Werktuigkundige Studievereniging "Simon Stevin"

HPV
SYMPOSIUM

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T.U. EINDHOVEN
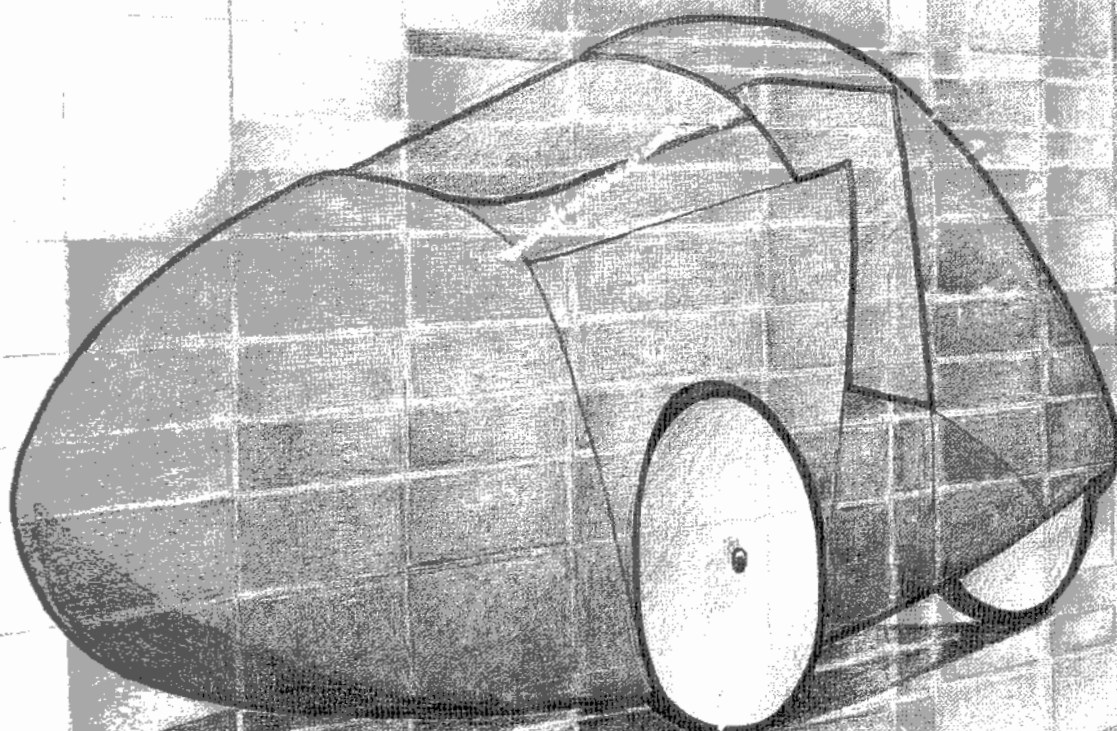
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This book is a special edition on account of the FIETS'93 event, held on 17 and 18 march 1993 at the University of Technology in Eindhoven, The Netherlands.

Editors: Patrick Asselman, Toni Cornelissen,
                                  Meike Moltzer and Gérard Vroomen

These people are actively involved in the association for mechanical engineering students at the University of Technology in Eindhoven "Simon Stevin", of which the adress is as follows:

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Preface

Despite the enormous pressure to get this book finished, I was able to find some time ro write the preface: it is now 10 march, 0:52 h.

The accomplishment of this book is mainly owed to the HPV-committee, consisting of Toni Cornelissen, Meike Moltzer, Gérard Vroomen and me. They are a fine group of people who know how to deal with things, and I'm glad they do: organizing a symposium as part of such a big event as this one in about three months is not to be taken lightly! How the University of Technology Eindhoven, and in particular the association "Simon Stevin" of the faculty of mechanical engineering, first got involved with the world of HPV's can be read on the next page. I hope the interest of students on the UT Eindhoven for HPV's has been aroused, and that the UTE can contribute in the future to the further development of HPV's.

We would like to thank here all the people who made the FIETS'93 event possible:

- René Quax, Gérard Vroomen and Hubert Vroomen for arousing our interest in the world of HPV's,
- Guus van de Beek, Vibeke Duyff, and all other cooperators at the FIETS magazine for starting the 365-days contest and for their knowledge of the world of HPV's,
- mrs. ir. Anita Heijkamp and the other people of the Masterplan Fiets, for the financial support, without which this event could not have taken place,
- Jos van Rijen who brought the 365 days FIETS prize to our attention, and who put his many contacts at our disposal,
- mr. Brian, mr. Maas, and others at DAF for put the DAF test track at the disposal of the 365-days FIETS prize,
- all the people who supplied us with HPV's for the exhibition,
- Leopold Manche and others at Studium Generale who help with the exhibition,
- Paul van Noorden, Walter van Hulst, and all others, who knew how to start up publicity for this event,
- Carla of the congress agency, who took much work out of our hands,
- Leo van de Bom for putting some of his photographs at our disposal,
- the speakers at the symposium for freeing their time and for delivering their texts at such a short term,
- all the participants in the 365-days FIETS prize who sent us information regarding their designs,
- prof. Schlösser for his performance as chairman of the day,
- the board of government of "Simon Stevin" for putting all their facilities at our disposal, and especially Jeroen Mertens for his share in the translations during the crisis situation preceding this book,
- mr. Verschuren who is assisting us with the financial matters,
- and last but not least our parents who enable us to enjoy the college world.

On behalf of the HPV-committee,

Patrick Asselman

3 Years of Human Powered Vehicles at the Eindhoven University of Technology.

At the 12th of august 1989, Hubert Vroomen and I returned from a holiday to Denmark. At home Gérard Vroomen showed us his new gain, a Flevobike. The bike wasn't painted yet but one could ride on it already. Of course we had to try it. That wasn't easy. After half an hour it seemed to be possible to ride a few meters. The interest for the Flevobike was exited.

Because we all three were looking for a way to develop some practical insight within our study of mechanical engineering, the idea grew to start a course after the example of Johan Vrielink to build a Flevobike by our own. At the 1st of march 1991 this idea was mature and the organisation of the "practice course of manufacturing techniques 1991" started. This organisation consisted of Hubert Vroomen, Gérard Vroomen and the undersigned.

The aim was to organize a course with 11 participants, who would all construct there own bicycle. The members of the course would make by there own as much parts as possible. A Flevobike offers excellent opportunities to do so. All parts of the frame would be assembled during the welding lessons, various parts would be manufactured by the members of the course and to make the plastic chair was thought during a workshop. The interest in participating was large, 37 students subscribed. Alas only 11 participants could be accepted.

With these 11 participants, all student mechanical engineering and member of the mechanical engineering study association "Simon Stevin", we started at the end of march a program of 8 lesson in welding, 10 mornings of milling and turning and a daylong workshop in manufacturing with plastic. After the 4th week enough frame parts were ready and the students had reached a level of welding ability to assemble the first parts of the bicycle. At the half of June all the steelwork is powdercoated with red paint and only one week rested for assembling the rest of the bicycle. On the 2nd of July the first red Flevobike of the course rode and the members of the course could start to learn riding on there Flevobike. At the beginning of october everybody was able to complete a 40 km long bicycle ride. Of course it wouldn't have been possible to us to organize this course without the help of several members of the personnel of the EUT, such as Toon Manders and Peer Brinkgreve, Ad Onzenoort and many others.

In 1992 this initiative has been followed up by a second course, this time for 16 participants. This course has already finished so besides 11 red Flevobikes another 16 gray ones can be seen in the streets of Eindhoven. Plans for another third course are already made. During this activities the idea of organizing an event for human powered vehicles started. In co-operation with the organisers of the "365-days-bicycle" competition the BICYCLE '93 event in Eindhoven has been achieved. During this event attention will be payed to innovation in the construction of bicycles and the daily use of a recumbent bike. I hope this event will be the start for a lot of innovations in the subject of human powered vehicles and that it will be the first one in a series of HPV-events at the Eindhoven University of Technology.

"Simon vóór de wind",

René Quax.

Predicting human powered vehicle performance using ergometry and aerodynamic drag measurements [1]

Chester Kyle
professor mechanical engineering
California State University, Long Beach

In order to predict the feasible performance of a person using a bicycle, a number of tests have been performed at California State University, Long Beach (CSULB)

Three categories of measurements can be distinguished:
1. Tests of the wind and rolling resistance of commercial HPV's such as bicycles, tandems and tricycles (1973-present).
2. Building and testing the wind and rolling resistance and performance characteristics of high-speed streamlined HPV's (1974-present).
3. Testing human subjects for maximal power output using bicycle ergometry and utilizing this data to try to predict the performance of HPV's (1975-present).

