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# HUMAN POWER

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## BACKWARD VERSUS FORWARD PEDALING: Comparison Tests

by Ramondo Spinnetti

### SUMMARY

*Recent ergometer tests show that pedaling backwards (on a suitably designed bicycle) can enable a rider to produce twenty percent more power than pedaling forward on a traditional bicycle, at cadences from seventy to one hundred revolutions per minute. Static propulsive-force tests at various crank angles also show how this is accomplished.*

### INTRODUCTION

After two years of pedaling backwards on prototype bicycles of various configurations, the next step was to prove by experiment what my subjective experience had already shown me. The problem then was to decide upon the best way to conduct a fair and conclusive comparison test to show the quantitative difference in performance between backward and forward pedaling. A traditional racing bicycle was used as a frame of reference to make the tests more meaningful, comparing it with a similarly configured backward-pedaling prototype.

To insure fairness and credibility, the tests were preceded by a ninety-day training program consisting of riding the bicycles daily, a total of 160 km (100 miles) each per week. This was followed by the ergometer tests described below.

### METHOD

The actual performance of the comparison tests posed some interesting and challenging problems for me with the limited resources available. Having recently retired, I had the time to build the equipment and perform the tests myself.

The ergometer consisted of a traction roller coupled to a synchronous electric motor through an over-running clutch (free-wheel unit) and an idler roller to support the rear drive wheel of the bicycle under test. The front wheel was removed and replaced by a tripod to stabilize the vertical position and alignment. The over-running clutch prevented the synchronous motor from driving the traction roller, while limiting its

*(continued on page 10)*

*The MIT Micholob Light Eagle at Edwards AFB*

## DAEDALUS ROLLOUT

The MIT project to fly an HPA from Crete to Greece continues with renewed energy following the assumption of primary sponsorship by United Technologies. Overwater flight testing was completed at Ninigret, Block Island Sound, RI on August 26 with a flight of 21 minutes in the Light Eagle using a new water system for the pilot and without using ailerons – because the new aircraft, Daedalus, the first of which, Daedalus A, had its official rollout on October 20, has none. In November and December half of the crew will be at Edwards AFB for flight tests with Light Eagle and Daedalus A, and the other half will continue building Daedalus B in Massachusetts.

MIT and the Shaklee Corporation of San Francisco announced the choice of three athletes to train for the flight: Kanellos Kanellopoulos, 30, national cycling champion of Greece thirteen times; and Greg Zack, 25, of Lexington KY and Erik Schmidt, 25, of Boulder CO, both bike racers who compete on the national level. These three join Glenn Tremml in training. ☐

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*Human Power*
The Technical Journal of the
International Human-Powered
Vehicle Association
David Gordon Wilson, Editor
15 Kennedy Road
Cambridge, MA 02138, USA
617-253-5121 (office)
617-876-6326 (residence)
IHPVA
P.O. Box 51255
Indianapolis, IN 46251, USA
Phone: (317) 876-9478

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IHPVA
P.O. Box 51255
Indianapolis, IN 46251-0255 USA

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## In This Issue—

# Editorials by David Gordon Wilson

## Coming of Age?

A few weeks ago there arrived almost together two publications of great potential significance for the human-power movement: the June 1987 issue of American Bicyclist, and the new edition of Richard Ballantine's Richard's New Bicycle Book. The cover of the magazine, which is a trade journal principally for bicycle dealers, a group generally rather skeptical about the prospects for recumbents, gave the theme of this issue: "Recumbents: The Laid-Back, Fast-Forward Alternative – The Market, the Makers, the Models." Richard Ballantine's book is the first I know of on bicycles in general that is frankly enthusiastic about HPVs in general and recumbents in particular. He has already had considerable influence on all of us: Richard bought one of the first Avatars to be exported; he lent it to Derek Henden of London who modified it to become the fully faired recumbent Bluebell, and with nonracer Australian Tim Gartside pedalling, came to the Carson (California) IHPSC October 3, 1982 to beat the Vectors, Easy Racer and Steve Ball's Dragonfly. Subsequently the emphasis shifted from tricycles to recumbent bicycles in the quest for speed. Richard's chapter fifteen is headed "ZZZWWAAAMMO!" and is as enthusiastic as the title on the new vehicles.

The two publications will give the HPV movement a great deal of favorable acceptance. We appreciate the recognition!

And on public TV the second in the series by Philip and Phylis Morrison called "The Ring of Truth" featured various HPVs including an aircraft and many bicycles. Shortly afterwards, even that old Sixty Minutes curmudgeon Andy Rooney extolled the bicycle as the friendliest of man's inventions. We are indeed honored.

## Apologies!

In the last issue I half-apologized for publishing letters favorable to *Human Power* because we had until then received no complaints. Pride goeth before a fall; we fell badly in that very issue, and we have been justifiably taken to task. We introduced so many errors into the mathematics of Y. Le Hénaff's article as to reduce its usefulness greatly. We list the corrections on page 6. We omitted the addresses of several authors and of manufacturers. And in my own article on a propeller development I did not hold myself to the international units I try to require of authors generally. Mea culpa! The journal is put out by many overworked people trying to squeeze time out of many other demands, and it has not been possible previously for issues to come back to me to be proofread. With this issue we are trying the experiment of paying for a professional layout house (which is giving us a break on its usual charges) and I will be able to see the proofs before final printing. Study it carefully and let us have your complaints or plaudits. As in so many innovations, President Marti Daily set up this new experimental arrangement.

## The Right to Privacy

And with regard to the publication of authors' addresses, we normally get their prior permission to do so in order that interested people can write to them directly rather than go through the nonexistent bureaucracy of this journal. In a way these addresses are privilieged information, and can lead to an invasion of privacy. It can lead also to unreasonable demands. Most come from nonmembers of the IHPVA, but because *Human Power* is, thank goodness, read fairly widely by nonmembers I would like to make this plea. If you write for information, include a stamped addressed envelope. If you call long distance, don't leave a message expecting our authors to call you back at their own expense. This month I, for one, have had a bumper crop of people who have called or written from near and far with long lists of requests, almost demands, for very specific information, requiring, often, library research, and much copying and postage, as if we were some sort of free reference service. Often they state that they have heard about the IHPVA or about, for instance, the book Bicycling Science, but they want to get information without subscribing to either. I feel used when I give them everything they want, as I usually do, and equally I feel that I am a lousy ambassador when I don't. All of the officers of the IHPVA spend a huge amount of their time and a great deal of their own money on the organization, and I would like our valiant authors to be spared that load.

### Enthusiasts in India and Sri Lanka

This August I made an all-too-brief visit to India at the invitation of faculty at the Indian Institute of Technology in Kanpur, where they have experimented with a wide range of HPVs for Indian conditions. (My air fare was paid for by our National Science Foundation using U.S. rupee balances.) I hope to write more about my impressions when we have space. But let me make these observations here. I agree wholeheartedly with Fred Willkie who wrote in HP 5/3&4 that one has to live in and experience another country before one can understand the situation there. I was in India only a short while, but I found myself enjoying riding a single-speed heavy Indian bike among the vast number of other bicyclists moving along at sedate speeds, and not longing for my 21-speed Avatar, which would have been simply inappropriate in those conditions. One should also not go to another country with too much confidence in one's sophistication. On the way to Kanpur I took the opportunity to visit long-time correspondent and HP author (3/3) Ray Wijewardene in Sri Lanka, a vital, enthusiastic and extremely effective force for change in that part of the world, and a very gracious and hospitable host. I tried all of his stable of experimental HPVs and transmissions. He also arranged for me to talk on the IHPVA at the Sri Lankan Institute of Engineers, and invited Arhur C. Clarke, probably the best-known science fiction author in the world and credited, among other developments, with the invention of synchronous-orbit satellites. Arthur Clarke invited us to his house subsequently, and gave me the early piece on HPAs that we publish on page 19 in this issue.

### Welcome Sun!

Today's morning paper (November 7) carried the news that General Motors' Sunraycer solar-powered car, to which Alec Brooks' team at AeroVironment made considerable contributions (as we learned at the IHPSC symposium), had won the World Solar Challenge Darwin-Adelaide race of 3000 km by a huge margin. This victory came a few weeks after the IHPVA board voted to approve Paul MacCready's proposal to create a new division that would be concerned with solar-powered and low-power hybrid vehicles within the IHPVA. Peter Ernst has already helped to make the Tour de Sol in Switzerland a major incubator of development and a very successful attraction. There were concerns expressed that the IHPVA would be in danger of diluting its mission, but those who felt that we should adapt and embrace won the day. Details are yet to be fully worked out. If you want to have input, write to HP, HPVNews, or Marti Daily. Meanwhile, our heartiest congratulations to Alec, who adds this stunning success to those of the Flying Fish HP hydrofoil and the flying flapping-wing model pterosaur made for the Smithsonian.

### Chapter Newsletters

Tom McDonald, VP Land until the end of 1987 (when he is resigning to go back to school), president of the North-West HPVA and editor of its newsletter, has sent me a set of recent issues. The Nederlandse Vereniging voor Human-Powered Vehicles (NVHPV) has also been kind enough to send me its HPV Nieuws. The high quality of both publications is impressive. I have been briefly reviewing the articles of HPV interest in Bike Tech (Rodale Press) and from now on I shall try to do the same for these and any other chapter newsletters I get to see. I will also ask permission to reproduce articles that are of general interest and on topics rarely covered here. The addresses of the chapter heads are given at the back of most issues of HPVNews. If you write them for copies of back issues, do send money (I'll guess $1.50 per issue) plus postage. Bike Tech costs $3.00 per issue from Rodale Press, Emmaus, PA 18098. ☐

# Briefly News: Recent Developments

## A Recumbent Tandem

Kurt Wold wrote about how he came to build a recumbent tandem, and sent along the photo of Kristin and himself on it. "The mystique of radical bike building was not an issue. Mysticism belonged to Italian bikes, the Pope, and the far shores of Sicily.... I also had an unfavorable mental list of tandem touring experiences that I wanted to see designed out of this project. One was a high-speed winding coast-line descent on a Paramount tandem with a blown front tire.... (Another was of) memories of touring for several days staring at nothing but my front tire... the posture in this instance was brought on by severe headwinds... the mountain that never crests. Anyway, my feelings about the inherent deficiencies in supine recumbents and conventional tandems cross-pollinated... and the result is a 1220-mm (48-inch) wheelbase tandem that steers easily one-handed." *(Kurt Wold, 533 West Doty, Madison, WI 53703 USA; 606-251-0946)*

## HP Submarine Competition

The H.A. Perry Foundation and the Ocean Engineering Department of the Florida Atlantic University have joined to offer the first human-powered underwater-vehicle design competition. The first prize is $5,000 for the highest overall score in innovation, cost effectiveness and performance. Judging will be by a

*(continued on page 6)*

*Kristin and Kurt Wold on their recumbent tandem*

# Angular Momentum and Bicycle Stability

by Brenan J. McCarragher

## ABSTRACT

*A flywheel was mounted to the front fork of a bicycle to investigate the effects of angular momentum on bicycle riding and steering characteristics. A range of angular-momentum settings were tested on a series of courses incorporating the situations most encountered by bicyclists. Test subjects were used and their lateral deviation from the test course was evaluated. Also a Cooper-Harper rating system was used to determine test riders' subjective ratings of the bicycle. The results showed that large amounts of positive angular momentum had an extreme stabilizing effect which made turning difficult, while negative angular momentum proved difficult to control. The learning curves generated indicated good improvement at the positive settings, while minimal improvement was shown at the negative stettings. Most importantly, the experiment showed that the angular momentum of the front wheel of a bicycle can have significant effect on the control and steering of the vehicle.*

## INTRODUCTION

The balancing and controlling of bicycles is a complex subject. The bicycle lean in addition to the offset of the front fork complicate the rigid-body geometry of the bicycle and make bicycle dynamics difficult to describe. Recent documentation shows that despite the complications, no real controversy exists concerning how a rider steers and balances a bicycle. One steers into or under a fall, similar to balancing an inverted pendulum on one's finger. However, when attempting to answer why some bicycles are easier to steer than others, experts are often in complete disagreement, even about fundamental concepts. Some experts assert that gyroscopic action has little influence, while others insist the opposite is true [1,2]. This uncertainty is a result of the complex dynamics described above. Specifically, it is this uncertainty concerning the effect of angular momentum and gyroscopic action that has prompted this study.

David Jones [3] constructed a bicycle in which the gyroscopic action of the front wheel was cancelled by a flywheel rotating backwards. He found that this made little difference on the stability of the bicycle. His only reaction was that "the 'feel' was a bit strange." He then tried to run the vehicle without a rider and found that with the flywheel spinning against the road wheels, it collapsed quickly. However, with the flywheel spinning with the road wheels it showed "a dramatic slow-speed stability, running uncannily in a slow, sedate circle before bowing to the inevitable collapse." Jones concluded that the light, riderless bicycle is stabilized by gyroscopic action, whereas the heavier ridden model is not and requires constant rider effort to maintain stability.

