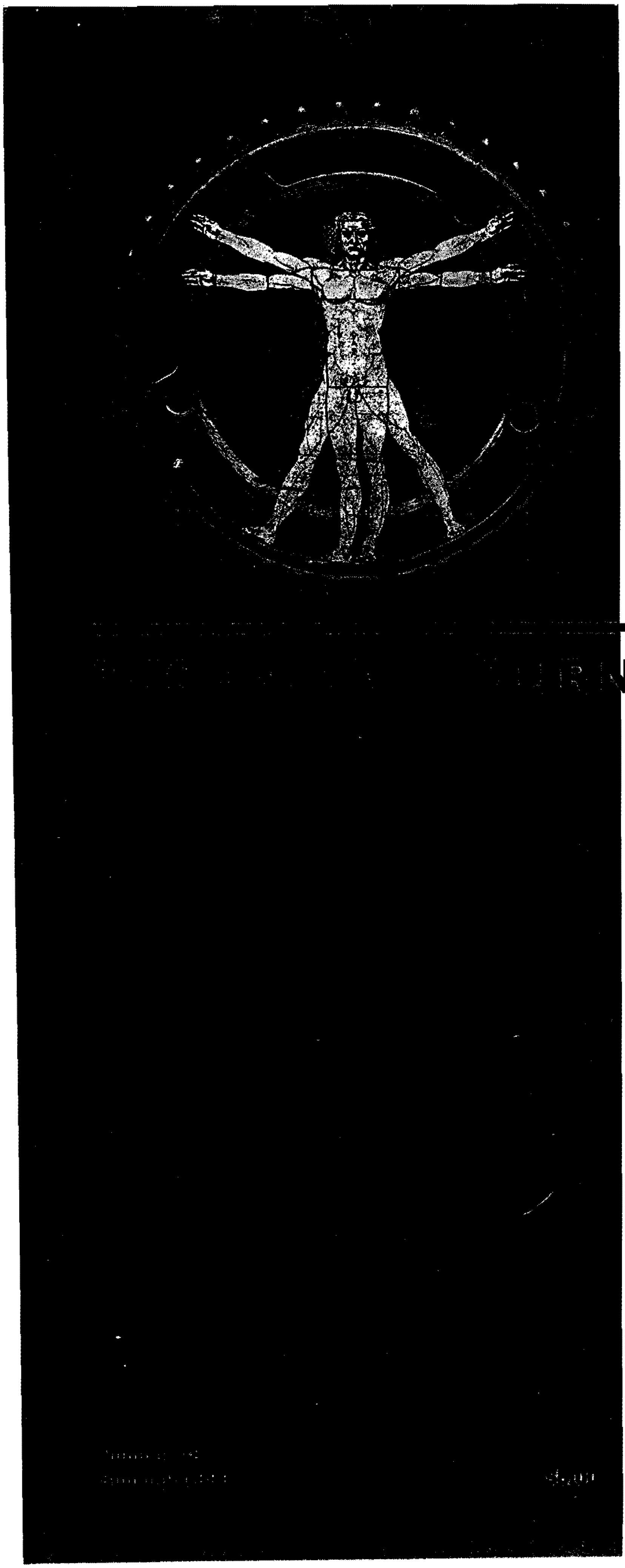
7-1-1999

Crank-arm Length

Danny Too
The College at Brockport, dtoo@brockport.edu



HUMAN POWER

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Editor
David Gordon Wilson
21 Winthrop Street
Winchester, MA 01890-2851 USA
dgwilson@mediaone.net

Associate editors
Toshio Kataoka, Japan
1-7-2-818 Hiranomiya-Machi
Hirano-ku, Osaka-shi, Japan 547-0046
HQI04553@niftyserve.ne.jp

Theodor Schmidt, Europe
Ortbühlweg 44
CH-3612 Steffisburg, Switzerland
tschmidt@mus.ch