I. Drag measurement in Human Powered Vehicles

A simple procedure in measuring the resistance forces against any common land vehicle is to coast the machine on a level surface in a straight line without applying power or braking, and to measure its speed as a function of time or distance. The rate at which it slows down is proportional to the total resistance forces against it. This measurement is called a coast down test. A 400 m. long indoor hallway was used at CSULB for the coast down drag measurements reported here. Six electric tape switches were evenly placed every 6 metres for 30 meters. By recording pulses on a strip chart recorder travelling at 150 mm/s, the coasting time between switches could be accurately measured, and the average speed found. This was plotted versus the distance and the total drag forces could then be calculated from:

(1) $\quad F = mv\dfrac{\Delta v}{\Delta x} \quad$ where m is the mass, v is the velocity, and x is the distance travelled.

It was found that the variation of velocity with distance $\Delta v/\Delta x$ was almost exactly linear in the range measured. Total drag measurements for several typical machines are shown in fig. 1 [1],[2].
It can be seen that the position that a rider assumes is much more important than any other factor. The type of tire used also can lower the drag, but not nearly so much as using the crouched racing position. The reason for this will be explained in the sections that follow.

Rolling resistance

In order to estimate the tire and bearing rolling resistance, a bicycle was towed on a motorized treadmill and the drag measured with a spring scale. The rolling resistance may be expressed approximately by the relation:

(2) $\quad F_r = m(a_0 + a_1 v) \quad$ where F_r is the rolling resistance in kg, m is the mass in kg, and v

the velocity in m/s. The constants a_0 and a_1 depend upon the type of tire used. (for 90 psi, 27 inch touring tires, a_0 and a_1 were 0.005 and 0.0002 respectively)

The effect of streamlining

It can be seen from fig. 1 that most of the resistance to motion is due to wind resistance even at moderate speeds. Wind resistance increases as the square of the velocity, and quickly becomes the dominant factor. Above 10 m/s, wind resistance is about 85% of the total. Therefore, if the energy efficiency of HPV's is to be increased, the logical method would be to improve the aerodynamics. Most aerodynamic improvement is done by either lowering the frontal area to the wind or by smoothing out the profile thus streamlining the object, or both. The common methods of aerodynamic improvement are:

1. A racing cyclist rides in a crouched position, and by so doing lowers his frontal area and improves his aerodynamic shape as well. The most efficient aerodynamic shape the human body can assume is a horizontal diver's position. Although this is not a possible riding position on an ordinary bicycle, still the racing cyclists approximate it as closely as they are able with their horizontal upper body position.

2. A special vehicle can be built to change the cyclist's pedalling position to either prone (on the stomach) or supine (on the back), thus drastically lowering the frontal area, and smoothing out the air flow.

3. Special aerodynamic devices may be fitted to a machine to completely change its shape. These are called fairings or shells, and they can either partly or completely enclose the rider.

The object of any of the above methods is to disturb the air as little as possible, the vehicle should pass through air cleanly without wasting energy in turbulent mixing. Unfortunately, the erect human body, and vertical bicycle tubes or tires are among the worst aerodynamic shapes in existence, leaving a broad turbulent wake behind them. Efficient aerodynamic shapes more resemble tear drops, arrows, or wing shapes.

Partial fairings

Fig. 2 shows drag measurements on several partial fairings fitted on a regular bicycle. These partial fairings smooth the flow of air around the upper body of the rider, and although they sometimes permit an appreciable wake at the rear, they still cut the wind drag significantly. The drag of a bare bicycle with the rider in racing position is shown in fig. 2 for comparison. Several versions of the Zipper road fairing are shown on the graph. This fairing is sold commercially in the USA by Glen Brown, and it was modified by adding paper sides, top and bottom in various combinations. The complete modification was quite effective, however the others were about the same or worse than the unmodified fairing.

One must be very careful in making claims about the effect of partial fairings unless they are actually tested. As can be seen from fig. 2, the Watson fairing, and the Zipper fairing

with the top only, have the same drag as a bare bicycle. The two Zipper fairings achieve a 12% over all drag reduction at 32 km/h, while the fully modified Zipper fairing achieved a 20% over all drag reduction. The commercial fairing would permit a rider to travel about 2 km/h faster (to 34 km/h) with the same expenditure of energy. The more elaborate Van Valkenburg Aeroshell fairing achieves a 36% over all drag reduction and would permit a 5 km/h speed increase (to 37 km/h) with the same energy expenditure.

Partial fairings can be extremely practical devices; they can provide protection from the cold and the rain, in addition to making the vehicles more efficient. Perhaps more important, they can give some safety protection in case of crashes. One of Paul Van Valkenburgh's models is a soft plastic inflated device which can be stored in a small space and will cushion falls. The hard plastic model will protect a fallen rider from abrasion. One rider took a fall at over 65 km/h at the 1977 International Human Powered Speed Championships, and not even scratched [8]. He was riding an ordinary racing bicycle with a hard plastic fairing that covered his upper body and thighs. There were also two crashes in 1978 with recumbent vehicles at over 75 km/h in which the rider was completely free from injury or abrasion [9]. These partial fairings could be just as easily applied to mopeds to increase their efficiency and safety.

Full fairings

Fig. 3 shows the drag of several standard bicycles and recumbents fitted with full fairings. The drag of two of the machines without fairings is shown for reference. The Van Valkenburgh Aeroshell with bottom skirt, reduced the total drag of a standard racing bicycle 48%, and the Kyle fairing decreased the total drag 67% at a speed of 32 km/h. They could travel at speeds of 41 km/h and 48 km/h respectively with the same energy consumption as a standard bicycle travelling 32 km/h. These vehicles were designed for sprint racing, and their top speed over 200 meters with a flying start is listed in table 1 along with a summary of other interesting results from the present drag measurements. References 15 and 16 give results of wind tunnel tests on this type of vehicle.

A supine recumbent tricycle designed by Mario Palombo with and without fairing is shown in fig. 3 along with a supine recumbent quadracycle with fairing designed by Paul Van Valkenburgh. Both vehicles use hand and foot cranks for propulsion. Van Valkenburgh's fairing was much more efficient than that of Palombo, and so the drag was much lower. It is interesting to note that the Kyle standard bicycle fairing also had a lower drag than Palombo's recumbent with full fairing. A redesign of this fairing would produce a much faster vehicle. Van Valkenburgh's prone fairing is 54 cm. wide, 89 cm. high, and 252 cm. long; the ground clearance is only 1.3 cm. The fairing is based upon an NACA 66021 symmetric wing profile. The Kyle fairing is 56 cm. wide, 132 cm. high, 279 cm. long, is based upon an NACA 0020 wing profile, and has 15 cm. ground clearance. The Palombo fairing has approximately the same dimensions as the Van Valkenburgh fairing; however it was hastily put together without wind tunnel testing in hurried preparation for a race; and therefore the results were not as good as with the other fairings.

Also listed in table 1, is the drag coefficient c_d based upon the frontal area. The drag coefficient is a measure of the aerodynamic efficiency of a particular geometric shape. Inefficient shapes such as cylinders or cubes have drag coefficients greater than 1.0, while efficient shapes such as wing sections or missile shapes have drag coefficients sometimes less than 0.1. The drag coefficient is defined by the equation:

(3) $\quad F_w = \frac{1}{2}\rho \cdot c_d \cdot A \cdot v^2 \quad$ where F_w is the drag due to wind resistance, ρ is the air density, A

is the frontal area, and v is the wind speed.

Unfortunately, since most of the vehicles tested were designed strictly for racing, some of them are not at all practical. Only the bicycles with partial fairings could be ridden on the street in any weather or wind conditions; the recumbents and the full bicycle fairings are unsuitable for road service for various reasons. The Kyle fairing is unstable in side winds, while the Aeroshell with bottom skirt won't make short radius turns even though it is stable in the wind. The recumbents were designed to go in a straight line with minor changes in direction; so they won't make short turns either. Also some of the fairings have problems with visibility, and all of the completely enclosed machines have trouble with the riders overheating in warm weather. A one hour road race for streamlined vehicles was recently held; and the streamlined recumbent convincingly defeated all standard bicycles, averaging almost 47 km/h for one hour. However, the riders complained about overheating, and stated that much higher speeds would have been possible with proper ventilation [9].