The intention of this project, then, was to test and expand Jones' conclusions in a more quantitative and systematic manner than was previously done. By mounting a flywheel to the steering column of a bicycle, this project tested the effect that the angular momentum of the front wheel has on bicycle stability. The flywheel was able to rotate forward and backward at high speeds allowing a wide range of angular momenta to be tested.

## THEORETICAL BACKGROUND

In this experiment, a rotating flywheel was mounted on the front fork of a bicycle. Due to its mass and velocity, this rotating wheel generated angular momentum H as defined by

$$H \int I \mathbf{p} \qquad (1)$$

where I is the moment of inertia of the wheel about the spin axis and **p** is the angular velocity, or spin velocity. By the laws of gyroscopic motion, when a rotor is forced to precess, as occurs with a bicycle wheel when a rider is executing a turn, the motion will generate a gyroscopic couple or torque M, given by

$$\mathbf{M} = \mathrm{I}\,\Omega \times \mathbf{p} \qquad (2)$$

where Ω is the precession velocity. **M**, **Ω**, and **p** are mutually orthogonal vectors with their relationship defined by the right-hand rule of cross products. The correct spatial relationship among the three vectors may be remembered from the fact that dH, and hence **p**, is in the direction of **M**, which establishes the correct sense for the precession **Ω**. Thus the spin vector always tends toward the torque vector.

Consider now a bicycle with forward angular momentum making a right-hand turn. The **M**, **p**, and **Ω** vectors are shown in Figure 1. As can be seen, if the spin vector tends toward the couple M, a set of forces representing the couple make the rotor turn into the circle prescribed, requiring the rider to lean into the curve. In the same respect, if the rider turns left with forward angular momentum, the opposite couple again forces the rider to lean into the turn.

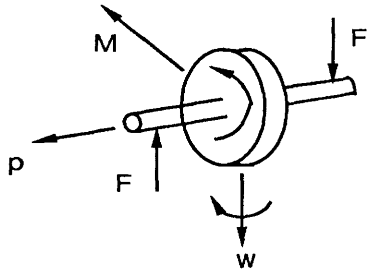

*FIGURE 1: Bicycle wheel with forward angular momentum making a right-hand turn*

On the other hand, if the angular momentum is in the reverse direction, the spin vector **p** switches directions (Figure 2). If the rider turns right, the torque tries to straighten the rider, requiring less lean. For the analogous situation for a left-hand turn the opposite couple again requires less lean.

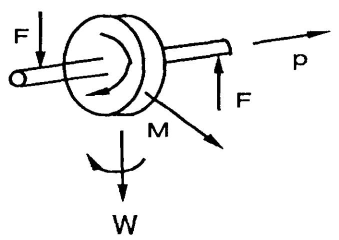

*FIGURE 2: Bicycle wheel with reverse angular momentum making a right-hand turn*

The strength of the gyroscopic couple, of course, depends on the strength of both p and **Ω**. Thus the faster a bicyclist travels and the quicker he turns the front wheel, the stronger will be the gyroscopic couple.

A rider traveling with a linear velocity v on a circular course with radius of curvature r has an angular velocity Ω equal to

$$\Omega = \frac{v}{r} \qquad (3)$$

According to these dynamics, the bicycle proceeding on a curved path with a lean angle Q will have three forces working on it (Figure 3). These forces are gravity W, centripetal C, and the gyroscopic force G.

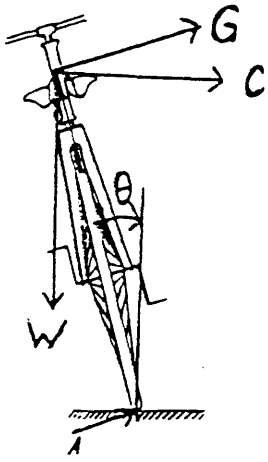

*FIGURE 3: Dynamic forces working on a bicycle*

In equilibrium, the sum of the moments of these forces about point A is zero, $\Sigma M_A = 0$. With counterclockwise moments being defined as positive, this equation becomes

$$-mgd\sin Q + \frac{mv^2}{r}d\cos Q + H\Omega\cos Q = 0 \quad (4)$$

where d is the height of the center of gravity of the bicycle and H is the amount of angular momentum. Knowing that angular momentum is the product of the moment of inertia I and the angular velocity w (1), and also substituting (3) for $\Omega$, the equation becomes

$$-mgd\sin Q + \frac{mv^2}{r} d\cos Q + Iw\frac{v}{r}\cos Q = 0 \quad (5)$$

Solving for the lean angle Q, one gets

$$\tan Q = \frac{v^2}{rg} + \frac{I\,v\,w}{r\,m\,g\,d} \quad (6)$$

or

$$Q = \tan^{-1}\left(\frac{v^2}{g\,r} + \frac{I\,v\,w}{r\,m\,g\,d}\right) \quad (7)$$

The lean angle, therefore, is dependent upon the velocity, the radius of curvature, and in the presence of angular momentum, the mass of the system, the height of the center of gravity, and, of course, the amount of angular momentum.

It has been suggested that the bicycle-rider system be evaluated as a two-body problem to better account for the control that the rider exerts. In order to determine and solve these equations, one needs to know many additional terms. First the center of mass of both the rider and the bicycle need to be found separately. In order to do this, one must assume a mass fraction and mass distribution of the two bodies to account for the rider's lower body being part of the bicycle system. Also an upper-body angle must be assumed in order to calculate the lean angle of the bicycle. The many uncertainties and assumptions warrant that this method not be used as a theoretical comparison for the actual data.

## TEST DESIGN: THE BICYCLE

The primary goal of the test vehicle was to design a bike that would have the capability for additional angular momentum without dramatically altering the other characteristics of the bicycle. This was accomplished by mounting on the bicycle a flywheel to provide the additional angular momentum, and a counterweight to provide balance. Because the front wheel is the main device used in steering a bicycle, it was decided to mount the flywheel on the fork of the front steering column so as to better examine the effects of the angular momentum on both the stability and steering characteristics. The flywheel was powered by a small motor mounted just forward of the front fork of the bicycle. The motor was in turn powered by a battery mounted behind the seat. Weight was added to the flywheel in order to obtain the necessary angular-momentum settings. The motor was able to spin in both directions so as to allow for forward and reverse angular momentum.

## TESTING PROCEDURE

Because the goal of the experiment was to investigate the effect of angular momentum on bicycle riding characteristics, a range of four additional angular-momentum settings was chosen. The desired test speed was 4.5 m/s (10 mph), so all angular-momentum settings were determined with reference to the amount of angular momentum generated by the front wheel of the bicycle when traveling at this speed. For this report, a negative setting means the flywheel was rotating in a direction opposite of the front wheel, while a positive setting means the two wheels were spinning in the same direction.

A setting of zero times angular momentum was chosen as the control and as a basis for comparison to other bicycles and other settings. This setting would show the effects of the physical construction only. A negative one additional angular momentum was used to cancel the front wheel's momentum, in order to discover what the effect the lack of a force couple may have. Thus by default, one can determine what effect the angular momentum of a regular wheel has. Also, it was desired to look at the two extreme cases, and therefore positive and negative ten times additional angular momentum settings were chosen. Due to the virtually uncontrollable nature of the bicycle at the negative ten setting, this setting was reduced to negative five times the angular momentum of the front wheel of the bicycle.

In order to investigate the riding and stability characteristics of the bicycle when traveling linearly, a straight course was used. The second course used was a circle so as to determine the riding characteristics when turning. And a serpentine test course was used to examine the characteristics of the bicycle when quickly changing directions. On each course the lateral deviation was taken at discrete intervals. Because each test rider is different, and because people learn and adapt, each bicyclist rode the test course three times, allowing for the generation of learning curves.

In order to fully test the effect of the coupling force created by angular momentum on the steering and stability characteristics of the bicycle as previously described, the lean angle had to be measured. A camera was set up on a tangent to the circle to take a photograph as the rider turned along the circular course.

Because the test rider has such an involved role in defining the riding characteristics of a bicycle, a system of subjective data collection was necessary. The Cooper-Harper Rating System [4] was used to help facilitate this aspect of data collection. Through slight modification, this system allows the riding characteristics of the bicycle to be defined in terms of the compensation required. Basically, the system entails deciding between three sets of opposites and assigning each a numerical value. For this experiment, the quality was either:

a. Satisfactory: good enough without improvement [value 1-3]
b. Unsatisfactory but Acceptable: just good enough, adequate for the purpose, but improvement is desirable [value 4-6]
c. Unacceptable: not suitable for the purpose but still controllable [value 7-9]
d. Uncontrollable: unacceptable for the purpose and of the poorest quality [value 10]

## RESULTS

### THE STRAIGHT COURSE

The straight course proved to be the easiest of the three test courses ranging between 50 and 125 mm (2 and 5 in) root-mean-square (rms) deviations, with no rider experiencing trouble maintaining

*(continued on page 13)*

# Corrections to "Dynamical Stability of the Bicycle"

by Y. Le Hénaff

We greatly regret that several errors occurred in our publication of this article in *Human Power* 6/1. Here are the corrected versions in the order the errors appeared, starting on page 15 of that issue.

### FIGURE 1 CAPTION

The caption should read: <u>Side view and bicycle dimensions</u>. Lengths: MM' = TT' =MP + PM' = 1 + L = a = 1.0m; 1 = 0.2r; wheel radius r = 0.33 m. Trail T = TO is measured positively forwards. The fork angle is $\varphi = 20°$.

### EQUATION (1)

$$\tan\theta + v^2\tan\alpha/ag \qquad (1)$$

### GEOMETRY OF THE BICYCLE

For the upright bicycle in Figure 1, the plane of the front wheel coincides with the plane of the frame and cuts the ground plane along XX'. M and M' are the centers of the hubs, T and T' the ground-contact points of the wheels. The front-fork axis makes an angle $\phi$ with the vertical, intercepts the ground at O and cuts the line MM' at P, defined as the fork point. P is fixed on the fork axis and projects at H on the ground trace OT' of the frame plane; P is also at a fixed position with respect to the center of gravity of the system supposed [4] within the frame plane. We write MP = 1, PM' = L and, of course, l + L = a.

The angles $\chi \equiv (POX)$ and $\varphi \equiv POX'$ are defined respectively in the front-wheel and frame planes; only when those two planes coincide do we have $\varphi + \phi = \chi - \varphi = \pi/2$. When the handlebar is turned, it can be seen experimentally that the front wheel slides slightly downwards; therefore, $\varphi$ increases and $\chi$ decreases.

Jones computed the height h of the fork point which is related to the height of the center of gravity and hence to its potential energy h = HP, in the frame plane for obvious dynamical reasons. Writing $OP \equiv \chi$, we have:

$$h = \chi\sin\varphi \qquad (2)$$

In the frame plane, the vector relation

$$\vec{OP'} + \vec{PM'} + \vec{M'T'} + \vec{T'O} = 0$$

projected on M'T' yields:

$$\chi\sin\varphi + L\sin(\varphi + \phi - \pi/2) = r \qquad (3)$$

where r is the radius of the wheel and $(\varphi + \phi - \pi/2)$ is the downward tilt of the frame in its plane.

Similarly, in the front-wheel plane, the corresponding relation

$$\vec{OP} + \vec{PM} + \vec{MT} + \vec{TO} = 0$$

projected on MT gives:

$$\chi\sin(\pi - \chi) + l\sin(\chi - \phi - \pi/2) = r \qquad (4)$$

### PAGE 16

On page 16, the last sentence in the caption of Figure 2 should read: "The front-fork axis is along OZ'." The Greek symbol in the first line of the first column should be $\chi$, and the second paragraph should be:

"A second relation can be obtained considering a bike running on a curved path (Figure 2). We take O as the origin of the coordinates; OZ' as along the fork axis;

$\vec{i}$, $\vec{j}$, $\vec{k}$, and $\vec{k'}$ as unit vectors on axes OX, OY, OZ and OZ' respectively; and finally $\vec{n}$ as the unit vector normal to the plane of the frame. Then we have:

$$\sin\theta = \vec{n} \bullet \vec{k}$$

$$\vec{k} \times \vec{j} = \vec{n}\sin\varphi$$

$$\vec{i} \times \vec{j} = \vec{k}\sin\alpha$$

### "DYNAMICAL EQUILIBRIUM"

The last line of the paragraph under "Dyamical Equilibrium" should read: "wheel allows it to swivel more freely."

### CLOSING MATTER

Reference 7 should be: Théorie générale.... The zip code in the author's address should be 92160. ❑

## BRIEFLY NEWS...

(continued from page 3)

seven member panel in Palm Beach County, Florida, in June 1989 where there will be speed and performance trials. Write for a brochure to M. Linskey Merrill, Director, NE Office, H.A. Perry Foundation, 147 Martin's Lane, Hingham, MA 02043, phone 617-749-9064, and state whether your interest is as a contestant, a sponsor of a vehicle, or of the race, or as a spectator.