Philip Thiel, Watercraft
4720 - 7th Avenue, NE
Seattle, WA 98105 USA

Production
JS Design & JW Stephens

IHPVA
Paul MacCready, Honorary president
Theo Schmidt, Switzerland, Chair
Christian Meyer, Germany, Vice-chair,
Jean Seay, USA, Secretary/treasurer

Publisher
IHPVA
PO Box 1307
San Luis Obispo, CA 93406-1307 USA
Phone: +805-545-9003; hp@ihpva.org

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IN THIS ISSUE

Propeller simulation with PropSim
Our IHPVA chair Theo Schmidt explains how he came to write a propeller-simulation program, what one can do with it, and how it works. He does so in a delightfully modest way, but it is a very useful program for all but out-and-out racers, and even then some races have been won with propellers designed with Prop-Sim. Theo makes it available to IHPVA members.

The Bodysail: improved bicycle sailing
There is now general agreement that fully faired HPVs are dangerous in cross-winds. Therefore Péter Sharp's report of the development in Canada of a seemingly huge sail carried high up on an "upright" bicycle and operated safely (though not in streets!) in high winds is stimulating and stunning.

Simple approximations for the effects of tire resistance, wind, weight and slope
Jim Papadopoulos provides rule-of-thumb (but mathematically derived) methods of estimating the effects of changes in the roadway, weather and HPV on speed. The rules often go against accepted beliefs.

MiniCal: an introductory spreadsheet for determination of power use while cycling
John Tetz's treatment of the power equation for vehicle propulsion is the complement to Jim Papadopoulos' approximations that can be used while riding. The spreadsheet MiniCal is used on a computer to generate points or lines or complete plots, often quite beautiful, showing the effects of various changes (in road slope, vehicle conditions, and wind) on the power input required. It is something that would therefore be used in the design stage of a new vehicle or in the analysis of the performance of existing vehicles.

MiniCal itself is not given here, but is available at cost to members as a separately published (and edited) monograph.

Optimum body shapes for bicyclists
Mark Drela, Jim Papadopoulos and Doug Milliken discuss the effects of body shape on bicycling performance in this short technical note.

Aerodynamic advantage from using fewer spokes, and Optimum pilot for a human-powered helicopter
These are two more technical notes by Mark Drela, who produces elegant simple and, for your editor, irresistible models of interesting aspects of HPV performance.

Crank-arm length
Danny Too updates his article in the last issue and gives a great deal of information on the optimum crank length for different circmstances.

A tandem recumbent design
Charles Brown gives sketches of his own tandems and discusses reasons for design choices.

Crashworthiness analysis of ultralight metal structures
This technical note is an abstract of an MIT doctoral thesis by Sigit P. Santosa.

Transmission efficiencies.
Your editor has constructed a technical note from various contributions giving sometimes varying measurements and estimations of the efficiencies of different transmissions.

Review: Chasing ricksaws
Carl Etnier, who is a pedicab driver, reviews an intriguing new book.

Editorials
Your editor has contributed a piece on HPVs, health and spinning. A longer and very interesting guest editorial on non-circular drives is by Dave Larrington, editor of the newsletter of the British Human Power Club.

Letters
Letters are on the effects of pedalling on wind resistance; on bottom-bracket height; on suspension specifications; and on a correction to the new numbering system introduced in the last issue (which becomes issue 47).

The force on the spoke (diameter D) at some radius r, pointing mostly normal to the spoke, is therefore:

$dF = 0.5\ \rho\ [V_n]^2\ C_d\ D\ dr$

(ρ is the air density)

The power required to drive the spoke against this force is $dP = dF\ V_n$

Also,

$dP = \text{horizontal-force} * V + \text{torque} * \omega$

which gives the same result. The bottom line is $dP = 0.5\ \rho\ |V_n|^3\ C_d\ D\ dr$

The quantity $r/R + \cos(\theta)$ relating V and V_n is negative only for a circular region joining the ground-contact point to the hub, [the circle is the set of points where $dP = 0$] and is never less than -1. So leaving it out has little effect on the final result for P.

dP is easily integrated, first over 0..r..R to get the power of one spoke at angle theta, and then averaged over $0..\theta..2\pi$ to determine its typical contribution over the entire wheel revolution.