This is not to say that a practical recumbent all weather road vehicle that is more efficient than a standard bicycle cannot be built. Such a human powered vehicle definitely can be built; however, at present there has been little incentive to do so, with the ready availability and convenience of motorized vehicles. Even so, excellent progress in the design of such an all weather HPV has been made by prof. Dr. Ing. Paul Schondorf of the Fachhoch-schule, Köln [10].

Table 1.

Drag and speed characteristics of streamlined human powered vehicles

Machine	Frontal area (m²)	Drag coefficient c_d	Percent drag reduction at 32 km/h	Required power at 32 km/h (Watts)	Speed with no power increase (km/h)	Maximum measured speed (km/h)
Racing bicycles						
Bare bicycle	.50	.78	0	203	32	-
Bicycle + Glen Brown Zipper 2	.50	.60	13%	177	33.5	54.72
Bicycle + modified Zipper 2	.55	.52	22%	159	34.7	-
Van Valkenburgh aeroshell	.65	.32	34%	125	36.8	54.22
Aeroshell + bottom skirt	.68	.21	48%	97	39.8	74.85
Kyle fairing	.71	.10	67%	68	46	74.77
Recumbents						
Palombo supine tricycle bare	.35	.77	20%	151	34.5	58.21
Palombo Tricycle with fairing	.46	.28	52%	92	40.9	71.42
Van Valkenburgh prone quadracycle with fairing	.46	.14	68%	64	46.9	79.47

II   Measuring maximal Human Power Output

A series of experiments measuring human output, using a modified Monarch bicycle ergometer, are reported here. In each case the drive chain of a working vehicle was hooked up to the ergometer, and the maximum mechanical power output measured for various time periods.

The effect of body position upon power output

The rate that a human can work naturally decreases with time. For very short periods, muscle energy does not depend upon oxygen consumption and is therefore termed anaerobic. Very high work rates are possible in this region. With continuous high levels of exercise, these anaerobic stores of energy are used up, and energy production must come increasingly from oxidation as with any heat engine. The power output continually decreases with time until a steady state is reached. This regime in which muscle energy is entirely due to consumption of oxygen is termed the aerobic region. The upper curve in fig. 4 shows that the steady state aerobic power is only about 30% of the anaerobic power measured at 6 seconds. Naturally, therefore, the maximum possible speed of a human powered vehicle will decrease with the period of exercise [6]. In order to obtain the maximum power output possible at any time it is important to choose an efficient pedalling position.

Seven test subjects who were recreational or racing cyclists in good condition were used for the experiments summarized in fig. 4 and in table 2 [4]. The maximum power output of the subjects was measured in the normal, supine and prone cycling positions for periods of up to 20 minutes. Test methods were similar to those used by Harrison [11]. Both the prone and the supine pedalling positions seem inferior to the normal position in power output. However, supine was only about 4% less on the average, and was very consistent. In contrast the prone position became progressively worse as the time of the exercise increased. This was probably due to the relative discomfort of prone compared to the other two. Both the supine and normal positions are very comfortable. It is quite easy to restrict the blood flow to the legs in the prone position unless the means of rider suspension is carefully designed. Also, difficulty in breathing was a problem.

Table 2.

The effect of pedalling position upon power output [4]

Average power output versus time of exercise - seven subjects

Standard cycling position	0.1 min.	0.2 min	0.3 min	0.5 min.	1 min.	2 min.	5 min.	20 min.
Power output (Watts)	936	883	833	733	521	394	316	258
Supine cycling position								
Power output (Watts)	878	839	803	717	510	380	298	254
Percent difference from standard	-6.1%	-5.0%	-3.6%	-2.1%	-2.0%	-3.4%	-5.7%	-1.5%
Prone cycling position								
Power output (Watts)	900	841	792	686	481	362	288	229
Percent difference from standard	-3.8%	-4.8%	-4.9%	-6.4%	-7.6%	-8.3%	-8.9%	-11.1%

From the tests it appears reasonable that recreational vehicles should avoid using the prone position; although for high speed racing vehicles, the prone position is the most efficient aerodynamically and therefore offers the advantage of a much lower drag which far outweighs the discomfort and minor loss in power.

Power output using both legs and arms

An incomplete study presently in progress is to measure the effect of using arms and legs for pedalling. Partial results are presented here. The Palombo Tricycle, mentioned previously, uses the supine position with the arms operating a push rod mechanism hooked to the cranks. This machine was hooked to the ergometer for the tests. Four modes of exercise were studied: legs only; legs with arms moving unilaterally (the right and the left arms move in the same direction in unison with their respective legs); legs with arms moving bilaterally (the right and left arms move in the opposite direction as their respective legs); and bilateral offset (the arms move 53° out of phase with the legs to avoid power dead spots). Table 3 summarizes the results of tests on 8 subjects for 6 seconds, and 4 subjects for one minute. The tests showed that there is little difference between the bilateral and bilateral offset position, but the unilateral offset position is clearly inferior. For the short "sprint" time period of 6 seconds, the average of all subjects showed a 22% increase in power using arms and legs compared to legs alone. For one minute the power increase was 17%, but still quite significant. More detailed tests for longer periods are now in progress.

Table 3

Power output in the supine position using arm and leg exercise

	Legs only	Arms and legs		53° bilateral offset	
		Unilateral	Bilateral	Legs and arms from start	Legs only until 30 seconds
Power output for 6 seconds-average of 8 subjects					
Power output (Watts)	838	948	1024	1017	
Power output (percent)	100%	113%	122%	121%	
Leg rpm	107	121	131	130	
Power output for 1 minute-average of 4 subjects					
Power output (Watts)	489	-	-	521	
Power output (percent)	100%	-	-	117%	
Leg rpm	77.7	-	-	94.9	
Power output for 1 minute - Mario Palombo					
Power output (Watts)	495	-	-	549	583
Power output (percent)	100%	-	-	111%	118%
Leg rpm	84.1	-	-	93.4	99.1

In the one minute test, one of the subjects, Mario Palombo used two different strategies in the arm and leg exercise. In the first test, he exercised at maximal effort with both arms and legs as did all of the other subjects, for the entire minute. In the second test, he exercised with legs only for 30 seconds, and then with arms and legs for 30 seconds. The first method improved the power output 11%, but the second method improved it even further to 18% greater than legs only. Thus, it appears that if one wishes to produce a maximum rate of energy during a fixed time period using arm and leg exercise, a strategy must be devised to optimize the process.

The above studies were done in an effort to predict the maximum velocity possible for a human powered land vehicle over 200 meters with a flying start. The results of actual field trials are given later, along with other similar tests.

III Predicting vehicle performance using ergometer data

Experiments with a standard racing bicycle

In an attempt to use ergometer data to predict the speed of a standard racing bicycle, the power output of 5 cyclists was measured for time periods up to 20 minutes using a Monarch Bicycle Ergometer with racing bicycle attached. The same cyclists were then timed individually riding a racing bicycle over a level distance for a period equivalent to the ergometer test time. The required power consumption was calculated from previously made drag measurements, and the ergometer power output was used to predict the cyclists' speed. This is compared to the actual speed in table 4. In predicting the speed, it was assumed that the power output on a bicycle was due to external resistance forces only and this was comparable to the ergometer power. Actually, the friction losses in the crank and chain of a bicycle should be almost exactly the same as those in an ergometer since the mechanisms are almost identical. However, the friction loss of the tires would certainly increase as more power is applied to the rear wheel and the tire deformation increases. In other words, coasting tests cannot predict exactly the rolling friction. Nevertheless, from the results above, errors do not seem to be large.