Maggie Linskey Merrill gave the IHPVA board a presentation on the competition at the Washington DC IHPSC meeting. The designs will be limited to fully flooded vehicles with a minimum of two persons, and safety concerns are being fully addressed.

### Bike Tech Articles

The June 1987 issue has two articles about training: "Test Conconi at Home!" by Pat Ennis and Michael Argentieri, about anaerobic-threshold training; and "Sepcificity of Training" by Peter J. Van Handel, about the details of the intensity and quantity of daily training. The third article is by Danny Pavish, and is based on his lecture in the Third IHPVA Scientific Symposium in Vancouver, 1986: "After the Gold Rush – Is HPV Mach 0.1 Just One Level Straight Away?"

The cover story article in the August 1987 issue is by editor Jim Redcay: "The Best Campy Gruppo Yet?" The second article is by our own Chet Kyle: "Unsolved Bicycle Design Problems," mainly about alternative transmissions and about regenerative braking. John Forester contributed the third piece: "Downhill Heat – The Thermal Effects of Steady-State Braking."

### NWHPVA Newsletters

Tom McDonald has good practical articles in these newsletters. The Nov-Dec, 1986, issue, no. II/6, has Greg Trayling's "Constructing a Fairing-Mold Plug." I don't have the next issue, but vol. III/2 has a short piece on shock absorbers made from clothes pins and rubber bands, and a tantalizing unillustrated report on Jim Schneider's "Pedaltroller" rowboat conversion. Two useful construction articles are in vol. III/5: Paul Dunham's "Create Perfect Mitered Joints;" and "Working with Coroplast" by Bob Stuart.

Interspersed among the technical articles are some well-done interviews with designers and builders, and book reviews and stories.

(continued on page 12)

# OXYGEN COST OF SUBMAXIMAL EXERCISE IN RECUMBENT AND CONVENTIONAL CYCLING POSITIONS

By Ingrid E. Antonson

[This article is from a thesis submitted to the Academic Faculty of Colorado State University in partial fulfillment of the requirements for the degree of Master of Education.]

## ABSTRACT

*It was the intent of this study to compare the physiological efficiency of recumbent and conventional cycling positions at submaximal workloads and to determine the effect of accustomedness to a particular position on the physiological efficiency of cycling in that position. Thirty healthy men, ten recumbent cyclists, ten conventional cyclists, and ten physically active noncyclists, 21 to 41 years of age, cycled for six minutes at 51.5 Watts (0.07hp) followed by six minutes at 154.5 Watts (0.21hp) in each position. Using an alpha level of $p<0.05$, no significant differences were found between the recumbent and conventional cycling positions for oxygen consumption (VO2), minute ventilation (VE) or heart rate (HR). There were no significant differences in VO2 or VE between the subject-groups. The noncyclists had a significantly higher HR in both positions than the conventional cyclists at the lower workload and than both the conventional and the recumbent cyclists at the higher workload. The results suggest that for submaximal cycling a recumbent position is no less efficient than a conventional position and, given a recumbent position can offer decreased wind resistance and may offer increased comfort, the use of a recumbent position for cycling activities such as touring and recreational riding is supported.*

## INTRODUCTION

Human-powered speed records clearly indicate an advantage of a semi-recumbent riding position; however, for submaximal efforts this advantage is not as clear. The effect of a semi-recumbent posture on the physiological efficiency of the rider must be assessed to determine if this postural change decreases the physiological efficiency beyond any gain offered by this body position at submaximal workloads.

Many of the effects of supine versus sitting positions during cycling-ergometer exercise have been known for some time. It is well established that HR is lower in a supine position than in a sitting position both at rest and during cycling exercise [1,2,3,4]. Several studies have shown no difference in VO2 between cycling in a supine position and an upright cycling posture for submaximal cycling [4,5,6,7] and one study [8] reported a lower VO2 in a supine position at 130.8 Watts (0.18hp). These previous studies [1-8] used a supine body position in which the subject was horizontal, a position which is impractical for a recreational HPV because of the cyclist's limited visibility in the direction of travel. Kyle and Mastropaolo [9] measured maximal power output using a "supine" racing tricycle, a conventional HPV, and a prone position and reported that the supine position resulted in 96% of the power output attained in the conventional cycling position. Physiological parameters were not quantified and submaximal efforts were not investigated in their study.

The primary objective of this study was to compare the physiological efficiency of recumbent and conventional cycling positions at submaximal workloads, where improved physiological efficiency would be indicated by consumption of less oxygen per kilogram body weight for a given workload. A secondary objective was to determine the effect of accustomedness to a particular position on VO2, HR, and VE (the rate of pulmonary ventilation in terms of volume expired per minute).

## METHOD

Thirty healthy male volunteers, 21 to 41 years of age, were selected as subjects according to the following criteria: 10 subjects were accustomed to regular cycling in a conventional cycling position, 10 were accustomed to regular cycling in a recumbent cycling position, and 10 were unaccustomed to cycling but were physically active. Accustomedness to cycling was determined by self-reported regular riding in the respective positions requiring an average of at least 40 km (25 miles) per week for the past three months. One recumbent cyclist was an exception, having ridden at least that amount for several months but having ridden a bit less than that in the three-month period immediately preceding the testing. Self-reported cycling of less than 1.6 km (one mile) per week for the past three months and no period of regular riding, as defined above, for the past five years was required to qualify as unaccustomed to cycling. The noncyclists participated in another type of regular physical activity for at least 30 minutes three days per week. A standard Monark model 868 ergometer with dropped-style handlebars, a touring saddle, and toe clips and straps was used for cycling in the conventional position. The same ergometer with a recumbent seat attached to the rear was used for cycling in the recumbent position. The recumbent seat was adjustable for the seat-back angle and the height of the bottom bracket relative to the seat bottom (the intersection of a line along the front of the seat back with a line along the top of the seat), although only one setting for these variables was used. The recumbent position used in this study had a seat-back angle of 120 degrees from horizontal with the seat bottom, a position approximately midway between the extremes of the recumbent vehicles ridden by the subjects. Both the standard and recumbent seat were adjustable to leg length. Each test consisted of six minutes of cycling at 51.5 Watts (0.07hp) followed by six minutes at 154.5 Watts (0.21hp). The subjects were randomly assigned to perform either in the recumbent or the conventional position first and a rest period of 30 to 40 minutes intervened between the two tests. The ergometer was equipped with a cadence meter with a gauge placed in view of the subject. Subjects cycled at a cadence of 70 rpm during all exercise tests. This cadence was chosen to accommodate both well-trained cyclists and those untrained in cycling. HR was continually monitored. The average HR for the last 10 seconds of each minute was recorded. VO2 was measured on a minute-by-minute basis using an open-circuit indirect calorimetric technique. The outputs from the ventilation meter and oxygen and carbon-dioxide analyzers were digitized, reduced by a microcomputer, and minute-by-minute values were displayed for VE (liters min-1), VO2 (liters kg-1 min-1), and HR. Mean values for VO2, VE, and HR from the last three

*(continued on page 17)*

# THE BIOENERGETICS OF POWER PRODUCTION IN COMBINED ARM-LEG CRANK SYSTEMS

by Richard Powell* and Tracey Robinson†

## SUMMARY

Tests on young adults of average athletic ability showed that maximum power output could be increased by over thirty percent using combined arm-and-leg cranking compared with leg cranking alone. Furthermore, the efficiency of lower-power steady-state power production was found to be higher for arm-and-leg cranking. Some differences between male and female subjects in the contribution from the arms was found.

## INTRODUCTION

A considerable volume of research has been generated over the years which has investigated the optimal speeds and expected work outputs for leg, arm, and rowing ergometry. When combined arm and leg ergometry has been studied in the past, findings suggest a greater *maximum* work output is possible (11-20% higher) when compared to leg ergometry along (Reybronck et al. 1975; Nagel et al. 1984). However, the efficiency of performing submaximal work using arm, leg, or combined arm-leg production systems is unclear.

Because sport and recreational cycling is predominantly a steady-state effort, the possibility of capturing greater muscle power through an arm-and-leg-powered mechanical drive system at an equivalent steady-state cardiac cost (heart-rate response) could translate into a more efficient human-powered cycling device. We were interested in determining if it is bioenergetically feasible to expect improved work output using arms and legs at equivalent submaximal physiological efforts when compared to work production using arms or legs alone.

## BACKGROUND

It's a well-known fact that maximum oxygen uptake ($VO_2$ max) is about 10% higher if a person is tested on a treadmill rather than on a bicycle ergometer. The reason for this occurrence is explained as being due to a greater total active muscle mass involvement in running compared to stationary bicycling; hence, $VO_2$ max is higher in running even though maximum heart rates achieved (cardiac cost) are the same in both types of all-out tests.

Because conventional bicycling uses only the legs for power production it seemed that using arms and legs together to produce steady-state work could result in a higher $VO_2$ at any given submaximal cardiac cost, and a larger potential work output as well compared to using legs alone. While it is clear that maximum work output is better in combined arm-leg systems when compared to legs alone, such maximum efforts are largely anaerobic and demonstrate little with regard to steady-state efforts.

The intention of our research was to compare the physiological cost of producing work under three types of conditions: arm ergometry, leg ergometry, and combined arm-and-leg ergometry. Two immediate questions to be answered were as follows:

1. *is combined arm-leg ergometry under various levels of steady-state work more physiologically efficient compared to arm or leg ergometry alone?*
2. *under maximum-power production conditions, how do the three ergometry methods compare?*

## APPROACH

A structural housing was developed in which subjects sat in a seat 500 mm. high with an arm-crank ergometer centered in front of them. The axis of the arm crank ergometer was 1220 mm. high and positioned to allow complete arm extension at the farthest point of the cranking cycle. A second leg-crank ergometer was centered in front of each subject with its axis 280 mm. high and positioned to allow complete leg extension at the farthest point of the cranking cycle. Both ergometers were electrically-braked systems.

Thirty-two subjects (17 males and 15 females; mean age - 25.3 years) were tested over three separate sessions at the same time one week apart. All three sessions were used to test progressive leg- and/or arm-cranking performance, with the order of testing (arms only, legs only, or arms and legs) randomly split among the subjects.

During all three exercise tests, oxygen consumption ($VO_2$) and carbon-dioxide production ($VCO_2$) were calculated every 15 seconds based on minute volume of expired air ($V_E$), true $O_2$ and $CO_2$ concentrations. In addition, heart rate (HR) was recorded every 30 seconds.

The exercise protocols were in two-minute step increments. The arm cranking started at 25 watts output and increased 25 watts following each two-minute step. This protocol, while not adjusted to body weight, conformed closely to similar protocols followed elsewhere (Williams et al. 1983). The leg cranking started at 33.3 watts output and increased 33.3 watts following each two-minute step; the approach conformed to protocols used elsewhere (Niemela, 1980). A two-minute leg-crank warm-up work stage at 33.3 watts preceded the combined arm-leg treatment. The combined arm-leg cranking started at 25 and 33.3 watts respectively (total watt ouput = 58.3) with 25 and 33.3 watt increments, respectively, following every two minutes (total watt increments = 58.3). All cranking was performed at 50 RPM and continued until fatigue.

Because of the expected differences among subjects in work-production capability, linear-regression equations were computed for each individual, plotting $VO_2$, $V_E$, and HR each against cumulative workload in watts; group equations were subsequently derived from individual ones. Cumulative workload was calculated by determining the workload in watts for each successive minute completed, plus the fraction (to the last completed 15 seconds) of the final minute of work. A 7:48 maximum work time for arms, for example, would yield a maximum cumulative workload of 475 watts (25 + 25 + 50 + 50 + 75 + 75+ 100 + [0.75 (100)]. In this way, every 15-second measure of $VO_2$ and $V_E$ and every 30-second measure of HR could be plotted against a cumulative work output to that point, and individual patterns of continuing physiological adaptation to discrete workload steps could be derived for each of the three exercise treatments.

## FINDINGS

After calculating linear-regression equations (the best "fit" for the data) for each individual, we then grouped the equations by sex. We examined the

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*Associate Professor, †graduate student, Department of Physical Education and Recreation, New Mexico State University slopes of the equations as an index of relative physiological cost of the exercise treatments in producing power output; the larger or more vertical the slope, the more taxing was the exercise treatment relative to the physiological variable examined. The ventilation data when plotted against cumulative workload (Figure 1) showed no statistically significant changes in the slopes of the equations for women and a significant difference in the men for arm cranking. Women, in particular, probably find arm cranking more taxing than legwork due to a relatively weaker upper body musculature compared to men; they stopped sooner than the men due to rapid local muscle fatigue long before breathing became labored at the higher workloads encountered by men. There appeared a tendency for combined arm-leg work to yield slightly more work output for a given ventilation, but it was not significant.