$2*\pi*P =$

($\int$ from 0 to R) (integral from $0 - 2\ \pi$) $0.5\ \rho\ |V|^3\ [r/R + \cos(\theta)]\ C_d\ D\ dr\ d\theta$

This gives:

$P = 0.5\ \rho\ V^3\ C_d\ A$

where $A = DR$ is the frontal area of spoke. Therefore the average power needed to drive a single spoke around on the wheel is the same as if it were simply held in the breeze at right angles to the flow (e.g., attached upright to the bike frame).

—Mark Drela <drela@orville.mit.edu>
[This was taken, with permission, from some correspondence on the HBS mail list. —Ed.]

CRANK-ARM LENGTH

by Danny Too

Since there has been quite a bit of interest and discussion about crank-arm lengths, and since I referred to my study in the last issue of *Human Power*, I thought I would provide some additional comments.

First, it is very difficult to generalize a specific crank length that would be optimal for everyone, and it is just as difficult to specify an exact crank length that would be optimal for any one person. The reason? There are many factors that would affect the "optimal" crank-arm length to maximize/optimize cycling performance, and there is a complex interaction among these factors. These factors include: height of the person, total leg length, thigh-length-to-leg-length ratio, seat-to-pedal distance, type of recumbent position, load/resistance/gear ratio used, pedalling rate, type of measurement (peak power, average power), training effect or familiarity with a specific crank-arm length, inter-individual variability, and intra-individual variability.

Second, it may not be the crank-arm length that is as important in determining cycling performance as the crank-arm length that optimizes the hip and knee joint angles (which then optimizes muscle lengths) to maximize force and torque to the pedals in cycling performance. For instance, the optimal crank-arm length for one individual 6 ft (1.80 m) tall (who has short legs but a long trunk) may not be optimal for another 6 ft individual (who has long legs but a short trunk). I would suspect that the joint angles (hip, knee, ankle) and joint kinematics during a pedal cycle between the two 6-ft individuals would be different and how/where force, torque, and power are produced (and during which part of the pedal cycle it is produced) would also be different and could have a major effect on cycling performance. By the same token, two 6-ft individuals with the same total leg lengths may have different ratios of the lengths of thigh to lower leg. One individual may have a very long thigh and a very short lower leg, and the other one may have a very short thigh and very long lower leg. Therefore, what is an optimal crank-arm length for one person may not be optimal for another (since the joint angles and kinematics of the hip and knee are probably more important variables to consider than crank-arm length).

Third, on the assumption that a certain crank-arm length is found that maximizes cycling performance on a recumbent for an individual (with a certain height, total leg length, thigh-to-lower-leg-length ratio, etc.), would this crank-arm length also maximize cycling performance for a second individual having the same anthropometric characteristics? The answer could be yes and no. It depends. If the second individual has had significant experience on a recumbent (while the first individual did not) and this second individual consistently trained and cycled with some given crank-arm length, then based on the principle of specificity of training, I would suspect performance to be better with the crank-arm length that the second individual had been training with. Using the "optimal" crank-arm length (found for the first individual) by the second individual would, initially, result in a decrement in performance before there is an adaptation and training effect (and an increase in performance that may surpass that the other crank-arm length originally trained with).