Table 4

Predicting racing bicycle performance using ergometer measurements

Subject	Time	Ergometer power output (Watts)	Predicted speed (km/h)	Actual speed (km/h)	Percent error
VC	20 min.	267	35.7	35.6	+0.3
CK	30 sec.	716	50.7	48.3	+5.0
	2 min.	373	40.2	40.1	+0.3
	4 min.	343	38.9	39.4	-1.2
	20 min.	298	37.0	37.8	-2.1
JM	2 min.	380	40.6	39.7	+2.3
	20 min.	291	36.7	35.5	+3.4
MP	20 min.	242	36.0	36.2	-0.6
KY	20 min.	224	33.8	35.6	-5.1
Average			38.84	38.69	2.3

For ten tests, the predicted speed averaged 38.84 km/h, while the actual speed averaged 38.69 km/h. In two of the tests, errors were 5%, but the others were much lower than this. In other words, laboratory prediction of field performance is quite accurate provided good drag and ergometer data are available. This seams to be in some conflict with previously reported ergometer tests by Nonweiler [12]. It is quite important in measuring maximal human power output on an ergometer, that the optimum load and rpm be used. It is also important that cyclists' be motivated and well accustomed to riding an ergometer. Otherwise, measured power output can be significantly lower on the ergometer than that produced on a bicycle. In some of our tests we have had proven champion racing cyclists put out less than touring cyclists because of unfamiliarity or dislike with ergometer exercise. In late tests by Whitt and others, ergometer and oxygen consumption data taken in a laboratory gave rather accurate predictions of oxygen consumption and power output on a bicycle when drag measurements were used for the prediction [13]. Whitt provides equations for predicting energy consumption from bicycle speed [14].

In another experiment, a stationary 200 pound (91 kg) unbraked inertia flywheel ergometer was used to measure power output and torque during acceleration for periods up to 10 seconds. This was compared to a bicycle rider's field performance accelerating from a stop over an equivalent time period. Results were quite accurate, and these have been reported elsewhere [6]. The technique was also successfully used to predict the optimum gear ratio for acceleration to maximum speed at the end of 100 meters.

It is quite important to comment here that the above experiments are examples of predicting athletic performance from laboratory measurements. This is becoming more and more wide-spread in sports, especially in the Eastern European countries. It is hoped that the cooperation between engineers, scientists, sports physiologists, and others will increase in the future to permit more applied scientific method in sport and recreation. The goal is to be able to predict human performance rather than just to measure it.

Experiments with streamlined vehicles

Here, the results were not as good as with the standard bicycle, principally because high speed drag data were not available, and attempts to extrapolate the low speed data were not always reliable. The tests described below were conducted using race vehicles that had the capability of travelling at speeds exceeding 70 km/h. Drag measurements at these speeds have as yet only been done in two cases (see fig. 3).

Predicting maximum speed

Using the Kyle-streamlined bicycle, two riders were ergometer tested for 1 minute and later they accelerated the streamliner from a stop for about the same time period; their speed was measured over the last 200 meters. Actually, their maximum speed could have been somewhat higher than the figure reported, since they were still accelerating through the 200 meters (as indicated by an electronic speedometer). Using an extrapolated drag equation for the Kyle Streamliner of

(4) $F = 2.67 + 0.179 \cdot v + 0.414 \cdot v^2$ where F is the total drag force in Newtons and v is the velocity in m/s, the predicted power is $P = F \cdot v$.

(5) $P = 2.67 \cdot v + 0.179 \cdot v^2 + 0.0414 \cdot v^3$ where P is in watts, and v is in m/s.

If equation 5 is plotted versus the speed, then the ergometer power may be used to predict the maximum speed. Results are given in table 5. Neither of the riders went as fast as predicted; however results are reasonable considering the variations in human performance, especially since there was some danger involved in the tests; (the vehicle was unstable in even slight cross winds and required some skill in handling).

Table 5.

Predicting streamlined vehicle performance using ergometer measurements

Subject	Vehicle	Ergometer power output for 1 min. (Watts)	Actual speed 200 meters (km/h)	Predicted speed (km/h)	Percent error
CK	Kyle streamlined bicycle	507	66.85	74.95	+12.1
RS	Kyle streamlined bicycle	537	74.83	76.60	+2.4
MP	Palombo supine tricycle bare	549	58.13	57.94	-0.3
MP	Palombo Tricycle with fairing	549	71.42	74.19	+3.9
Average			67.81	70.89	4.6

The hand and foot powered tricycle of Mario Palombo was also used for speed prediction. Here however, the vehicle used a friction clutch for freewheeling, and this seemed to cause a large error in the drag measurements. If an equation of the form

$F = a_0 + a_1 \cdot v + a_2 \cdot v^2$ is used, it will not fit the data properly. If an equation of the form

$F = a_0 + a_1 \cdot v^n$ is used, it fits the data almost exactly; however, the exponent n is much less than the 2.0 that might be indicated from theory. For the tricycle without fairing an

equation $F = 0.401 + 0.042 \cdot v^{1.38}$ fits the data very well, while for the tricycle with

fairing $F = 0.497 + 0.0521 \cdot v^{1.25}$ was very close. Here, F is in kg and v in m/s as before. Using these equations to extrapolate the data to high speed, one gets the predicted speeds listed in table 5. Because of the possible error in the coast down tests, the above example is only included as an illustration, and even though the results are reasonable, they should not be considered valid.

Predicting speed, distance, and time during acceleration

To check the acceleration characteristics of a recumbent vehicle, several field tests were made; these are listed in table 6. The Palombo tricycle was started from a stop with Mario Palombo as the rider, and the machine was accelerated at maximum exertion for a fixed distance, with the speed at the end of the run, plus the elapsed time for the entire run being measured. The elapsed time was under 1 minute for runs up to 610 meters. The highest speed of 69.67 km/h was achieved with 457 meters acceleration distance using maximum effort with arms and legs from the start.

Table 6

Field acceleration tests - Palombo streamlined supine tricycle

Field measurements		Calculations assuming average thrust								Calculated time assuming constant acceleration	
Acceleration distance (meters)	Maximum velocity (km/h)	Elapsed time (sec.)	Predicted time (sec.)	Percent error	Average thrust (kg)	Total energy expended (Joules)	Kinetic energy (Joules)	Friction energy expended (Joules)	Required power (Watts)	Predicted time (seconds)	Percent error
305	62.70	36.0	32.0	-10	6.29	18810	13550	5260	523	35.0	-3
381	68.57	40.5	36.2	-11	6.35	23730	16200	7530	586	40.0	-1
457	69.67	44.2	42.0	-5	5.81	26040	16710	9330	589	47.3	+7
533	66.71	51.5	50.3	-2.3	4.90	25610	15330	10280	497	57.6	+12
610	67.95	55.3	55.5	+0.4	4.72	28240 (*)	15890 (**)	12350	510 (***)	64.6	+17
Average									541		

(*)   Total energy expended = (average thrust)x(distance)
(**)   Kinetic energy = $\frac{1}{2}mv^2$, where m = 89.27 kg, and v = maximum velocity m/s
(***)   Average power required = (average velocity)x(average thrust)

As with the ergometer tests, using the arms from the start was not the best strategy. In another test, Palombo started from 914 meters (3000 feet), and accelerated slowly using legs only, and with 150 meters to go (500 feet), he used both his arms and legs at maximum effort for the remaining distance. In this case his top speed was higher (71.02 km/h with an elapsed time of 86 seconds). So apparently there is a strategy of exertion in reaching a maximum speed with an HPV; this is not necessarily using maximum effort from the start.

Given a level surface, with no wind velocity, Newton's equation for our problem is:

(6) $T-F=m\dfrac{dv}{dt}$ where T is the wheel thrust on the pavement, F is the total drag force

against the vehicle, m is the mass, v is the velocity, and t is the time. This equation can be solved for the time or distance x by using:

(7) $t=m\displaystyle\int_0^v \dfrac{dv}{T-F}$, or $x=m\displaystyle\int_0^v \dfrac{v \cdot dv}{T-F}$

In the case of constant thrust T, if F is of the form $F=a_0+a_1 \cdot v+a_2 \cdot v^2$ or $F=a_0+a_2 \cdot v^2$

then the equations can be integrated directly provided F<T over the range of integration. See the appendix for the solution.

For the case of constant power output (P = T·V = constant), or for the more realistic case of variable thrust, the equations must be integrated numerically. Since little confidence can be placed in the low speed drag data for Palombo's machine, the following calculations are shown as examples only.

Assuming constant thrust, a drag equation of the form $F=a_0+a_2 \cdot v^2$ was used for

simplicity and to permit easy integration of equation 7. The best estimate of c_d for

Palombo's streamliner is 0.28. Using $a_2=\frac{1}{2}c_d \cdot A \cdot \rho$ with A=0.465 m², and ρ=1.2 kg/m³,

we get:

(8) $F = 4.45 + 0.0781 \cdot v^2$ Here F is in Newtons, and v in m/s.