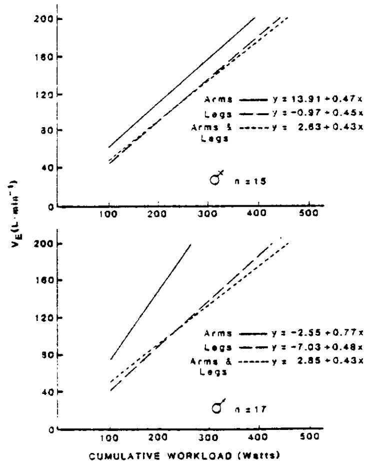


FIGURE 1 Ventilatory Response to Three Conditions of Power Production

The oxygen-consumption data when plotted against cumulative workload (Figure 2) showed no statistically significant changes in the slopes of the equations for the men or women. This seems reasonable because oxygen consumption should relate directly to power produced. The tendency again for arm cranking to appear less efficient probably reflects the more anaerobic nature of such work by itself.

What was most revealing was the heart-rate data plotted against power outputs (Figure 3). In both the men's and women's grouped data, there was significantly more power output at heart rates beyond 140 beats/minute using combined arm-leg cranking. In short, even at a given steady-state cardiac cost, power output is highest when using arms and legs together; further, it appears that this advantage increases as one approaches fatigue.

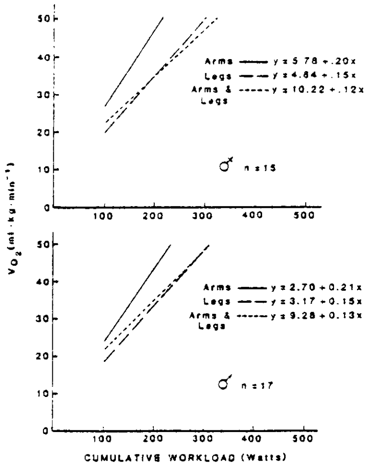


FIGURE 2 Oxygen Consumption Response to Three Conditions of Power Production

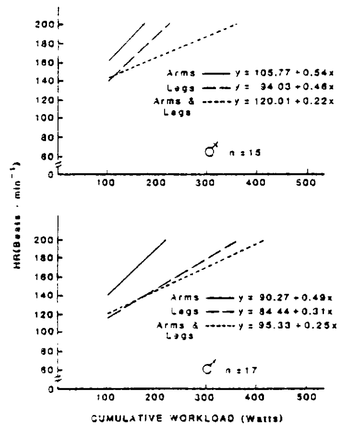


FIGURE 3 Heart Rate Response to Three Conditions of Power Production

When we looked at the "maximum" data of all subjects combined (the maximum cumulative powerloads reached at fatigue and the physiological data corresponding to that failure point), the advantage of combined arm-leg cranking over legs only was dramatic (Table 1). The maximum cumulative power output was approximately 31% greater using arms and legs compared to legs alone. To achieve that difference cost approximately 15% more in oxygen consumption. One could roughly assume that the 31% advantage in all-out power production was partly due to greater aerobic metabolism (15/31 = 48%) and partly due to anaerobic metabolism (17/31 = 52%). Arm cranking can clearly be seen to be an inferior method of power production by itself, and, at least at maximum effort, is probably limited by local muscle fatigue rather than aerobic support systems (given that an average maximum heart rate achieved by our subjects was only 160).

## CONCLUSIONS

Based upon the foregoing research, we concluded the following.

1. Combined arm-and-leg power production provides a decided advantage over leg cranking alone, especially in all-out work. About half of this advantage seems to be due to increased aerobic metabolism and half due to anaerobic work.
2. The efficiency of steady-state power production can be enhanced by combined arm and leg work. We cannot say decisively by how much at this time, because the power advantage is apparently influenced by how intense the steady-state work is, and by the relative contribution of arm power to leg power.
3. The advantage of any arm-leg powered machine is largely going to be offset by the possibility of additional weight/frictional resistance of a drivetrain system that would enable all limbs to generate power.

## POSTCRIPT

While we are not alone in our endeavors to develop an efficient and *practical* arm-leg powered cycle, the obstacles we have experienced and observed in other prototypes revolve around

*(continued on page 18)*

TABLE 1

MAXIMUM POWER OUTPUT AND CORRESPONDING PHYSIOLOGICAL RESPONSES TO THREE TYPES OF HUMAN POWER-PRODUCTION SYSTEMS

| EXERCISE SYSTEM (Rotary Cranking) | MAX. H.R.-1 (Beats min) | $VO_2$ max (ml kg min) | $VE_{max}$ -1 (L min) | MAX CUMULATIVE Power Watts |
|---|---|---|---|---|
| Arms | $160.06^a$ | $23.73^a$ | $76.98^a$ | $499.09^a$ |
| Legs | $169.75^b$ | $33.75^b$ | $97.85^b$ | $1021.86^b$ |
| Arms & Legs | $170.03^b$ | $38.77^c$ | $103.33^b$ | $1339.55^c$ |

Note: Components with different letters are significantly different ($p<0.05$) when compared columnwise.

## BACKWARD VERSUS FORWARD PEDALING

*(continued from page 1)*

maximum angular velocity to an absolutely fixed value under any possible human effort. Thus when the traction roller had reached its angular-velocity limit, the synchronous motor functioned as an alternator, delivering electrical energy back into the power line. This gave the rider instant control over the loading of the ergometer without manipulating any control knobs.

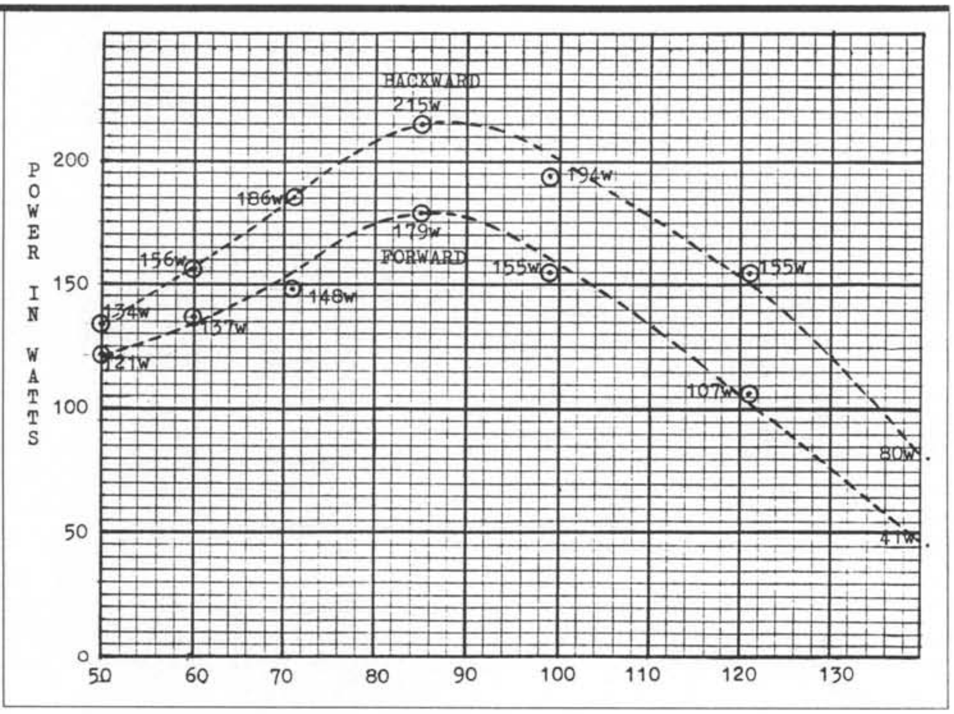
The frame of the motor was pivoted on ball bearings along its rotational axis so that the propulsive force of the bicycle could be measured as a torque reaction between the motor frame and the ergometer chassis. Since the propulsive force of a bicycle fluctuates considerably with crank angle, a hydraulically damped spring scale was used to measure the motor torque.

With angular velocity limited to a constant value, the output power was directly proportional to motor torque. Thus, the spring scale (with an appropriate scale factor) indicated power output independent of gear ratio. Tests at seven different cadences were run by selecting appropriate gear ratios on the bicycle under test, these being the same on both bicycles. The rear-tire size, type, and inflation pressure were also the same for both bicycles.

### POWER-OUTPUT TESTS

The power-output tests were distributed over a seven-day period, making two alternate runs on each bicycle at a single value of cadence each day. These runs were all made at one-hour intervals after a light breakfast, and completed before lunch to avoid conflict with digestive processes.

Each power-output test consisted of a brief surge of effort, just long enough to read my maximum power on the spring scale. This effort was preceded by a warm-up period (usually fifteen minutes) with only the rolling resistance of the bicycle as a load. The warm-up period was shortened at higher cadences to avoid fatigue, while keeping it equal at each cadence. Ample cooling was provided by a large forced-air-furnace blower sitting on the floor in front of the bicycle in a well-ventilated room. After each run, the remainder of each hour was devoted to resting for the next run. Power-output data, plotted against cadence, are shown in the graph above.



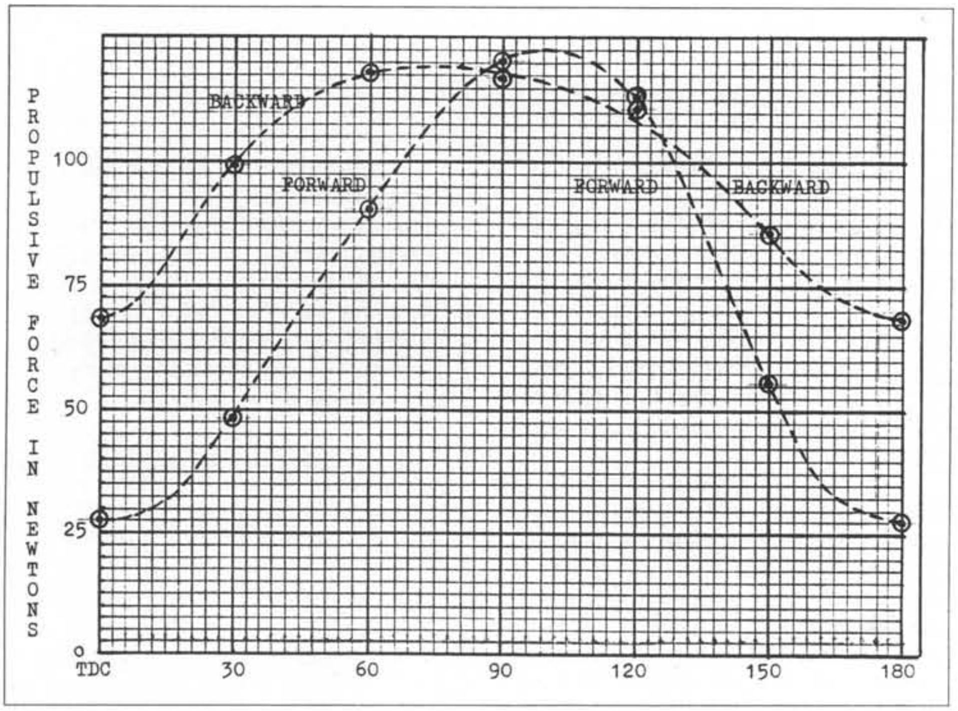
*Cadence revolutions per minute*

### STATIC-PROPULSIVE FORCE TESTS

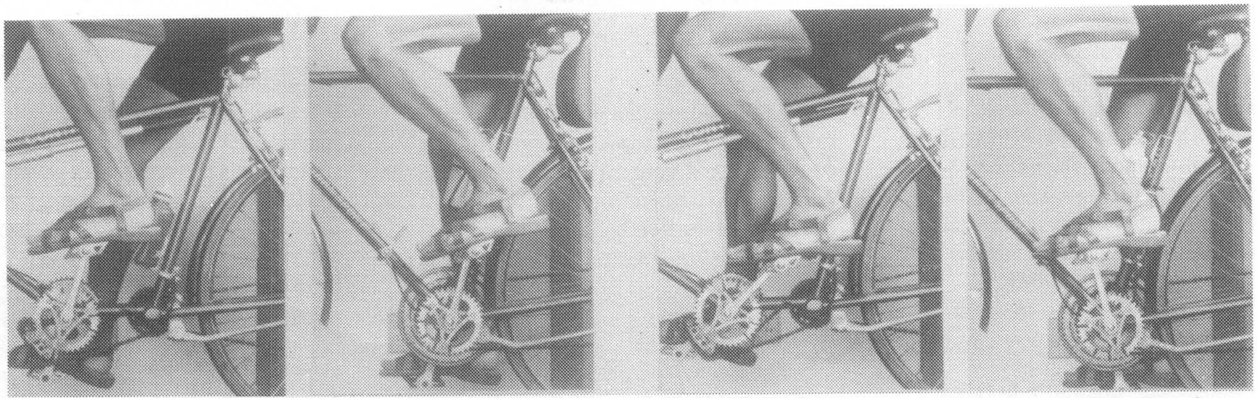
In order to explain the results of the power-output tests, static propulsive-force tests were run at thirty-degree increments of crank rotation, starting at top dead center. A photograph was taken at each position to show how the leg position and crank angle produced the end result. A thirty-six-tooth chain ring was used as an accurate angle for the crank position. Each value shown in the graph below is the average value for both legs. The photographic sequence shows the leg positions.