Fourth, there are also inter-individual variability and intra-individual variability in cycling performance. Individuals (even elite cyclists) will vary in performance from one day to another (intra-individual variability) and some individuals will have greater day-to-day variability than others (inter-individual variability). A certain crank-arm length that maximizes performance on one day may result in an increased or decreased performance on another day. Multiple trials would be needed to determine what would be considered to be an average performance value for that particular crank-arm length. This is on the assumption that there is no longer a learning curve or training effect due to repeated trials. The exact same procedure would have be repeated for different crank-arm lengths and statistical analysis undertaken to determine if differences in average performance between different crank-arm lengths are attributed to chance (random performance variability from a day-to-day basis), or truly to differences in crank-arm length. (Note: there are other factors to consider, such as randomizing the crank-arm length experimental conditions and trials). This is obviously a lengthy and tedious process since it becomes a research-oriented project with controls implemented to remove any confounding variable(s) that may affect the results. But controls of this sort would reveal (to the person willing to undertake this task) what is the crank-arm length that would maximize his/her performance for that particular test protocol. There are also other difficulties encountered, such as what crank-arm lengths to examine. Based on my research, 35-mm changes in crank-arm length will clearly (although not always statistically significantly) affect performance. Changes of this magnitude will significantly alter hip and knee angles. However, will there be a difference in cycling performance between cranks that differ by 10 mm (e.g., 170 vs. 180 mm) or 5 mm (e.g., 145 vs. 150 mm) or 2 mm or 1 mm? And will the differences be equally applicable to individuals of different heights and leg lengths? I don't know. There are a lot of questions, but very few answers because very few people are involved in this area of human-powered-vehicle research (especially for recumbents). In addition, if the test protocol involves a maximum-endurance test, or a test for an extended period of time, then motivation becomes a very large and important factor and could confound the results. This is the reason why I have used a 30-second all-out power test for my experiments (since it has been determined to be extremely simple, reliable, consistent, and a robust test with minimal intra-individual variability from day to day. But then the training effect has to be accounted for if the same individual is tested repeatedly over time). To illustrate the effect of motivation on performance, a simple example will be used. If you were to cycle the same route (e.g., 42 km, 26 miles) each day with maximal effort, but on some days you were chased by a fairly large dog for several miles at various parts of the route, I would predict faster/shorter average times during those days being chased (although maximal effort is given on all days). This information was provided by a friend of mine (a "regular" cyclist) who, with his friends, noted that their cycling times were significantly faster on days they were chased by farm dogs in open areas along their route.

Fifth, to add to the confusion, there is an interaction among crank-arm length, pedalling rate, and load/resistance gear ratio. This would suggest that there may not be one optimal crank-arm length that maximizes power production, but several (depending on the load and pedalling rate selected). The optimal crank-arm length to maximize power would be dependent on the load and pedalling rate, and could be one where the maximum pedalling rate is maintained with the largest load that can be applied (without a decrement in maximum pedalling rate). Based on the muscle force-velocity-power relationship, for a given power output, optimal pedalling rate would decrease with increasing load (with a constant crank-arm length). This would suggest that increased loads to maximize power, resulting in a decreased pedal rate, would favour longer crank-arm lengths. For a given power output, it is possible that a shorter crank-arm length with a higher pedalling rate and lower resistance would be equally effective when compared to a longer crank-arm length pedalling at a lower rate (but higher resistance). I have collected data examining these interactions, but have not had the opportunity to crunch and analyze them. I have been too busy making revisions to reviewers' comments to a manuscript submitted to the Journal of Sports Sciences (on how changes in crank-arm length affect power production in upright-cycle ergometry. With the same load, it appears the effects on power production are different in recumbent-cycle ergometry. But this is a paper that is currently in review for publication in *Ergonomics*).

