each seat-tube angle tested, the trunk was always kept perpendicular to the ground, and the seat-to-pedal distance adjusted to maintain the same distance. Sixteen subjects were tested in each of the five seat-tube angles. The tests were on a Monark bicycle ergometer, with increasing load or cadence every three minutes until exhaustion. The results revealed a parabolic curve in cycling duration with changes in seat-tube angle from 0 to 100 degrees. The longest duration occurred with the 75-degree seat-tube angle and the trunk perpendicular to the ground. This same result was found regardless of whether a trained cyclist, triathlete, or untrained subject was tested. This corresponded to a minimum hip angle of 56.5 degrees and a maximum hip angle of 97 degrees during one pedal cycle. It may not be the seat-tube angle that is as important as the joint angles. Changes in joint angles affects muscle length and other variables that interact to produce force and power. Changing the seat-tube angle changed the minimum and maximum hip angle during a pedal cycle, but did not change the range of motion.

This changes where the fatigue is felt. In an upright position (e.g., seat-tube angle of 25 degrees), the stress occurs more on the quadriceps. In a very low sitting recumbent position (e.g., seat-tube angle of 100 degrees), the stress occurs more on the gluteal (buttocks) region. The 75-degree seat-tube angle apparently distributes the stresses more evenly over the quadriceps, hamstrings, and gluteal region, thereby reducing local fatigue in any particular muscle group (which may be one of the limiting factors to prolonged cycling performance). A change in seat-tube angle apparently changes the points at which the various muscle groups are active and inactive during a pedaling cycle (although there is no change in the pattern or duration of activation). This was based on another study I had published (titled: The effect of hip position/configuration on EMG patterns in cycling). This has major implications regarding efficiency and force and power generation.

**Conclusion**: the optimal mean hip angle that maximizes cycling duration and total work output with incrementing workload is 77 degrees, with a minimum of 57 degrees, a maximum of 97 degrees, and a hip range of motion of 41 degrees. This was found with a seat-tube angle of 75 degrees with the trunk perpendicular to the ground, and a seat-to-pedal distance of 100% of leg length (as measured from a standing position from the greater trochanter to the ground).

**Too, D. (1991).** The effect of hip position/configuration on anaerobic power and capacity in cycling. *International Journal of Sports Biomechanics*, 7(4), pp. 359–370.

This study was, in essence, the same as the previous one (summarized above). The difference was that testing was done anaerobically (with a 30-second all-out power test, using a resistance based on body mass) instead of aerobically. This information is more appropriate for those constructing HPVs to set new speed records, as opposed to distance/endurance records.

The purpose of this investigation was to determine the effect of systematic changes in hip position/configuration, while maintaining an upright trunk orientation, on cycling peak anaerobic power and anaerobic capacity. Fourteen male recreational cyclists (age 21–32) were each tested in four hip positions (25, 50, 75, and 100 degrees), as defined by the angle formed by the seat tube and a vertical line. Rotating the seat to maintain a backrest perpendicular to the ground induced a systematic decrease in hip angle from the 25- to the 100-degree position. The Wingate Anaerobic Cycling Test was used on a Monark Cycle ergometer with a resistance of 85 gm/kg of the subjects' body mass (5.0 joules/pedal rev/kg BM).

Repeated measures MANOVAs* and post-hoc tests revealed that (1) anaerobic power (AP) and anaerobic capacity (AC) in the 75-degree hip position was significantly greater than that in the 25- or 100-degree position ($p < .01$); and (2) a second-order function best describes the trend in AP and AC with changes in hip position ($p < .01$).

It was concluded that there is/are some hip position(s)/angle(s) that will maximize cycling performance as determined by AP and AC and that an intermediate position (50–75 degrees) produces the greatest power. To fully address the issues in this area require further research involving a series of investigations where selected body position, configuration, and orientation variables are systematically manipulated.

*MANOVA – Multiple Analysis of Variance (used when comparing 3 or more groups and there is more than one measured/dependent variable [e.g., peak power output and average power output])

In summary, the same parabolic trend was also found for anaerobic cycling performance. The 75-degree seat-tube angle resulted in the largest peak power (during any 5-second interval) and the largest average power over the 30-second test. This was true whether a trained cyclist was used or an untrained subject. The 0-degree seat-tube angle was not used because subjects were unable to complete the test with the load selected.