Using the solution to equation 7 given in the appendix, the average thrust was chosen arbitrarily so that the distance and velocity would agree exactly with the field data; the predicted time was then calculated. A simple iteration scheme on a programmable calculator was used for computation. Errors in the predicted elapsed time averaged about 6% (see table 6). The required average thrust is seen to decrease as the distance increases. This is reasonable considering maximal rider power output, and thus thrust, will decrease with time [6]. The average of about 6 kg thrust seems within limits.

Also shown in table 6 is the energy expended during each run as calculated from average thrust T, distance travelled x, and maximum velocity v. Total energy is $T \cdot x$, the kinetic energy is $\frac{1}{2} m \cdot v_2$ (the mass m of the machine plus rider was 89.27 kg), and energy expenditure due to friction is the difference between the two. The illustration shows that kinetic energy is from 60-70% of the total, so it is critical to avoid high weight for race vehicles. Another interesting calculation is to compute the required power, using the average velocity
($v_{avg} = t/x$) times the average thrust. This seemed to be very consistent, and the mean of all the tests agreed well with the ergometer measurement (541 Watts versus 549 Watts).

For reference, the time required for constant acceleration was also calculated ($t = 2x/v$). As can be seen from table 6, this is fairly accurate at shorter distances, but gives large errors at longer distances. Several unsuccessful attempts were made to use the average power, and various equations for the drag to integrate equation 7 numerically and obtain satisfactory agreement with field data. The use of average power may be quite accurate at higher speeds, but at low speeds it is greatly in error. Since power is equal to velocity times thrust force, if the velocity is zero which it was at the start, then the thrust force would have to be infinite for power to be produced. This of course is impossible. It is thrust force that actually moves the vehicle, not power per se. The use of average thrust is therefore more logical as an approximation than the use of average power; however neither one is an exact analog of what really occurs. Thrust and power vary continuously throughout the entire run, they are not constant.

In order to properly solve the problem, the rider's torque characteristics as a function of time would have to be known accurately as would the total drag of the machine with respect to the velocity. At present there seems to be no way available to measure the torque without building an accurate laboratory simulator of the actual vehicle. This would have to include an inertia flywheel equivalent to the mass of machine plus rider, plus drag characteristics equivalent to rolling resistance plus wind friction. It is planned to build such a machine in the near future at CSULB. Until that time, it will be possible to predict maximum speed with fair accuracy using ergometer data, but probably not the acceleration characteristics of the machine.

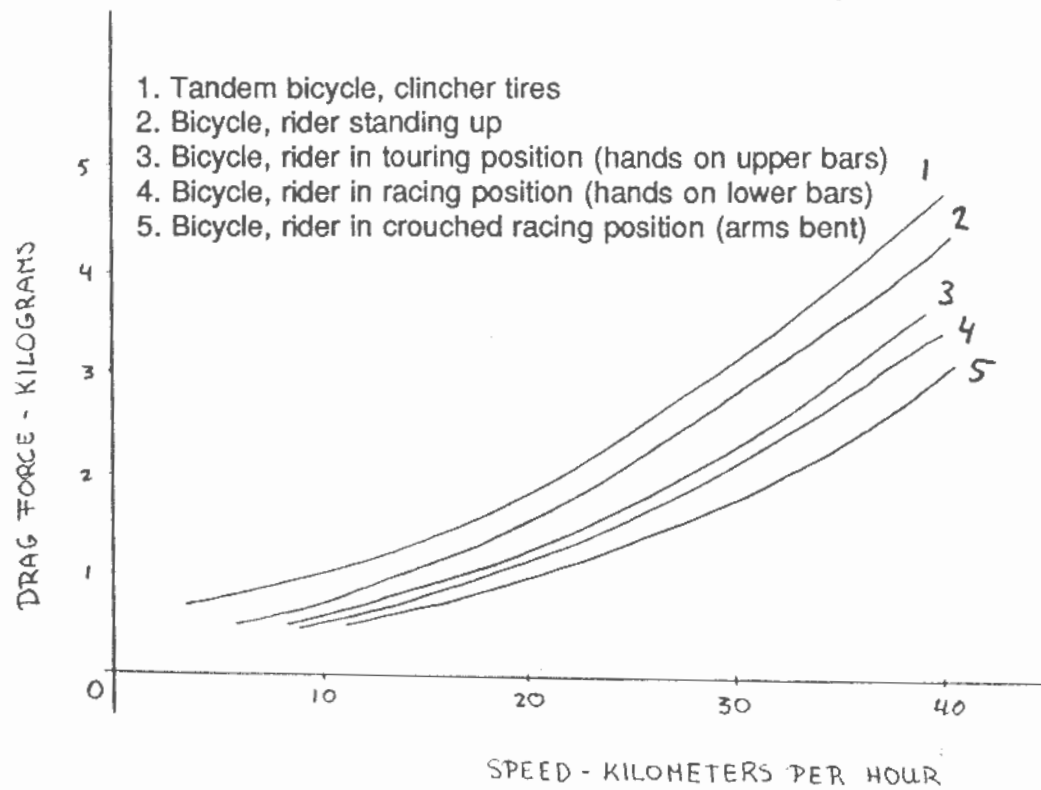Figure 1: Drag force versus speed, commercial bicycles.

1. Tandem bicycle, clincher tires
2. Bicycle, rider standing up
3. Bicycle, rider in touring position (hands on upper bars)
4. Bicycle, rider in racing position (hands on lower bars)
5. Bicycle, rider in crouched racing position (arms bent)

Figure 2: Drag force versus speed, bicycles with partial fairings.

1. Glen Brown, bare bicycle
2. Bicycle + Zipper 2
3. Bicycle + Zipper 2 + paper sides, bottom and top
4. Bicycle + Van Valkenburgh Aeroshell
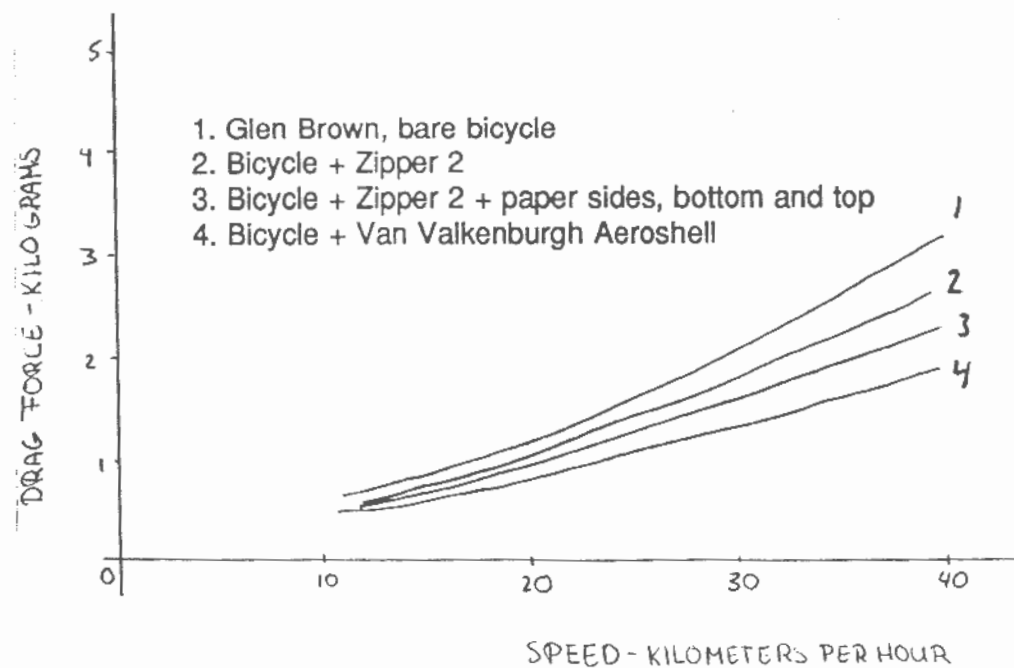
Figure 3: Drag force versus speed, vehicles with full fairings