To conclude, and to perhaps, shed some light on the "optimal" crank-arm length to maximize power, I will provide a brief summary of my paper currently in review. In that paper, a recumbent position was used to test crank-arm lengths of 110, 145, 180, 235, and 265 mm. Nineteen untrained males (most have never cycled a recumbent) were each tested in all five crank-arm-length conditions according to a different randomized test sequence for each subject. The test was a 30-second all-out power test with a load of 85 gm/kg of body mass. The results on power production showed a parabolic (inverted U-shape) curve with increment in crank-arm lengths from 110 to 265 mm. Peak power (highest power produced in any five-second interval during the 30-second test) was found with the 145-mm crank. The largest mean power (average power produced for the entire 30-second test) was found with the 180-mm crank, and the largest minimum power (power produced during the last five seconds of the test) was found with the 230-mm crank. What does all this mean? It means that there is an interaction among crank-arm length, load, pedalling rate, and power output. For the load selected (85 g/kg of body mass), a crank-arm length of 145 mm (based on the five cranks used in this study) with a pedalling rate of approximately 170 rpm will produce the largest power output. However, as fatigue sets in during the latter part of the test (especially during the last five seconds), the pedalling rate decreases to somewhere between 82 rpm (for the 110-mm crank) and 93 (for the 230-mm crank). This decrement in pedal rate with the load selected favours the use of a longer crank (230 mm for this study). The 180-mm crank happened to be most advantageous if the power production (mean power) over the entire 30-second test was considered. Would the results have been different if a significantly greater or lesser load/resistance was used (or if trained recumbent cyclists were used)? I would think so. Care must be take in interpreting the results of any study. It should be noted that the average leg lengths of the subjects were: total leg length measured from the greater trochanter to the floor was 941 mm; upper leg length measure from the greater trochanter to the knee center of rotation was 409 mm, and the lower leg length was 534 mm. Not all subjects showed the same parabolic trend in power production with increments in crank-arm length from 110 to 265 mm. This is attributed to intra- and inter-individual variability and the a training effect with repeated testing. However, this training effect was accounted for in the research design of the study where each subject was tested with a different crank-arm length test sequence. Finally, this study was a power test for 30 seconds and not an extended aerobic study. Again, I have other data sets collected, but have not had the time to analyze them.

To provide information about cranks that is a little bit more substantial, I have run regression analyses on the data set for that particular study. The results from the regression equations obtained predict that peak power (5-second interval) would be obtained with 124-mm cranks, highest average power (for 30 seconds) would be obtained with 175-mm cranks, and the largest minimum power (last 5 seconds in an 30-second all-out power test) would be obtained with a 215-mm crank.

One final caveat. These predicted crank-arm lengths are limited to the subjects, recumbent position, and test protocol used in that particular experiment. It is not necessarily true or applicable for experienced recumbent cyclists or their particular recumbent position.

—Danny Too <dtoo@po.brockport.edu>
Dept. of Physical Education & Sport
State University New York at Brockport
Brockport, NY 14420-2989
Tel: (716)-395-2403
Fax: (716)-395-2771

A TANDEM RECUMBENT DESIGN

by Charles Brown

I'd like to share some thoughts with you on the design of recumbent tandems. Reliability tends to be a problem on tandems, whether upright or recumbent, because they often take parts which were designed for single bikes and impose on them twice the load.

Wheel strength varies with size, so a wheel that's half the diameter needs approximately half the spokes for equivalent strength. 20" (500 mm) rims and hubs are readily available with 36-hole drilling; these should provide a sturdy foundation for your steed. Further, the drive wheel(s) could be built up without dish, the off-center rims being compensated for by moving both dropouts 1/3" (10 mm) to the right. This gives even more strength without added weight, just from using the materials more intelligently.

Drive-train troubles caused by having the power of two applied to parts made for one could be reduced if the front rider powered the front wheel, and the rear rider powered the back. Independent pedalling cadence comes automatically with such a design. This may incur a slight weight gain, but you get the advantage of not having to transfer the front rider's power seven feet (2 m) to the back wheel, with the attendant losses of power.

The two-stage drive train often used in fixed-boom/front-wheel-drive designs would gear up the front wheel nicely. A good design is one made from an old back hub. A cog is attached to one of the hub flanges, and a chain runs down from this to a single sprocket on the front wheel. The 'power' or highly-tensioned side of the chain should be nearly parallel to the steering axis. One end or the other of this chain can be a little closer to the steering axis than the other, but looking at it from the top, the chain must be going straight out from the steering axis. This is so that the forces from pedalling do not try to turn the steering a little bit to the right or left with each pedal stroke, which forces must be resisted by the rider's hands on the handlebars.