**Too, D. (1994).** The effect of body orientation on power production in cycling. *The Research Quarterly for Exercise and Sport*, 65, 308–315.

This study, based on the results obtained from the paper just summarized on anaerobic power and capacity, was a continuation to determine the most effective cycling position to maximize power production. Since a 75-degree seat-tube angle (with the trunk perpendicular to the ground – 90 degrees) apparently resulted in the largest peak and mean power, this seating position was selected. The purpose of this study was to manipulate the trunk orientation relative to the ground while maintaining the same 75-degree seat-tube angle, and maintaining the same hip, knee, and ankle angles. To accomplish this, the entire cycling apparatus was rotated forward 30 degrees to obtain a trunk angle 60 degrees to the ground, and rotated backwards 30 degrees to obtain a trunk angle 120 degrees to the ground. Differences in cycling performance between the 60, 90, and 120 degree trunk angle can be attributed only to differences in trunk angles and not to changes in hip, knee, or ankle angles. This was a major flaw in the following two studies:

"The influence of body position on maximal performance in cycling.", Welbergen E. and Clijsen L.P.

"The effect of posture on the responses to cycle ergometer exercise." Begemann-Meijer M.J. and Binkhorst, R.A.

These two studies did not control for joint-angle changes when seating position or trunk angles were changed. Therefore, it is unknown whether differences in cycling performance (if differences were found) were attributed to changes in the seating position, joint angles, trunk orientation, or an interaction of all of these variables.

## ABSTRACT

The purpose of this investigation was to determine the effect of three different trunk angles (60, 90, and 120 degrees relative to the ground) on power production of 16 male recreational cyclists (age 20–36) when the hip, knee, and ankle angles were controlled. Wingate anaerobic tests were performed on a modified Monark cycle ergometer against a resistance of 85 g/kg of the subjects' body mass (5.0 J/crank rev/kg BM). The order of test conditions was randomly assigned, with a minimum of 24 hours between sessions. A DM MANOVA and post-hoc tests revealed that peak power at the 60- and 90-degree trunk angle was significantly greater than that at the 120-degree angle, and mean power in the 90-degree angle was significantly greater than that at the 120-degree angle. It was concluded that changes in cycling trunk angle may affect peak power and mean power.

The results of this study would suggest that, although a reclining position (120-degree trunk angle) may be more comfortable, it is not effective in power production. The reason? A reclining position where the feet are above the hips forces the cyclist to overcome not just the ergometer resistance, but also the weight of the legs. An analogy to this would be to cycle in an completely inverted position. In this position, it would be more effective to pull on the pedals, using gravity and the weight of one's legs (than to push against the pedals to overcome the leg weight and gravity). A neutral position (90-degree trunk angle to the ground) or one where the leg weight assists in pushing the pedals (60-degree trunk angle) would be more effective than a position where one has to overcome gravity. This clearly explains why recumbents (especially those where the pedals are above the hips) are not effective in climbing hills.

This study dealt with peak power production in a 30-second test because another study that I had conducted aerobically (cycling duration) with the same three trunk angles revealed no significant difference between all three angles. An EMG study, examining possible differences in muscle activity patterns with these three trunk angles revealed no differences in muscle timing, patterns, or duration among these three trunk angles. Unfortunately, quantitative data were not available, and may have supported the "overcoming leg weight" explanation of why the 120-degree trunk angle was less effective.

**Too, D. (1994).** The effect of body position/configuration and orientation on power output. In C. R. Kyle, J. A. Seay, & J. S. Kyle (eds.), *Fourth International Human Powered Vehicle Scientific Symposium Proceedings* (pp. 59–65). Cycling Research Association, Weed, CA.

This study is really a compilation and presentation of the data from the previous two studies on manipulation of seat-tube angle (presented as experiment 1) and manipulation of trunk angle (presented as experiment 2). See the preceding two summaries for the results and discussion.

**Too, D. (1996).** Comparison of joint angle and power production during upright and recumbent cycle ergometry. In J. A. Hoffer, A. Chapman, J. J. Eng, A. Hodgson, T. E. Milner, & D. Sanderson (eds.) *Proceedings of the Ninth Biennial Conference and Symposia of the Canadian Society for Biomechanics* (pp. 184–185). Simon Fraser University, Burnaby, British Columbia, Canada.