1. Paul Van Valkenburgh, bare racing bicycle
2. Mario Palombo, supine recumbent tricycle, bare
3. Mario Palombo, same as (2), with streamlined fairing
4. Van VAlkenburgh, Aeroshell + bottom skirt on bicycle
5. Van Valkenburgh, streamlined prone, quadracycle, 1978
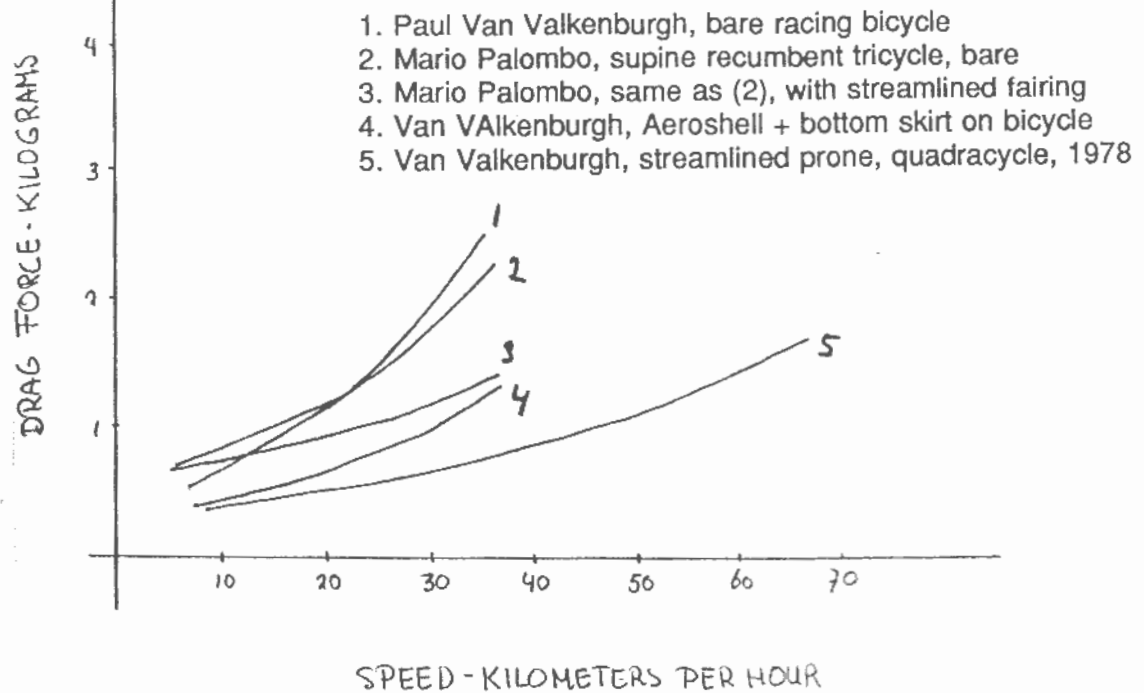
Figure 4: The effect of pedaling position upon power output

Average of 7 subjects

1. Standard cycling position
2. Supine cycling position
3. Prone cycling position
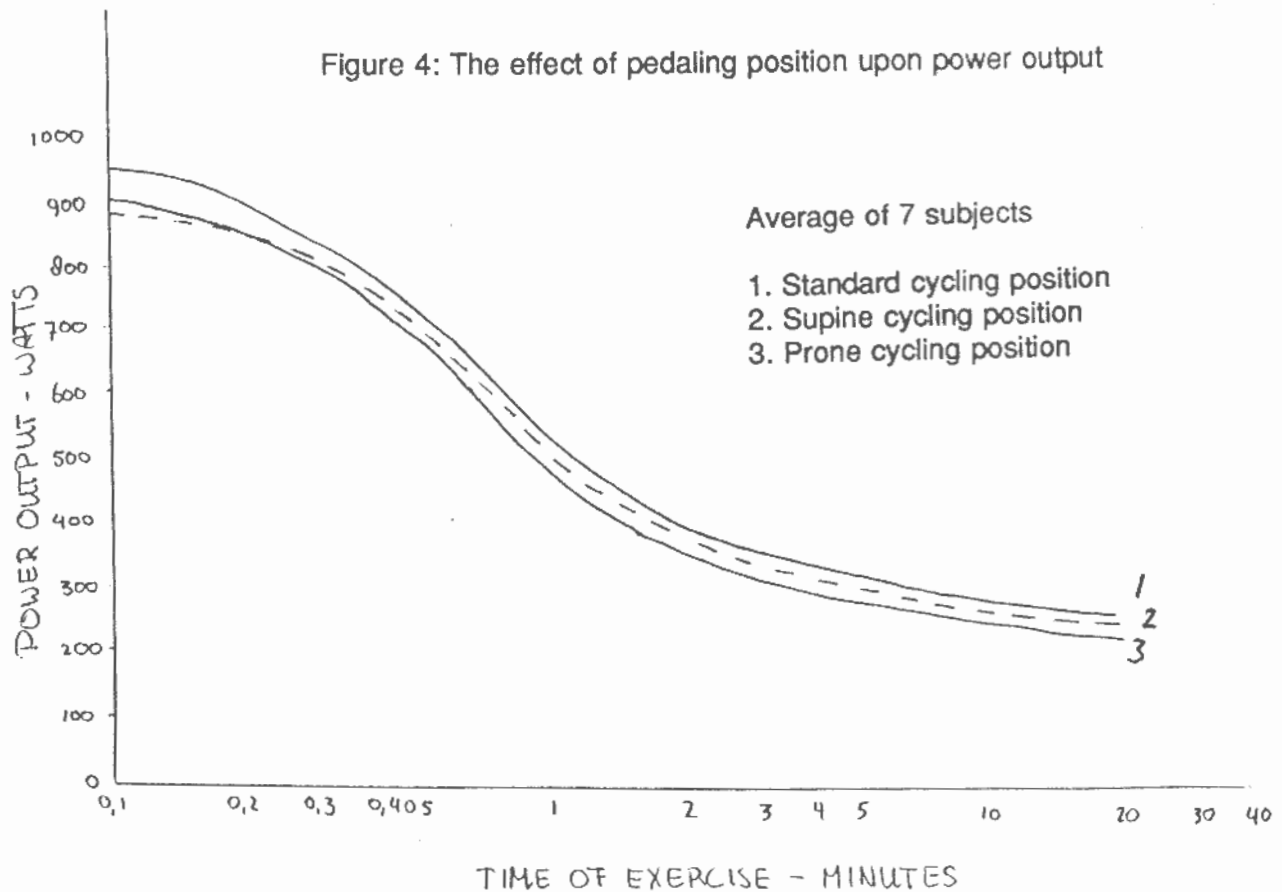
Appendix: solution to equation 7

If the drag force is of the form $F = a_0 + a_1 \cdot v + a_2 \cdot v^2$ in Newtons, and the thrust force T is a constant in Newtons, then the solution to equation 7 is:

$$t = \frac{m}{\sqrt{q}} \cdot \ln \left\{ \frac{\dfrac{2 a_2 \cdot v}{a_1 + \sqrt{q}} + 1}{\dfrac{2 a_2 \cdot v}{a_1 - \sqrt{q}} + 1} \right\} \quad \text{and}$$

$$x = \frac{m}{2 a_2} \ln \left\{ \frac{T - a_0}{T - F} \right\} + \frac{a_1}{2 a_2} t \quad$$ where a_0, a_1 and a_2 are constants, m is the total mass of machine plus rider in kg, t is the time in seconds, v is the velocity in m/s, x is the acceleration distance in meters, and $q = 4 (T - a_0) \cdot a_2 + a_1^2$. In one example, m=89.27 kg, a_0= 4.45, a_1= 0, a_2= 0.0781, T=61.70 N, v=17.42 m/s; from this t = 32.2 sec., and x = 305 meters. The solution is not valid for a_2=0.

Muscle involvement in cycling: can we get more efficient?

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Introduction

Man has been searching for aids in increasing the maximum speed he can reach with his own strength for many centuries. Without aiding devices the performances of human locomotion is not exactly impressive. Even the worlds aces in the 100 meters run cannot achieve speeds of over about 40 km/h. At longer distances, like the marathon, the cruising speed lies at about 20 km/h. In comparison to our quadrupeded friends, these results are very meagre indeed.

For nature's aces, the cheetah and the pronghorn, top speeds of about 100 km/h have been recorded. Although the cheetah can only maintain this fantastic achievement for a short distance, many hoofed animals appear to be able to maintain speeds of 40-50 km/h even on long distances. The causes of these big differences between human and animal capabilities are mainly due to differences in the design of (hind) legs and our upright way of moving about [Ingen Schenau, 1992]. One of the major disadvantages to quadrupeds stem from the fact that we walk with our heels on the ground. Most quadrupeds walk on their toes, and their feet have grown to a length comparable to or (for hoofed animals) even longer than the upper or lower legs. For man, this leads to a relatively big moment of inertia of the legs.