### CONCLUSION

Although tests of this kind are never precise, the data are adequate to show that a considerable advantage can be realized from pedaling backwards. The broad peak of the propulsive-force curve clearly shows why this is possible. A close examination of the photographic



*Crank angle, degrees*

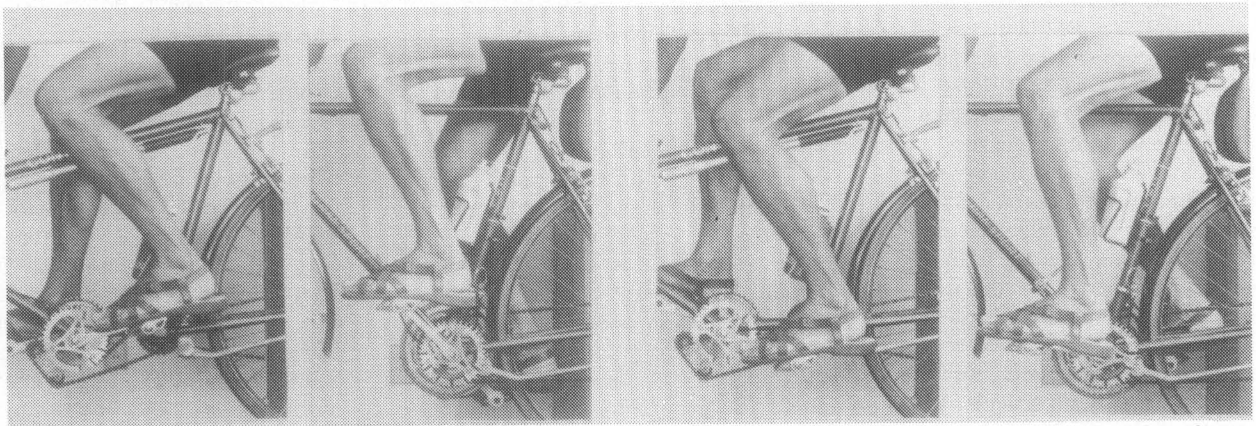


backward t.d.c.
f=68.3 newtons

forward t.d.c.
f=27.2 newtons

backward 30 deg.
f=99.4 newtons

forward 30 deg.
f=48.3 newtons

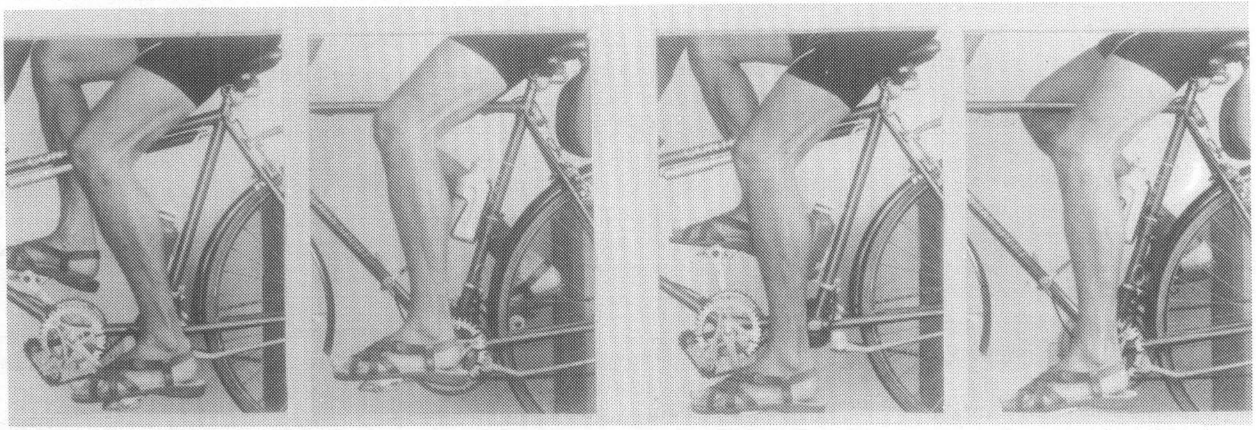


backward 60 deg.
f=118 newtons

forward 60 deg.
f=90.5 newtons

backward 90 deg.
f==117 newtons

forward 90 deg.
f=120 newtons



backward 120 deg.
f=111 newtons

forward 120 deg.
f=114 newtons

backward 150 deg.
f=86.0 newtons

forward 150 deg.
f=55.3 newtons

*Photographic sequence of leg position*

sequence can also reveal how the rider's legs have more leverage in the backward direction.

## AUTHOR

Ramondo Spinnetti
2531 S. Salta St.
Santa Ana, California 92704 USA
714-545-2842

## COMMENT

*(I sent Ramondo Spinnetti's paper to Steve Bussolari, director of flight operations of the MIT Daedalus project, for comments. Dave Wilson)*

The paper presents a comparison of the maximum torque and power produced on two upright cycles: one conventional diamond-frame upright racing cycle and an upright cycle that is designed for reverse-pedaling. The data indicate that there may be an ergonometric advantage to the reverse pedaling direction (approximately 20% in maximum power). This difference appears to be due to the ability of the rider to exert greater torque throughout the pedal cycle (the area under the static torque vs. crank angle curve for reverse pedaling is approximately 40% greater than for forward pedaling).

The resources available to the author were clearly a limiting factor. Definitive conclusions are difficult to draw from a single-subject experiment. From the information in the paper, I was not able to determine the scatter in the measurements. How many repetitions of the maximum power measurement were made for a single pedaling frequency and direction? How were the static tests performed (there appeared to be differences in the photographs between the angles reported and those visible in the photograph, e.g., backward and forward 30 degrees)? The balance of my comments will assume that the techniques and measurements reported are indeed stable for a larger population.

It is well established that maximum mechanical power output on a cycle-ergometer is very sensitive to the pedaling position. In our work, we have observed differences of approximately 20% in peak power output between upright and recumbent positions. I feel that this is due to changes in the mechanical relationship of the muscle groups involved as well as recruitment of different numbers and types of muscles (particularly those of the upper body). It is clear, upon examination of the photographs in the paper, that there is a large difference between both cycle designs in the relative position of the rider with respect to the pedals. It is possible that this difference may contribute much to the observed difference in power output, independent of pedal rotation direction. A definitive study would need to compare power output measured in the optimum position for forward pedal motion with that measured in the optimum position for reverse pedaling. The word "optimum", of course, implies quite a lengthy study indeed!

Many thanks again for passing the article to me. I am not quite yet ready to turn the gearbox in the aircraft around, but I found Mr. Spinnetti's work interesting.

## RESPONSE

I thank you and Dr. Steven Bussolari for reviewing my article and this opportunity to respond. There are five points of interest that I shall respond to in the same order in which they were mentioned in his review.

*(1) Scatter in the Measurements*

The maximum power output data for each bicycle was the average of two alternate runs at a single cadence value.

*(2) Crank Angles*

The crank angles in the photographic sequence represent the two directionally divergent angular displacements of the pedals from the T.D.C. positions of the two bicycles. Therefore, the two thirty-degree positions are quite different.

*(3) Pedaling Position*

The twenty-percent difference that he observed between upright and recumbent pedaling positions is understandable. I would also expect to observe this sort of difference when pedaling backwards as well. The upright position seems to have a gravitational advantage.

*(4) Bicycle Design Difference*

There is a large difference in the relative position of the rider's legs with respect to the pedals throughout the power stroke, but this is my whole point! Pedaling backwards causes this difference because the four-bar linkage formed by: (1) the pedal crank, (2) the rider's leg, (3) the rider's thigh, and (4) the bicycle frame (commonly called a quick-return mechanism) is not kinematically symmetrical with respect to its direction of rotation. When pedaling backwards, it has a slow, smooth power stroke with a high average torque and a quick return stroke. Conversely, when pedaling forward it has a quick power stroke with a high peak torque, but low average torque and a slow, smooth return stroke. Consequently, contrary to his speculation, the difference is dependent upon the direction of rotation rather than being independent of it.

*(5) The Daedalus Project*

Turning the gearbox around for backward pedaling of the aircraft would be premature at this point, but so would a lengthy study to investigate optimum performance. I would suggest that at least a modest training program involving at least one rider be run on the Daedalus flight simulator, pedaling in both directions. A subsequent comparison test could then indicate whether further investigation is warranted.

Ramondo Spinnetti ☐

## BRIEFLY NEWS. . .

*(continued from page 6)*

### HPV Nieuws

As mentioned earlier, this is the magazine of the Dutch HPV Association. It is a substantial journal, usually 20 pages, well-illustrated, and demonstrates that there is a great deal of inventiveness in Holland. In a recent issue there seemed to be a strong emphasis on recumbent bicycles and tricycles with front wheels that were both pedalled and powered, like geared "Big Wheels." The June 1987 issue has an article, promising to be the first in a series, on power production in various recumbent positions. If I run into a Dutch acquaintance again, I will ask for help to produce a digest of this and other articles.

### Daedalus Gear Transmission

Here is some information omitted when I discussed this transmission in the editorial of the last issue of HP. The off-the-shelf gears are made by ARROW GEAR, 2301 Curtis Street, Downers Grove, IL 60515, phone 312-969-7640. They were machined for weight reduction, and the housing was designed and made, by Bob Parkes of the Daedalus team, phone 408-253-0246 (home number).

### HP-Helicopter Activity in Britain and Japan

An article by A.D. Cranfield, leader of the "Vertigo" project and former engineer at Westland Helicopters, in the September 1987 Chartered Mechanical Engineer (Inst. Mechn. Engrs., UK) "Pedalling Towards a Vertical Take-off" states that "any design would work only within ground effect," which means that the height must be within one rotor diameter. The graph shows the theoretical power saving achieved by reducing the height/diameter ratio (Z/D). The group is using the AeroVironment Gossamer airfoils and twin counter-rotating two-bladed rotors beneath the pilot. "A group at Nihon University in Japan has built a rigid-rotor-hub machine virtually identical in configuration to Vertigo. It is known that very similar dynamic problems are being encountered by the group." This refers to blade-to-blade interference during crossovers, and wake interference from a reflection of the downwash from the walls of the hangar.

Toshio Kataoka wrote from Japan confirming some of the above, after he

*(continued on page 16)*

# ANGULAR MOMENTUM

*(continued from page 5)*

speed. When tested, a normal bike averaged just under a 50 mm ( 2 in) rms deviation.

Figure 4 shows the average rms for all the trials versus the amount of angular momentum. From this graph one can see the slight 'bowl-shape' one might expect from theory, with a greater average deviation at angular momentum settings of negative five and positive ten. Also the graph shows almost no disparity between the negative one and zero settings, implying little effect of small amounts of angular momentum, for the straight course at least. The difference between the normal bike and the zero-angular-momentum setting is due to the additional weight added to the front fork of the bicycle.

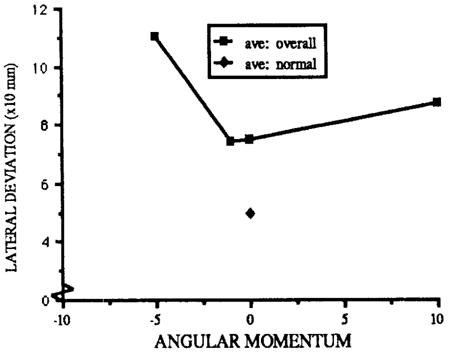


*FIGURE 4: Root-Mean-Square deviation for straight course*

The corresponding Cooper-Harper data agree with the general trend of the rms data. Interestingly, however, Cooper-Harper shows a considerable discrepancy between the negative one and the zero settings (ratings of 4.5 and 3.5 respectively). The ratings also jumped the gap between satisfactory and unsatisfactory. These results seem to imply that although a rider may not do that much more poorly in terms of lateral deviation, the bike does not 'feel' as stable at the negative-one setting as it does at the zero setting. As one rider wrote, "a different feel for some reason," and another wrote, "strange but unidentifiable effect."

A different trend is evident when one examines the three trials separately. A significant drop in rms deviation at the positive-ten setting is clear. In fact, the third trial at positive ten had the lowest rms of any test run. This finding is also supported by the corresponding Cooper-Harper data. When examining this trend in light of the theory presented, it would suggest that the additional angular momentum creates a large force couple making it difficult to turn the front wheel of the bicycle. Consequently, because this is a straight course, the bicycle becomes more stable at this angular-momentum setting.