A freewheel or cassette would be attached to this upper hub, allowing gear changes, and a second chain would run forwards from this to the crankset. Proper positioning of the intermediate gear unit is essential, and the builder might want to allow for some fore-and-aft adjustment of it. This would allow fine-tuning of the chain line of the final drive if someone wants to change the gearing there. The mountings for this intermediate drive must be made very strong and rigid.

Gearing up the 20" (500-mm) rear wheel is more problematical. A rear cassette with an 11-tooth top cog combined with a 60-tooth big chain ring would give a 110-inch top gear. Alternatively, an internally-geared hub could step up the gearing.

Bicycles are controlled by a combination of balancing and steering; it helps the captain pilot the machine if she or he has firm control over the balance. A stoker moving around unexpectedly can make a tandem hard to manage. To improve this, the captain's center of gravity should be up higher than the stoker's, so the person steering the craft also has more leverage, and thus more control, over the balance. This is particularly important if the lighter person does the steering.

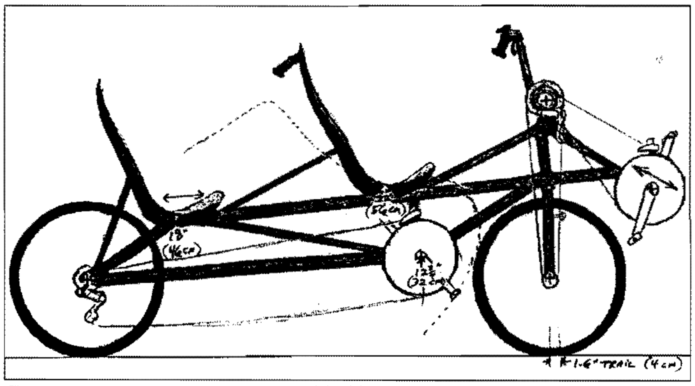

Figure 1. Side view. Drawings provided by author.

In the sketch I've placed the captain's seat over the stoker's pedals to make the bike more compact: other arrangements are of course possible. Note that on tandem recumbents with a 20" front wheel under the captain's knees, like this one, a 20" back wheel makes for a better front-to-rear balance than the more usual 20" front-, 27" rear-wheel sizes, improving the ride and handling. In the drawing, adjustment for different-size riders is by moving the rear seat forwards and back, and by moving the front pair of pedals fore and aft. This will probably require changing the length of the chain, but the captain's will probably not require adjustment very often.

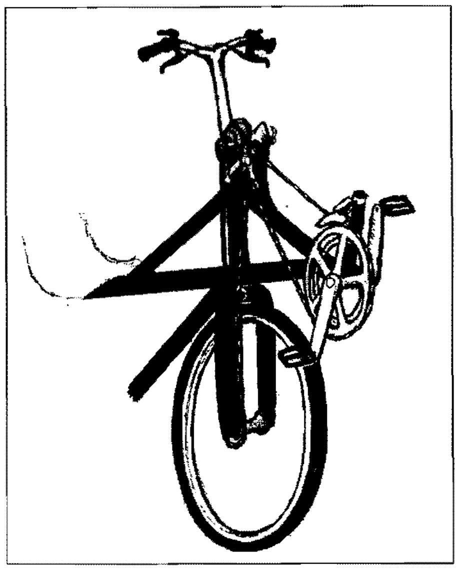

Figure 2. Front details.

—Charles Brown
1875 Sunset Point Rd., #206
Clearwater, FL 33765

[Editor's note: chain management takes on critical significance in front-wheel-drive systems. There must be no chance that the chain could come off and lock the front wheel. Dave Wilson.]

CRASHWORTHINESS ANALYSIS OF ULTRALIGHT METAL STRUCTURES

by Sigit P. Santosa

Abstract of a doctoral thesis presented at MIT, May 1999.

In the design of lightweight crashworthy metal structures, thin-walled prismatic components have been widely used in aircraft, high-speed trains, fast ships, and automobiles. Two new types of such components are proposed, both of which consist of a thin-walled member and an ultralight metal core such as an aluminum