The major part of the energy we can free while running will therefore be used for constantly accelerating and slowing down our leg segments in relation to the torso [Ingen Schenau, 1992]. For short running distances it is calculated that about 80% of the liberated mechanical energy will go to this process, and only about 10% is used to overcome air resistance. The remaining 10% goes to the distortion of shoes and underground (comparable to the rolling resistance in cycling). The aids that man has come up with in the course of centuries to achieve higher speeds, seem mainly to influence these internal losses. After a few vain attempts in the antiquity to fly on one's own strength, the chief inventions concerning this area are the skates and the bicycle. Some 700 years ago the gliding technique was accomplished on the ice, where one could propel oneself to the ice on thin sharpened irons while the skate keeps on gliding. This can only be done effectively by propelling perpendicular to the gliding direction, whereby the back and forth rotations of the leg are considerably less than during running. This is why the internal losses are much less during skating than during running. Top skaters with excellent control over the gliding technique have thus shown to be able to use as much as 75-80% of the liberated mechanical energy to conquer the air and ice resistance. During sprinting, they can reach top speeds of 55 km/h.

Although the wheel was known as early as the Stone Age, man has only used this invention effectively in the last century for reaching high speeds on his own strength. Notably the transmission of the extension of the leg to the propulsion of the hind wheel through pedals, chain wheels and chains enabled man to catch up with a big part of his backlog to quadrupeds: on an ordinary racing bicycle well trained cyclists prove to reach top speeds of over 60 km/h.

Now the question arises: is this the maximum attainable or can we go even faster? If we leave out of consideration the first phase of the sprint start then we can put that the optimum speed we can reach during cycling is the result of a balance of the cyclist's

effective external power output on one hand, and the air and rolling resistance on the other (effective external power output defined as the power that can be used completely for conquering the external forces). In this contribution attention will mainly be paid to the first part of the mentioned balance: the capacity, effectivity and efficiency of the human engine. The other authors will concentrate on the friction losses and the minimizing of the friction losses.

The human engine

Capacity and trainability

As is the case with many engines, man derives his energy from energy rich fuels, whereby a certain part of the Gibbs free energy is converted in mechanical energy. The efficiency of this process is referred to as "mechanical efficiency" in biological sciences. The estimated maximum theoretical efficiency on the level of isolated laboratory animal muscles proves to be about 26%. Since man and animal also need energy to be able to get the contraction mechanism going (and for internal friction, heart and lung muscle activity, digestion, nervous system, etc.) the entire system will need to have a smaller mechanical efficiency (the so called gross efficiency) than the efficiency found for a muscle-tendon complex; under 26%. We will get back on this at the end of this argument. The immediately deployable fuel in the contractile elements of our muscles are energy rich phosphates. The stock of these phosphates is however so limited that after 5-6 seconds of maximum effort we are already dependent of the supply systems of these phosphates. This means that apart from the first phase of the sprint, the performance in cycling is not so much dependent of the quantity of contractile proteins per muscle, but much more from the capacity of the supply systems. To make the comparison with a petrol engine: in the long run we are more dependent of the energy supplying capacity than of the cylinder capacity. The production of energy rich phosphates can be achieved in two ways: aerobically (where oxygen is consumed) and anaerobically (without oxygen, whereby lactate is produced). The aerobic system is to a certain extent comparable to the processes taking place in a petrol engine. As long as nutrients are available from which the phosphates can be formed (for maximum efforts especially glycogen) this system can take care of a certain power that can be maintained for some time. This power is however quite small and amounts to 400 Watts (effectively) for top cyclists. The anaerobic system can in first approach be compared to a set of thrust rockets with a certain amount of extra energy. With this system the energy rich phosphates can be produced much faster than in the aerobic way, but the higher the power one extracts from this system, the faster the system is exhausted. In this way, well trained people prove to be able to produce an average power of about 1200 Watts during a 30 s. sprint test on a bicycle ergometer. The same athletes will only perform half as well (500-600 Watts) in a 3½ min. test. In this period of time already some 70% must be produced anaerobically, while in the 30 s. test over 90% of the energy is derived from the anaerobic system.

A burning question that occupies many people (in particular in sports) concerns the trainability of these metabolic systems. So: in which way can we increase the aerobic and anaerobic power.

Though the adapting capability of biological systems is generally impressive. The trainability of these metabolic systems is limited. A good physical condition proves to be genetically determined. (Much) literature has appeared on this terrain, and shows that the maximum effect of training to be expected is an increase in aerobic power of about 20-25% [Hollander, 1992]. For people who are already considerably active this is even less. A longitudinal study of six years of the physical condition of all members in the Dutch junior skating team and the members of the senior team selected from it during the study, showed in all these years no increase in aerobic or anaerobic power whatsoever; this despite the fact that the

extent of training and its intensity was increased strongly. The absence of such results with already well trained athletes is also found by other researchers (however, there are clues that the subjects increase their tolerance for lactate.

For as far as the performances with human powered vehicles were achieved by optimally trained cyclists, one should not get high hopes of a further expansion of the metabolic engine. Neither should one expect much (or anything at all) from strength training. Strength training can lead to a expansion of the amount of contractile proteins in the muscle, but this is useless if the performance is limited by metabolic capabilities. Strength training does definitely not lead to an improvement of the aerobic capability (rather the opposite), and even a possible training effect on the anaerobic capability has not been proven unequivocally. What can be influenced by muscle size seems to be the very first phase of a sprint start where the energy rich phosphates are abundant.

The optimal muscle loading

The contractile elements of muscles have a number of properties that have to be considered when designing human powered vehicles.
The two best known properties concern the force-velocity relation and the force-length relation (fig. 1).
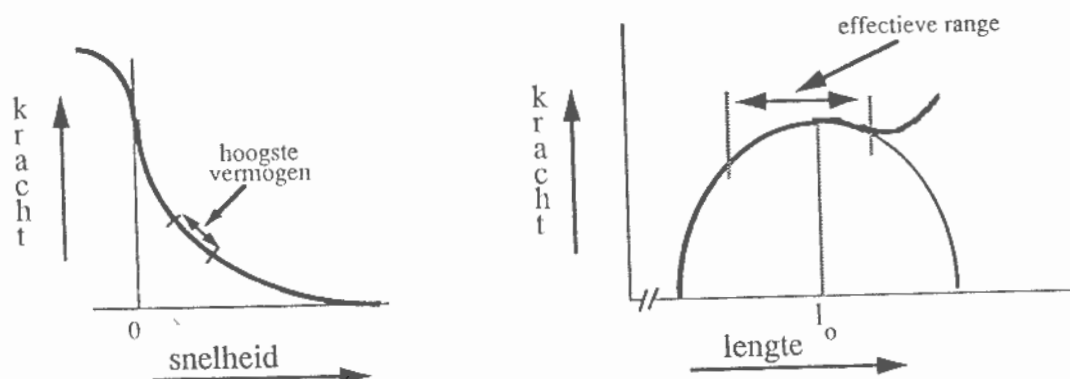
Fig 1: The maximum force a muscle can provide depends of the contracting speed and the length of the muscle as shown in the force-velocity characteristic (on the left) and the speed-length characteristic (on the right) of a muscle.

The force-velocity relation shows that with equal stimulation from the central nervous system the muscle force seems to decrease with an increase in contraction velocity. The power of a muscle (with equal stimulation) proves to reach a maximum at about 1/3 of the maximum isometric force (so the product of muscle force and contraction velocity reaches its maximum there). At this combination of force and velocity the muscle efficiency also reaches its top. The force-length relation shows that, dependant of the muscle length, the maximum force varies too. The question arises by which route we should contract the muscles to achieve the maximum possible work output. If we do so over a long route, not only do we utilize the largest possible forces, but also the much smaller forces, and it takes more time before we can start the next contraction (at a given optimal contraction velocity). How to optimize these factors is hard to predict from theoretical deliberations, for

many different factors play a part simultaneously. In the first place we rarely broach the maximum contractile capacity we saw in the force-length and force-velocity relations. Furthermore we have to deal with activation losses at the beginning of each muscle contraction, of which the contribution increases with increasing pedalling frequency, and the need for blood supply to the muscle in the relaxed state (for provision of oxygen, discharge of lactate, etc.). Besides that, changing muscle lever arms play a role, and of course the energy needed here as well to accelerate and slow down the leg segments. Too little of all these aspects is known up to now in order to develop a reliable simulation model with which an optimal loading of the muscles can be predicted.