This study compared the 75-degree seat-tube-angle recumbent-cycling position with the standard upright-cycle ergometer position. Hip, knee, and ankle angles were compared; as was peak power and average power during the 30-second power test. All subjects were tested in both the recumbent and upright positions. The load selected was based on each subject's body mass. The recumbent position was found to result in significantly greater absolute and relative power (relative to body mass) in peak power and average power, when compared to the upright position. Only the minimum and maximum hip angles between the upright and recumbent positions were significantly different. There were no significant differences in the minimum, maximum, and range of motion of the knee and angle between the recumbent and upright position. This would suggest that differences in power production between the upright and recumbent positions were attributed to differences in hip angles.

**Too, D. (1998).** Comparisons between upright and recumbent cycle ergometry with changes in crank-arm length. *Medicine and Science in Sports and Exercise*, Vol 30, No 5, S81 (Abstract).

This study is a continuation of the preceding study, comparing the upright and recumbent position, but also manipulating crank-arm length. The crank-arm lengths examined were 110, 145, 180, 230, and 265 mm.

This investigation was: (1) to compare power production between an upright (UP) and recumbent (REC) cycling position with changes in crank-arm length (CL); and (2) to examine how joint angles (JA) change. Six male subjects (ages 24–35) were all randomly tested on a Monark bicycle ergometer (Model 814E) at 5 CL (110, 145, 180, 230, 265 mm) in an UP and REC position. For each CL in the UP and REC, the seat-to-pedal distance was standardized, the subjects' trunk kept perpendicular to the ground and pedal toe-clips worn. A 30-second Wingate anaerobic cycling test was used, with a resistance of 85 gm/kg of each subject's body mass (5.0 joules/pedal rev/kg BM) and at least 24 hours between tests. In each condition, JA for the hip, knee, and ankle for one pedal revolution were measured. Peak power (PP) and mean power (MP) were determined by a SMI Power Program for 5 and 30 sec, respectively. The mean JA, PP, and MP in the UP and REC position with changes in CL are as follows (see table on following page).

With increasing CL, there is: (1) a decrease in mean JA; with the JA for the REC less than for the UP; (2) a curvilinear trend for PP and MP in the UP; and (3) a decreasing and a curvilinear trend for PP and MP, respectively, in the REC. Paired t-tests between UP and REC with increasing CL revealed: (1) $p = 0.04$, 0.005, 0.001, 0.017, 0.099 for PP; and (2) $p = 0.018$, 0.026, 0.019, 0.019, 0.021 for MP. The data and results suggest that greater PP and MP in the REC position may be attributed to a more effective JA.

In summary, the recumbent position resulted in significantly higher mean power output with all five crank-arm lengths when compared to the upright position; and the recumbent position resulted in significantly higher peak power with all crank-arm lengths other than the 265 mm, when compared to the upright. Although this study revealed the highest peak power occurring with the shortest crank-arm length (110 mm), ergometer flywheel acceleration and deceleration was not accounted for (and if it was, slightly different results would be found).

The interaction between crank-arm lengths and cycling performance is much

**Danny Too: Table showing differences depending on crankarm length (CL)**

| CL (mm) | 110 | 145 | 180 | 230 | 265 |
|---|---|---|---|---|---|
| | hip/knee/ank | hip/knee/ank | hip/knee/ank | hip/knee/ank | hip/knee/ank |
| **UP (deg)** | 142/124/111 | 137/119/107 | 134/113/108 | 130/109/106 | 123/105/112 |
| **REC (deg)** | 80/115/100 | 80/109/96 | 77/105/94 | 75/95/93 | 73/94/91 |
| **POWER** | PP / MP | PP / MP | PP / MP | PP / MP | PP / MP |
| **UP (W)** | 880 / 546 | 913 / 690 | 949 / 741 | 859 / 697 | 843 / 683 |
| **REC (W)** | 1123 / 757 | 1103 / 786 | 1093 / 806 | 979 / 772 | 896 / 748 |

more complex, since changes in crank-arm length affect not only hip angles, but also knee angles. There are also other variables and factors to consider, including the interaction between muscle force-length, and force-velocity-power relationships; since there apparently is an interaction between crank-arm length, load, and cadence.

Currently I have two papers related to crank-arm length in review for publication:

1. Too, D., & Landwer, G. The effect of pedal crankarm length on joint angle and power production in upright-cycle ergometry. Submitted to *Journal of Sport Sciences*.
2. Too, D. The effect of pedal crankarm length on joint angle and power production in recumbent-cycle ergometry. Submitted to *Ergonomics*.