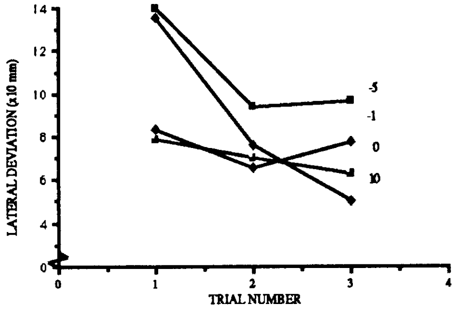


*FIGURE 5: Lateral-deviation learning*

*Curves for the Straight Course*

The learning curves for the straight course are shown in Figure 5. The graphs indicate slight learning at the negative-five, negative-one and zero settings, with possible difficulties at the negative-five and negative-one settings. On the other hand the learning curves show a significant decrease in the deviation at the positive-ten setting, implying that not only does the large coupling force help maintain course, but also that it is easy to learn to control this force.

### THE CIRCULAR COURSE

The circular course exhibited some of the same trends as did the straight course. Figure 6 again shows the bowl-shape one might expect from theory due to the increased force couple on the extreme ends. This difference between the normal bicycle and the zero-angular-momentum setting is again about 25 mm (1 in). The corresponding Cooper-Harper data also demonstrate the bowl-shape thus agreeing with the rms lateral-deviation findings. So once again one can say that the lateral-deviation results agree with the "feel" of the riders.

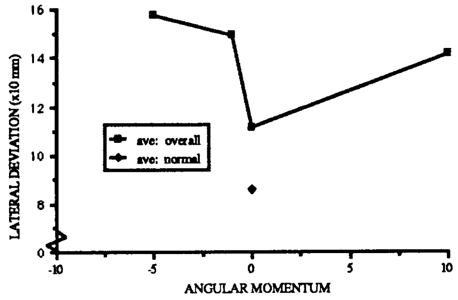


*FIGURE 6: Root-Mean-Square deviation for the circular course*

A definite difference exists, however, between the rms deviation on the circular course and on the straight course at the negative-one setting. Figure 6 shows that the negative-one setting has a very effect when riding a circle. In fact, the negative-one setting had as great a rms deviation as the positive-ten setting. The straight course did not demonstrate this adverse effect. Also there was a dramatic increase in rms deviation at negative one in all three trials, clearly implying that lack of angular momentum is highly undesirable when riding a curve.

The data for the learning curves further demonstrate the apparently extreme undesirability of the negative-one setting (Figure 7). Although the curve shows a propensity for learning at negative one, the values of deviation are still high compared to the zero setting. In fact, all three trials of the ten-times-angular-momentum setting are below their corresponding negative-one trials.

In this instance, the Cooper-Harper data slightly disagree with the lateral-deviation findings. For example, all three trials of the negative-one setting are rated better than the positive-ten setting. Also the ratings for negative one are relatively close to those for zero additional angular momentum (4.1 and 3.5 respectively). Apparently the riders did not notice a large difference in the characteristics at the negative-one setting, despite the rms data showing a discrepancy.

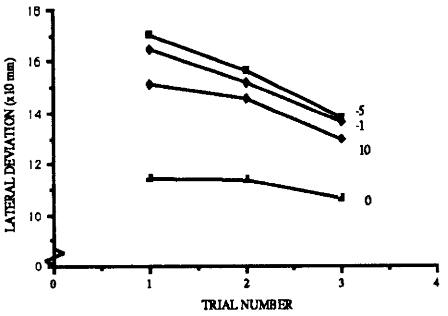


*FIGURE 7: Lateral-deviation learning curves for the circular course*

### THE SERPENTINE COURSE

In an effort to describe the characteristics of a bicycle when changing direction, a serpentine test course was used. Once again the data were consistent and maintained a bowl-shape (Figure 8). For this course, however, there is a dramatic increase in rms lateral deviation at the positive-ten times angular momentum. By comparison, the increase for both the positive- and negative-five settings are small, although still significant. Again, the negative-one and zero settings exhibit similar rms deviation with the negative-one setting still somewhat higher.

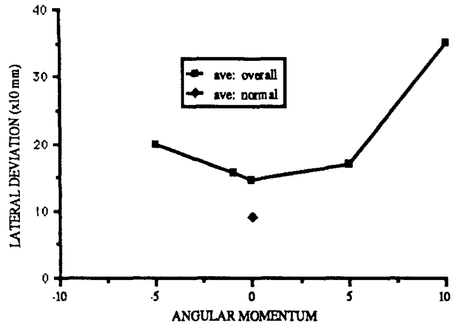


*FIGURE 8: Root-Mean-Square deviation for the serpentine course*

The Cooper-Harper ratings showed a bowl-shape. Again, the negative-one setting received more than 1.5-point higher rating than the zero setting despite the fact that their rms deviations were so similar. Another interesting point is the rating for negative five. The lateral deviation of negative five is comparatively close to the positive five, and yet the riders rated the negative-five setting much more difficult. Apparently negative angular momentum was not well liked by the test riders.

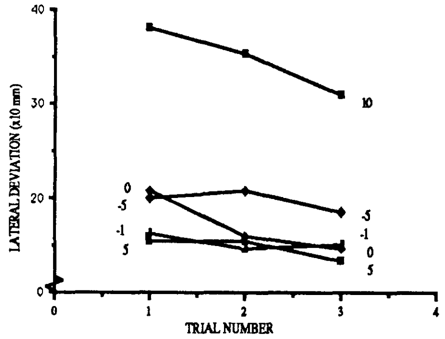


*FIGURE 9: Lateral-deviation learning urves for the serpentine course*

Figure 9 shows the learning curves for the serpentine course. These plots show, however, the negative-five times angular momentum actually has a lower rms deviation than does the positive-ten setting. This course is the only one to exhibit such a result. And again, the positive-angular-momentum settings show promise in ease of learning.

### THE LEAN-ANGLE STUDY

The test results of the lean-angle study are shown in Figure 10. The rigid-body theory consistently predicted a larger lean angle than was actually experienced. The actual data, however, do support Sharp's [2] idea of a larger lean angle at positive angular momentum and a smaller lean angle at negative settings. The theoretical values were calculated using the average speed and weight of the test riders involved. The actual values shown are the mean averages of all lean angles collected.

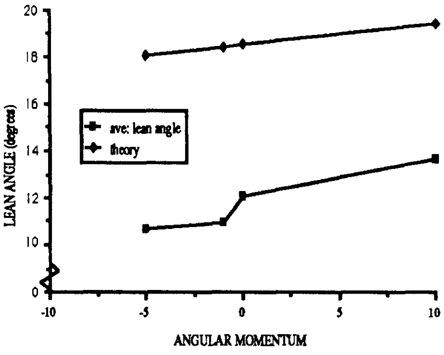


*FIGURE 10: Lean angle versus angular momentum*

## DISCUSSION

### THE ZERO SETTING

Overall, the zero times additional angular momentum showed nothing unusual or extraordinary. In all three courses the zero setting was at the base of the "bowl-shape", leading one to believe that the angular momentum of the front wheel did add a needed support for better control. In most cases the zero setting produced average rms deviations of about 25 mm (1 in) greater than a normal bike. These numbers help define the actual effect on the riding characteristics due to the added weight.

The riders also found the zero setting the easiest to control as demonstrated by the Cooper-Harper ratings. On the average, the riders found the zero setting to be 0.5 to 2 points lower than the negative-one setting. In all three courses, the zero setting received an average mark of about 3.5. This corresponds to the border between satisfactory and unsatisfactory. The zero setting is the only one to consistently remain below the unsatisfactory range.

A possible explanation for the Cooper-Harper rating being the lowest at this setting may have to deal with the riders' psychological view of the experiment. Some riders began the experiment with preconceived notions as to what was expected to happen. "This is supposed to be the easiest, isn't it?" was a common question when a test rider began a course at the zero-angular-momentum setting. Although this reasoning may have had some actual effect, it is difficult to say how much. One instead must rely on the consistency of the data to draw conclusions.

### THE NEGATIVE-ONE SETTING

Because of the negative-one setting, one begins to realize the importance of the angular momentum created by the front wheel of a normal bicycle. Although the negative-one setting may not have been dramatically different than the zero setting, it consistently demonstrated a greater rms deviation. These data are supported, and even enhanced, by the significantly higher Cooper-Harper ratings. Also the negative-one setting made the important jump from the satisfactory to the unsatisfactory but acceptable category on the Cooper-Harper scale. The riders felt that some improvement was warranted for this case.

On the straight course, the difference in rms deviation between the negative-one and zero settings is a few millimeters. When one considers the theory as described previously, this result can be easily explained. The rider is traveling in a straight line and therefore tries to minimize the amount of turning of the front wheel. Only small turning angles are necessary to maintain this course: that is, minimal external moments are applied. Thus by the conservation of angular momentum, no significant torque is created; therefore the rider will experience no significant force couple to overcome. Any torque created, assuming the rider stays relatively close to the course, will be dwarfed by the gravitational forces present, and indeed, the rider's own strength. Because very little turning is needed, there is little difference between the zero and the negative-one settings, due to the small torque created.

If one examines the circular and serpentine courses, however, one notices a considerable difference between the negative one and zero settings. In both instances there is an average rms deviation difference of approximately 25 mm. Again, by examining the theory, this difference can be explained.

Contrary to the straight course, the rider is required to turn the front bicycle wheel. This turning creates a force couple in the case of the zero setting, but in the case of the negative-one setting the force couple is cancelled by the flywheel. Apparently, the force couple created helps the rider keep the bike in place. However, the rider first needs to establish the proper lean and turning angles. So once the rider gets on the course and has the wheel turned the proper amount, the angular momentum helps the rider maintain that direction.

This theory also helps explain why many riders commented about difficulty beginning the course, but once on track found it easy to handle. Some riders even gave two Cooper-Harper ratings, one for the first part of the course, and another, better one for the second part of the course.

On the other hand, the negative one setting has no angular momentum vector. Therefore, no torque is created to impede any slight movements the rider may make. Instead these unimpeded movements lead to lateral deviation. This is definitely clear on the serpentine course where the rider is required to change the direction of turn. In this instance, when the rider turns too far, there is no torque to resist the sudden change.

The above explanation must also be considered when examining the Cooper-Harper data. In all instances, including even the straight course, the negative-one setting received noticeably less favorable marks than did the zero setting. This can be attributed to the lack of angular momentum and of the supportive torque at the zero setting, but also must be attributed to the expectations of the rider. All but one of the test riders classified themselves as 'experienced' bicyclists. Because they had previous bicycling experience, they depended on the angular momentum and force couple to resist any sudden changes they maymake. Now when that resistance is removed, the riders found it more difficult to ride the bicycle. The unexpected lack of resistance is probably responsible for the strange "feel" many of the riders said to have experienced.

### THE NEGATIVE-FIVE SETTING

Originally, the plans of this experiment had called for a maximum reverse setting of negative ten times the angular momentum of the road wheel. This setting was first tested on the straight course and proved to be uncontrollable by two riders. One rider, in fact, had difficulty making it to the course. As such, it was decided to reduce the negative limit to a negative five times instead of ten.

Overall, five times the angular momentum of the front wheel in the reverse direction proved to be the most difficult setting to control with sharp increases in rms deviation on all courses. In fact, the negative-five setting proved to be more difficult than the positive-ten setting on all runs except the serpentine. The negative-five setting, however, did prove to be more difficult than a positive-five setting on the serpentine course.

The Cooper-Harper data show further that the negative-five setting was the most difficult to control. For the straight and the circle courses the negative-five setting received marks on the upper bound of unsatisfactory but acceptable. Furthermore, for the serpentine course an unacceptable rating was recorded. The riders' comments also mentioned a great deal of compensation and physical strength required to operate the bicycle at this setting.

Theory indicates that a large torque is created due to the additional angular momentum. The theory would seem to imply that the additional momentum would lead to a stabilizing force when travelling in a straight line, similar to but larger than that experienced at the zero-angular-momentum setting. By the same arguments presented there, the bicycle should experience a force helping to keep it on course. The data taken, however, do not support this claim. On the contrary, the data seem to show the exact opposite—that negative angular momentum leads to a destabilization of the bicycle.

From the circle and serpentine course data, one again sees a large increase in rms deviation at the negative-five setting. Once more a torque is created due to any changes in the angular momentum vector. Understandably then, the rider has more difficulty turning at this setting. Nevertheless, it is intriguing that the negative-five setting has a greater rms deviation on the circle than the positive-ten setting; and that the negative five has a greater rms deviation than the positive five does on the serpentine course. In addition, the riders at this amount of reverse angular momentum averaged 25 mm more in rms deviation than the positive ten on the straight course where no turning is necessary. According to theory, the larger amount of angular momentum should produce a larger torque making it more difficult to turn.

Why should a negative setting exhibit such bad results compared to a positive setting? The answer to this question most likely lies within the rider. As was stated previously, all but one rider was 'experienced', and therefore expected certain things from a bicycle. In terms of angular momentum, the cyclist had always experienced a positive amount of angular momentum. Therefore, when the rider turned to a certain direction, he expected a certain torque. At the negative setting, however, the rider instead experiences the opposite torque than he was expecting. Instead of enhancing his lean angle, it resisted the angle; instead of helping the rider turn a corner, the move was impeded.

This explanation is also supported by the comments of the test riders. As one person wrote, "I can't figure out how to compensate for it [this setting of angular momentum]. You just can't turn the wheel when you want to and where you want to. It surprises you." Another wrote, "Unpredictable, I can't figure it out."

### THE POSITIVE-TEN SETTING

Despite the fact that the negative-ten setting was uncontrollable, the positive-ten setting proved to be quite controllable. According to theory, the positive-ten setting should produce a large torque relative to a normal bike. Most instances showed this to be the case.

For the straight course, the average rms deviation for positive ten was slightly greater than the rms deviation for the negative-one case and considerably less than that of the negative-five case. At first glance, this is a curious result considering the vast difference in the total amount of angular momentum. One can see a better explanation for this curiosity if one looks at the three trials separately (Figure 5). In this case, the great variance within the three trials at positive ten is apparent. Between the first and third trials, the rms deviation decreased by almost 100 mm (4.5 in). The course and setting generate one of the steepest learning curves in the entire experiment. Apparently, the rider learns to control the bicycle and the additional forward angular momentum. In fact, the third trial at the positive-ten setting has a lower rms deviation than does the zero setting, and even reaches the level of rms deviation for a normal bicycle.

In this case theory suggests the torque is so large the rider is capable of moving without affecting the bicycle a great deal, and that any slight deviation will be quickly corrected. Apparently, however, the cyclists took some time to get used to this strong effect. Nevertheless, once the rider learned how to work the bike at this setting, he rarely had problems. "Just let the bike do it," wrote one rider. Another said, "I could not have changed course if I wanted to." A third felt it was extremely stable, relating it to "a helping hand that wouldn't let you fall."

While the positive-ten setting may help a cyclist run a linear course, the large amount of angular momentum makes turning very difficult. The results of both the circle and the serpentine showed this result, with the serpentine demonstrating an even greater difficulty in changing the direction of turn. The rms deviation for the circle increased 25 to 50 mm at this setting, while the serpentine exhibited as much as a 200 mm (8 in) increase, being the only course and setting to have a higher rms than the negative-five setting. The Cooper-Harper ratings also support the theory with the riders finding positive ten more difficult than both the negative-one and zero settings on all three courses.

Such dramatic increases warranted further study, so an intermediate value of positive five times additional angular momentum was studied for the serpentine course. This setting performed as expected, and received marks between the positive ten and the zero settings. Also, the positive-five setting fared better than the negative-five setting in both rms deviation and Cooper-Harper data.

Undoubtedly the additional ten times positive angular momentum generates a large force couple. This large torque lends an extreme stabilizing effect which facilitates linear travel, but makes turning the bicycle highly difficult. This extreme effect is brought within acceptable levels when the positive-ten setting is reduced to a positive five times forward angular momentum of the front bicycle wheel.

### LEARNING CURVES

Learning curves are important because they show how well a rider adapts to unfamiliar circumstances. This adapting process may shed light on the stability characteristics of a bicycle. Also, insight into the interpretation of rider evaluations may be gained through learning curves.

All three sets of learning curves show that the rider adapts to the varying amounts of angular momentum. In all instances, the Cooper-Harper rating generally agrees, showing that the test riders also realize that they are adapting to the unfamiliar circumstances. The zero and negative one settings have the flattest learning curves showing the least amount of learning. Most likely this is because these settings are closely associated with a normal bicycle, so not much needs to be learned.

The negative-five setting does not exhibit typical learning curves (i.e. ones with negative slopes). In two of the three instances, the rms deviation actually increases on the second or third trials. In light of the counter-intuitive effects discussed previously, it appears as though the negative-five setting is difficult to learn because of its unexpected reactions.

The positive-ten learning curves (and the positive five in the case of the serpentine course) exhibit a consistent and relatively steep downward slope. Examining both the rms-deviation learning curves, the Cooper-Harper learning curves, and the riders' comments, it is evident that the positive-ten setting is easiest to learn. In fact, on both the straight and the circle course, the third trial at this setting proved to be the best test run for that course. Clearly, there is an aspect about forward angular momentum that enhances the rider's ability to adapt to the bicycle. Yet, this aspect definitely does not exist with the reverse amounts of angular momentum.

### LEAN ANGLE

As was previously stated, the lean-angle data varied noticeably from the rigid-body analysis. The obvious reason for this is the bicycle-rider system is not a rigid-body system. The rider has too much freedom and variation to be considered as a rigid body. Figure 9 shows that theory call for lean angles around 20°. Although this should be an equilibrium condition, the rider compensated for the large angle with shifts of weight and orientation so as to keep the bicycle at a more comfortable lean angle. The rider, therefore, plays too involved a role in the stability and riding characteristics of a bicycle for the bicycle-rider system to be modeled solely as a rigid body.

The data do, however, follow the general trend that theory suggests. They display a greater lean angle at the positive-ten setting and a lesser lean angle at the negative five. The negative-one setting exhibited a peculiar drop in lean angle when compared to the zero setting. This difference supports earlier claims of a noticeable effect due to the normal angular momentum of a front bicycle wheel. It is difficult to say, however, whether this drop is indicative of the test rider's expectations or actually a direct effect of the angular momentum. Most likely, the explanation is a combination of both reasons.

## CONCLUSIONS AND COMMENTS

Undoubtedly, the gyroscopic action of bicycle wheel has an effect on the riding of the bicycle. Although the couples produced are unable to account for dynamic equilibrium, they do add to the stability and ease of riding a bicycle. Forward angular momentum is an advantage to a limited extent, while reverse angular momentum has adverse results. The question remains as to how much angular momentum is the optimal amount. Having extensively ridden the test bicycle, I have found that an angular-momentum setting between four and five times the normal amount was most controllable for my general riding. For racing, where weight is a serious factor, there is a tradeoff between the extra weight required and the extra stability gained.

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## AUTHOR

Brenan J. McCarragher
233 Massachusetts Avenue
Cambridge, MA 02139
(617) 661-4111

## BRIEFLY NEWS. . .

*(continued from page 12)*

### HP Helicopters . . .

visited Professor Naito. He said that the old HPH is in the Kawaguchi Lake Automobile Museum. Toshio Kataoka was also kind enough to send a videotape of the Eleventh Annual Japanese Birdman rally, held on August 2, 1987 at Lake Biwa, a delightful, funny competition. I will send the tape to Marti Daily for the IHPVA collection.

## OXYGEN COST

*(continued from page 7)*

minutes of exercise were used in the data analysis. Three-way subject-group by workload by position ANOVA's were employed ($p<0.05$) for HR, VO2, and VE.

### RESULTS (Table 1)

No significant differences were indicated between the two cycling positions for HR, VO2 or VE at either workload. For both positions and workloads, no group differences were shown for VO2 or VE. For both postures, group differences were shown for HR between noncyclists and the conventional cyclists at the lower workload and between the noncyclists and both cyclist groups at the higher workload. The subject group differences in HR are summarized in Table 1.

### DISCUSSION

*Effect of Body Position*

Cycling in the recumbent position used in this study did not significantly alter the physiological efficiency of the subjects from that of cycling in a conventional position at submaximal workloads. Although previous studies found a decreased HR [1,2,3,4] and a lower VO2 [8] in a supine position, the lack of any difference in this study may be explained by the recumbent position used. The recumbent position used in this study differs from a conventional cycling position in both gross body position and in that there is no weight supported by the arms; however, it is a much more upright position than the supine position used in these earlier studies [1-4,8]. The gross body position used in recumbent cycling in this study is closer, in degree of being upright, to a conventional position than to a supine position, and thus, the differences between recumbent and conventional cycling can be expected to be less than between conventional and supine cycling.

*Effect of Accustomedness to Position*

The recumbent cyclists did not show a greater physiological efficiency in the recumbent position than the conventional cyclists, nor did the conventional cyclists demonstrate a greater physiological efficiency in the conventional position than the recumbent cyclists. This lack of difference may be at least partially explained by the subjects' cycling experience. The group of recumbent cyclists included several cyclists who spent more time cycling in a conventional position than in a recumbent position, although both were done on a regular basis. There was variation in the quantity and intensity of riding done by the cyclists and there was variation in the seat-back angle and bottom bracket height of the recumbent vehicles ridden by the subjects. All the noncyclists had, at some time, ridden a bicycle and, without exception, this experience was in a conventional cycling posture. More strictly controlled subject-groups and training regimes may demonstrate a difference in physiological efficiencies for the different positions based on the subjects' cycling backgrounds.

The HR for the noncyclists may be higher at the higher workload than that of both groups of cyclists because of a difference in the types of training of the two groups. Endurance training, such as cycling, will decrease the HR response to a given level of submaximal exercise [10]. Six of the ten noncyclists engaged in weight lifting, rather than an endurance type of exercise, as their primary source of physical activity. The effect of the cyclists' endurance training was more evident at the higher workload where both cyclist groups had significantly lower HRs; however, the noncyclists had the highest mean HRs at both workloads and in both positions.

TABLE 1 OXYGEN CONSUMPTION (ml kg-1 min-1)

| | Recumbent position | | Conventional position | |
|---|---|---|---|---|
| Group | 51.5 Watts | 154.5 Watts | 51.5 Watts | 154.5 Watts |
| R<br>(n-10) | 13.39+3.26 | 32.45+5.11 | 13.23+2.93 | 32.27+3.73 |
| C<br>(n-10) | 14.46+1.44 | 32.83+4.81 | 15.18+1.95 | 33.38+4.58 |
| N<br>(n-10) | 14.08+3.56 | 32.17+5.06 | 13.53+2.83 | 31.44+4.91 |

HEART RATE (beats min-1)

| | Recumbent Position | | Conventional Position | |
|---|---|---|---|---|
| Group | 51.5 Watts | 154.5 Watts | 51.5 Watts | 154.5 Watts |
| R<br>(n-10) | 96.3+8.2 | 133.1+9.5 | 93.3+9.1 | 130.0+10.1 |
| C<br>(n-10) | 88.8+8.3 | 124.2+11.2 | 88.6+5.9 | 122.2+10.2 |
| N<br>(n-10) | 99.8+14.1* | 142.8+22.7^ | 100.5+15.4* | 141.5+22.6^ |

MINUTE VENTILATION (1 min-1)

| | Recumbent Position | | Conventional position | |
|---|---|---|---|---|
| Group | 51.5 Watts | 154.5 Watts | 51.5 Watts | 154.5 Watts |
| R<br>(n-10) | 27.65+6.39 | 67.48+3.92 | 27.34+6.02 | 64.50+3.18 |
| C<br>(n-10) | 29.12+5.13 | 64.83+8.78 | 29.25+4.95 | 62.88+6.58 |
| N<br>(n-10) | 31.23+10.40 | 74.10+16. | 52 28.53+7.66 | 69.00+12.62 |

Values are mean for the last three minutes of each workload +S.D.
R- the recumbent cyclists.
C- the conventional cyclists.
N- the noncyclists.
* significantly different from conventional cyclists.
^ significantly different from conventional cyclists and recumbent cyclists.

### CONCLUSIONS

Since a recumbent posture can offer decreased wind resistance and no loss in physiological efficiency at submaximal workloads, this posture can offer improved mechanical efficiency; i.e., less energy output to achieve a given velocity, over the conventional posture. Although for submaximal workloads, such as touring and recreational cycling, the full advantage of the decreased wind resistance will not be realized, the recumbent position, with no loss in physiological efficiency, may also offer increased comfort over the conventional bicycle.

### RECOMMENDATIONS FOR FURTHER STUDY

1. A similar study should be conducted using more homogeneous subject-groups. Cyclists groups should train in as similar body positions as possible and in similar quantities. Noncyclists should undertake endurance training of an amount equivalent to that of the cyclists. All subjects should be of similar height and weight to minimize variation due to individual differences in optimum crank-arm length.
2. A similar study should be performed using a high-quality ergometer for

which workload is independent of pedal cadence to minimize variation due to individual differences in optimum cadence.

3. A study should be conducted to seek the optimum body position for submaximal cycling in the recumbent position by using different seat-back angles and bottom-bracket heights.
4. Prone body positions should be studied in addition to conventional and recumbent postures.
5. Similar studies using higher workloads applicable to racing cyclists and speed attempts should be conducted.
6. Larger subject-groups and female subjects should be included in similar studies.

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## AUTHOR

Ingrid E. Antonson
1340 E. Lewis
Pocatello, ID 83201 USA ❑

## LETTERS TO THE EDITOR

### Shaft Drives

As I read your comment on shaft drives in *Human Power* 6/2 I was reminded of a day in 1979 when I was in the American Embassy in London with Frank Whitt looking at the Gossamer Albatross, which was on display prior to the historic Channel flight. I do not know much about HPAs, but I did remember reading something about the shaft-drive mechanism used by one of the early teams of experimenters. Frank was very interested in drive systems and gears and we talked a little about the subject in relation to the Albatross... I had a miniature tape recorder and decided that I would like to have Frank on record saying something. He said he was happy to talk into it – what should he say? On the spur of the moment I suggested that he tell me why bicycles don't use shaft drive anymore.