I am currently analyzing data for a paper, comparing the power production between an upright and recumbent position with changes in crank-arm length. The same subjects were used for all test conditions in the upright and recumbent.

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## DANNY TOO RESPONDS TO QUESTIONS

*(Danny Too responded to some questions on aspects of his papers, and was gracious enough to allow us to publish them. Questions are shortened in several cases. —Dave Wilson)*

**Question**: John Riley (j.riley16@genie.com) wrote: "Out in the real world things get very complex and with unfaired bikes, people manipulate the position to get better aerodynamics. That said, the Tour Easy and Rans Stratus come close to matching your optimum position and they do have a reputation for good performance. The BikeE is also close, but does not have a good reputation for performance. The BikeE does apparently perform better when the rider hunches forward, and I think the rider also hunches forward in the fully faired Tour Easys that have won so many races. Your optimal position seems to have a riding angle (angle formed by a line from the BB to the seat base and a line up the seat back) of 115 degrees. Perhaps a slightly tighter riding angle, with the BB still below the seat, might be even better, especially for anaerobic work. The tighter riding angle can constrict the lungs and so might not be best for aerobic work."

**Danny Too**: There are many factors that affect cycling performance.

A cycling position that maximizes power production and cycling effectiveness, but also happens to maximize aerodynamic drag, may not necessarily maximize cycling performance (as defined by maximal velocity or minimal time to cover a pre-set distance). The optimal cycling position may very well result in a trade-off between the two. Rider conditioning and training in any given position will also be a factor.

But I would speculate that recumbents with similar cycling positions will not necessarily result in similar cycling joint angles and kinematics during a pedaling cycle. This would explain why different recumbents with similar cycling positions may not result in identical cycling performance. This would also explain why "hunching forward" in certain vehicles may improve performance. This "hunching forward", probably results in more effective hip and knee angles in the production of force. Recumbent cycling positions are as exclusive and diverse in trunk angles, joint angles, seat-tube angles, and crank-arm lengths as the vehicles themselves (and the people who design them). This, I believe, is what makes comparisons among recumbents very difficult. Each recumbent vehicle available on the market is unique in some fashion, and it is the interaction of a multiple of variables (trunk angle, joint angles, etc.) that ultimately results in performance. Therefore, to compare different recumbent vehicles is like comparing apples with oranges.

What I have attempted to do in my research is to eliminate all these interactions and confounding variables by systematically manipulating one variable while controlling for all the others. This, then, provides objective information regarding trends and patterns with extreme manipulations in crank-arm lengths, seat-tube angles, joint angles, trunk angles, etc.

**Question**: Cyril Rokui (croku@juno.com) wrote: "Thanks very much for the summary of your papers. I found it to be very interesting reading and may incorporate some of the findings in future bikes I intend to build. Have you done longer-duration (30 minutes or one hour) crank-arm-length studies that would simulate a bike ride rather than a very short test just for peak power? Also, I notice that mean power output is highest in the recumbent position for the 180-mm cranks and this was for 30 seconds vs. the 110-mm cranks at 5 seconds for the peak-power measurement. Does this mean that the 180-mm cranks are more efficient for long-term production of power?"

**Danny Too**: No, I have not examined longer-duration (30 minutes or 1 hour) studies with changes in crank-arm length. It may simulate a bike ride, but subject motivation would probably be a confounding variable affecting the results, and it would also be difficult to obtain subjects who would be willing to participate in such a study. However, I have collected data examining the effect of incrementing workload on cycling duration with changes in crank-arm length. I have not yet had the time to analyze the data.

First, a correction for flywheel acceleration and deceleration was not accounted for in that abstract. In the full manuscript (submitted to *Ergonomics*), this correction has been made and results in the 145-mm crank-arm length producing the highest 5-second power. Second, mean power, being highest for the 30-second test, would suggest that they are more efficient for long-term power. However, it is more complex than that. There appears to be an interaction between crank-arm length, pedaling rate and workload/resistance. When fatigue sets in (15 seconds into the 30-second test), pedaling rate starts to decrease. When pedaling rate is least during the last 5 seconds, the crank-arm length that results in the largest minimal power is the 230-mm crank-arm length. The 180-mm crank-arm length