I have just rummaged through my old tapes thinking how nice it would be if I could report his answer word-perfect. Alas! I cannot find the tape! (John goes on to report on his work with a moped that used a timing belt, and on the new folding "Strida" bicycle, that apparently also uses a toothed timing belt.... We have to report his last sentence:) Please forgive me for not being able to find something negative to say about *Human Power.*

John Stegmann
1 Heath Street
Newlands 7700, South Africa

*("Letters" continued on page 20)*

## ARM-LEG POWER

*(continued from page 9)*

devising acceptable steering systems that are comfortable, compatible with more conventional rear-wheel drive/transmission systems, and yet elegant in simplicity.

In pedalling some of our arm-leg powered prototype cycles, I've noticed (more subjectively) that there is some unknown "equation" that would make combined arm-and-leg powered cycles more efficient. I find that periodically resting my arms while still pedalling with legs, "feels" the best. On the theoretical side of this issue, the next step we are following is to look at the bioenergetics of producing power under varying contributions of arm and leg efforts; the purpose here would be to determine what kind or length of rest periods might be optimum for the arms under sustained arm-leg pedalling.

Physiologically speaking, the arm musculature is not designed for aerobic (endurance) work. There seems to be found naturally a disproportionate number of fast-twitch fiber types (anaerobic) in the arms compared to the more aerobic slow-twitch fibers. The results we reported were based on average young adults. My suspicion is that specific endurance training in the arms (witness wheelchair sports) would enhance still further the advantage already demonstrated in combined arm-leg power production.

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## AUTHORS

Richard Powell and Tracey Robinson
Dept of Physical Education & Recreation
New Mexico State University
Box 3M
Las Cruces, NM 88003 USA
505-646-2215 ❑

# Oh For the Wings

### Arthur C. Clarke

*(This short piece was given to me by Arthur C. Clarke after he came to a talk I gave on the IHPVA at the Sri Lanka Institute of Engineers. He is a well-known author of science fiction, credited with many accurate predictions of future inventions. The piece is from "The Challenge of the Spaceship" (Harper '59) and originally appeared in Holiday 1955.—DGW)*

The rapid development of automation now makes it virtually certain that there can be no escape from an age of compulsory leisure in the not-too-distant future. It is also equally certain that most of mankind won't be content to occupy its spare time exclusively with painting, ballet dancing, orchestral composition, poetry recital, monumental sculpting and similar aesthetic activities. Which leads us to conclude that one of the greatest benefactors of the human race in the years ahead will be the man who can invent a new sport.

A completely new and original sport is a very rare invention indeed. We are lucky enough to have witnessed the birth of a major one – skin diving – during the last decade.* It now seems quite possible that an even more spectacular and unexpected recreation will arrive in the quite near future. That new sport may be–flying.

Before you ask indignantly where I've been hiding since 1903, let me make clear exactly what I mean. The flying I refer to is one of man's most ancient dreams, forgotten since the internal-combustion engine gave us (at a price) the freedom of the air. It is flight by muscle power alone – the practical achievement of the legend of Daedalus, the conversion into reality of Leonardo da Vinci's sketches.

We are so accustomed to the roar of thousands and tens of thousands of horsepower in the sky that we have taken it for granted that muscle-powered flight is an aerodynamic impossibility as far as human beings are concerned. Our bodies, it has been generally assumed, are far too heavy and underpowered for the job. And anyway – who cares?

Let's deal with the last point first. A great many people would care, if they had the slightest idea that such a feat as man-powered flight was even theoretically possible. There is always a sense of achievement in doing something without mechanical aid, and discovering the limits of the human body's ability. Only the most torpid and unimaginative of men can fail to feel some sense of excitement at the idea of competing with the birds in their own element, on their own terms.

The development of aerodynamics as an exact science now allows us to analyze the problem of manned flight as a straight-forward engineering proposition. There is a certain whimsical interest in the fact that the subject is now being studied by a group of young British aerodynamicists at the College of Aerodynamics, Cranfield – in the intervals between calculating what happens to vehicles re-entering the Earth's atmosphere from outer space at twenty times the speed of sound.

The crux of the problem is how much power a man can develop. For very short periods (say a couple of seconds) this may be as much as 1-1/2 hp, if the legs and arms are used simultaneously. This is equivalent to lifting one's own weight through five feet every second – a sort of high-jump performance, in fact. It obviously has no relevance to sustained, steady operating conditions, but may be of importance in connection with take-offs.

The continuous power which a man can produce for longer periods – up to an hour – is just under half a horsepower, and a little more if arms as well as legs are used. (.45 hp legs alone; .6 hp all limbs working). When one looks at the disparity in size between a horse and a man, this figure is quite surprising. However, the definition of a horsepower – a rate of working of 550 foot-pounds per second – was laid down at the beginning of the steam-engine age by James Watt, and we can be quite sure that he chose a small and skinny horse for his standard so that the performance of his engines would appear correspondingly impressive. Even then, he probably cooked the figures.

The basic problem of manned flight, therefore, is that of building an aircraft that can fly on a half-horsepower engine. This would be a considerable feat of aeronautical skill, and it is not certain that is is possible. What does appear to be possible, however, is to build a two-man machine that could be sustained in the air by muscle power alone. The point is that an aircraft carrying two men would have double the power, but much less than double the drag and weight, of a "single engined" one, and would be correspondingly more efficient. It might be even better to have a still larger crew, all but one of its members pedaling furiously with hands and feet while the odd man out steered the machine and provided power with legs alone.

To concentrate on the minimum-sized, two-man machine, calculations made by B.S. Shenstone indicate that it would have to weigh about five hundred pounds (more than half that being the weight of the crew) and would have a wingspan of about sixty feet. The very large wingspan arises from the fact that the aircraft must have the extremely low wing loading – the amount of dead weight each square foot of wing area has to support – of about two pounds per square foot, as compared with the fifty or more pounds per square foot of a modern airliner (not to mention the hundred pounds per square foot and up of a supersonic fighter).

Incidentally, it might be mentioned that Mr. Shenstone is the Chief Engineer of British European Airways. His interest in this particular problem should cause no alarm to BEA passengers; it is a purely private one and doesn't indicate that the company fears that its customers will ever have to get out and push.

The airframe would have to be extremely "clean," since no power could be wasted overcoming unnecessary drag, even at the low speed of 30 mph, which is about the limit to be expected from such a vehicle. To obtain the required low drag, what is known as "boundary-layer control" would be needed. This involves sucking air from the wing through slots placed at strategic locations, thus preventing the build-up of turbulent eddies. One of the most difficult engineering problems in the design would be getting the power out of the men and into the airscrew without too much loss through gears, chains or bearings. A very efficient transmission system would be required, as the crew would be at the front or center of the aircraft, and the propeller would probably be at the rear.

Without going into too many details which still remain for the experts on subsonic flight to work out, we can get a fairly clear idea of the two-man aerial bicycle of the near future. It would look very much like one of today's gliders, and would be built from similar materials. The wing would be excessively long and thin – only about five feet wide at the roots, but with a total span of sixty feet. There would be no undercarriage, a spring-mounted skid serving for landing gear.

To keep frontal area to a minimum, the crew would sit – or even lie in a reclin-

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*This was written c. 1955. Ed.

ing position, like bobsled riders. The pilot would pedal with his feet and use his hands for control; the rear man would be working flat out with all his limbs.

There is one slight difficulty we haven't mentioned yet. Such an underpowered aircraft could fly, but it couldn't take off. It would have to be launched into the air like a glider by winch, catapult or rockets.

The take-off could be purely man-powered if the vehicle contained some energy-storing device which would be revved up by the crew while they were still on the ground, and then coupled to the propeller to give a brief burst of power. A spinning flywheel is the obvious example of such a device, but would be far too heavy to be practical. Perhaps a compressed-air system might do the trick, and would also solve the transmission problem. The crew could pedal away until they had built up starting pressure in a cylinder, and at the right moment this would be connected to a tiny piston engine driving the airscrew. The use of compressed-air lines instead of shafts or chains would simplify the engineering problems, but the increased weight and complexity of the system might make it impractical.

In any event, it is clear that the aircycle will be a fairly expensive piece of machinery – at least as expensive as a glider, though of course the cost of production would fall sharply if the demand was sufficiently large. The two-man machines would certainly be within the reach of most sports clubs, colleges and athletic organizations. And as for the larger ones, it is obvious what their destiny would be.

It's about time that Harvard and Yale, not to mention Oxford and Cambridge, moved ahead with the times. Can't you picture the excitement as the beautifully streamlined aircraft, fragile and delicate as dragonflies, are brought out of their (ivy-covered) hangars? The crews – representing the highest power-to-weight ratio their colleges can muster – file into the long, slim fuselages and take their places in line astern. They won't see much of the race; but then they never did. Only the coxes under their tiny Perspex blisters will know what is happening and will control the flight of the graceful, man-powered birds.

The propellers spin into invisibility, the rudders and ailerons swing back and forth as the controls are tested. The elastic launching cables have been attached; the two aircraft are lined up side by side, waiting for the starting signal.

They're off! Leaping from the ground under the smooth yet steady tug of the catapults, the two machines rise steeply into the sky. At the same instant the launching cables drop away; they're on their own now, as they head toward the starting line, at all of forty miles an hour, on the first lap of the unforgettable race of 19 .

What date shall we fill in there? As far as technical considerations are concerned, the aircraft could be ready in five or ten years at the most, and if anyone has a large fraction of a megabuck which they would like to donate to a spectacular but completely useless cause this time scale might be compressed.

Useless? That, it seems to me, is one of its chief virtues. A feeble and far-fetched case might be made out for some military applications, but only the dimmest of generals would be convinced by it – perhaps one who was still pining for the days of cavalry. Though the glider has been turned into a weapon of war, the man-powered airplane appears to have about as promising a military future as the crossbow.*

Perhaps for this very reason we won't develop it. We may be so busy building rockets and starting on the conquest of space that we'll leave it to the twenty-first century to complete the conquest of the air.

*Postscript*

There have been further developments in this field since the above article was written. In England, the Royal Aeronautical Society has formed a Man Power Flight Group, and the Russians (here we go again!) have also set up a "Muscle Powered Flight Committee." The aero Club de France is organizing a competition for such aircraft, and the startling fact has emerged that it might have been won in 1936 by Haessler and Villinger in Germany, who made several officially observed single-seat man-powered flights of over two hundred yards at heights of between three and fifteen feet.

Anyone who is interested in technical details will find a paper of great value by T. Nonweiler in the October, 1958, issue of the Journal of the Royal Aeronautical Society.

## AUTHOR

Arthur C. Clarke
25 Barnes Place
Colombo 7, Sri Lanka

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*Arthur Clarke wrote in the margin here, "Hurrah!"

# LETTERS

*( continued from page 18)*

### Practical HPVs

Charles Fortuna's article "Let's Get Practical", HPV News March/April 87, encourages me to write this letter. He points to a very important item. Races have been and still are a very good means of attracting the attention of the public and TV to the idea of HPVs. But in order to spread the idea of HPVs, a further development to every-day use is absolutely necessary. The most important step in this development is a good, light fairing which can be easily removed. When it is raining the rider of a recumbent bike is worse off than the rider of a normal bike. For the latter it is enough to have a simple poncho or raincoat. We should not dream of a rain cover which is 100% perfect but we should immediately construct a rain cover which achieves 75% efficiency.

I myself have ridden recumbent bikes for five years and I have constructed several of them. I include two photos and sketches of the bike I use in the moment. It is extremely comfortable, because the spring of the front suspension gives 70-mm travel, and the spring of the rear suspension 150 mm. Pedaling does not influence the rear suspension, because the chain goes directly through the turning center of the rear suspension. The fact that a friend was eighth in the European championship '86 in Nuembrecht proves that there is no loss of energy caused by the suspension.

The fairing weighs 1600 g and I think that a weight of 1000 g is possible. The fairing can be mounted and removed without tools in two minutes. In dry weather the rear part can be completely folded to the front. Even for getting on and off the fairing is folded.

My experiences in constructing recumbent bikes have been summed up in a small brochure, which I am sending, although my English is not good enough to translate it. At the moment I photocopy the brochure if people ask for it. Unfortunately this results in bad photo quality. The brochure is likely to be printed next winter.

The latest type which I constructed is called Merkur. It also has a rear suspension and therefore I can use a small wheel with a high-pressure-tire. Thus I have a low rolling resistance. Even in the city it is a great joy to ride this bike because it is only 1.95 m long. I include a photo and a construction plan, in order to convey an idea of what I do.

Werner Stiffel
Huebschstr. 23
7500 Karlsruhe
West Germany

(If a volunteer would be willing to translate Werner Stiffel's plans, he has given permission to the IHPVA to reproduce them for sale. Please write to me. Dave Wilson)