The bicycle however is, in contradiction to all other ways of locomotion, preeminently suitable for experimentally optimizing the muscle load. By varying the adjustments of saddle height and by choosing the gear we can adjust both muscle contraction velocities, muscle length changes and pedalling frequencies, and therefore optimize them. Such experiments have been carried out by many laboratories and evidently by trial and error in practice as well. Based on all these results no major breakthroughs should be expected on this terrain (a more optimal combination of adjustments than those recommended up to now should after all have been discovered a long time ago). But many question are still waiting to be answered. Well known themes are the supposed benefits from crank lengths alternating during the pedalling cycle, elliptic chain wheels or translatory instead of rotatory drive systems. How much gain can be made in this terrain is, for the same reasons as mentioned above, hard to predict on theoretical grounds. The supposed benefit of a alternating movement in a straight line will be discussed in the next paragraph. However, the last paragraph will show that there is probably little that remains to be achieved in this area for the designers of human powered vehicles.

Straight lined or rotating; with or without prestretch

An objection that is widely adduced against the current transmission system of the bicycle, concerns the circular route followed by the pedal. This objection is mainly pointed towards the obvious observation that at a part of the route, the direction in which the extension of the leg can produce maximum force (roughly the direction hip-pedal) is perpendicular to the direction in which the pedal moves. This is the case around TDC (top death centre) and BDC (bottom death centre). A force F on the pedal can of course only do work on the pedal if this force have a component F_e in the moving direction of the pedal (fig. 2). We shall call this the effective component from here on.

The component perpendicular to the moving direction does not contribute to the propelling and is considered by many as a wasted force. One speaks of the efficiency of the pedalling force F, defined as F_e/F_N, thus suggesting that only this fraction of the leg extensioning work is utilized effectively. F_e can be optimized by adjusting F to the moving direction of the pedal or by using a system with which the pedal can move up and down in the direction of a virtual line from hip to feet. Such a straight lined movement would averagely permit larger push off forces and one could (more than with a circular route) think of systems that allow a prestretch of the extensor muscles. The advantages of such a prestretch, where the activation of the muscle takes place in the final phase of muscle elongation, have been described at length in the literature; both for isolated laboratory animal muscles as well as for leg work. These advantages relate to the fact that the muscle has already deployed its maximum force at the beginning of its (productive) shortening phase, something that is not even by far the case without prestretch, and to the finding that the muscle, apart from this effect, also seems to be able to deliver more work in the phase later on with a prestretch than without a prestretch. This last effect is known as "potentiation". These often described effects have tempted the writer of this contribution to speculate on the possible advantages of such a translatory drive system in a book on
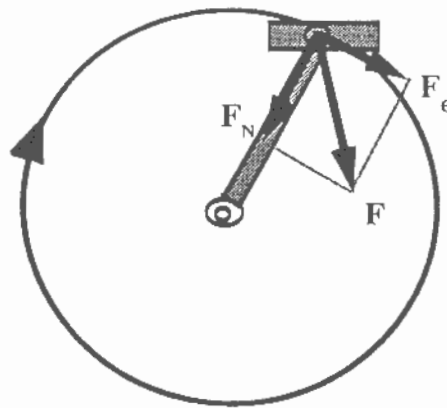
Fig 2: Of the force F on the pedal, only the effective component F_e contributes to the propulsion.

cycling [Clarijs and Ingen Schenau, 1985]. The results mentioned in the literature were so convincing that these hypotheses were tested in our laboratory. In cooperation with colleagues employed in the area of muscle physiology we checked if the imposed prestretch directly before the shortening is indeed advantageous for the mechanical output and the mechanical efficiency of the muscle-tendon complex, using isolated hind leg muscles of rats [de Haan et al, 1990]. Although the results reported in the literature were completely confirmed, such a contraction pattern proves not to be advantageous in any way whatsoever in cycling. For what was never measured (or mentioned) was the quantity of negative work that one loses during the prestretch. It turned out that the previously mentioned authors only reported the amount of (positive) work delivered during the shortening, and also based their calculations of muscle efficiency on this work (in this way it can become more than 50% for short contractions, which is of course thermodynamically impossible). We did however not find any way of contraction (not even with very short prestretch phases) that could lead to more extra work during the shortening than the work needed for the preceding prestretch of the muscle. The underlying processes of potentiation and storage and reuse of elastic energy can only yield profit in cycling if the ratio between these extra work and the preceding negative work exceeds 1. The opposite is the case so we had to discard the hypothesis launched in 1985.

Additional proof for this statement can be derived from research in power supply and mechanical efficiency of drive systems of the wheel chair. Colleagues at our faculty have compared the old fashioned "coffee grinder" (a circular pedalling movement with chain transmission) to an alternating translatory drive and to the rim propulsion. The coffee grinder proved to be superior by far compared to other drive systems, both concerning maximum powers and the gross efficiency. So we can conclude that the circular pedalling movement is apparently not all that bad.

But what to think of that wasted force component F_N on the pedal?

According to the lectures on international congresses there are sports scientists and trainers who even learn cyclists (by feedback) to minimize F_N, so to steer the direction of F as well as possible in the direction of the pedal's moving direction. Because only F_e can contribute to the propelling this approach does not seem senseless. Unfortunately there have been no reports of successes from this area so far, for as far as power output or mechanical efficiency are concerned.
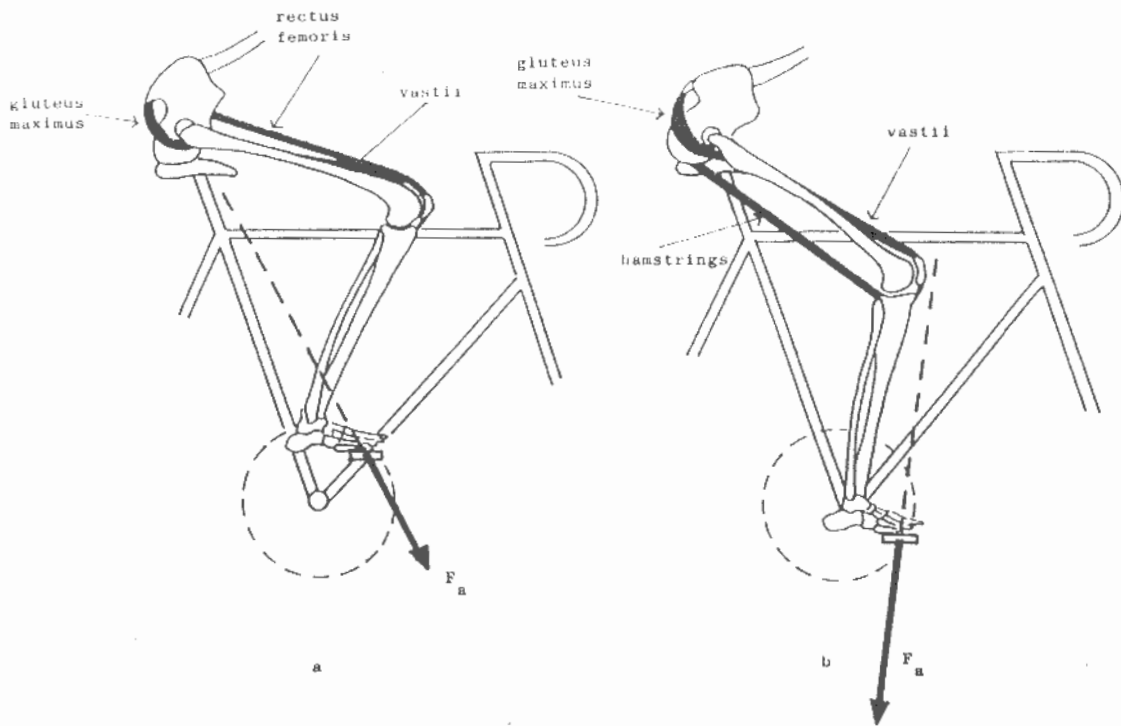
Fig 3: Active muscles in two phases of the leg stretching (for details read the text).

The control of the direction of the external force is done on the basis of the net torques in the joints (fig. 3). If we want to push the pedal forward around TDC, it takes a small or even negative net extending torque in the hip joint combined with a large extending torque in the knee joint. If we want to pull the pedal backwards in the final phase it is the other way around: now a large extending torque in the hip and a negative (and therefore bending) torque in the knee are needed (mind that the knee is still extending). This varying in net torques require a very complex use of muscles (the existent generations of robots tilt completely by these demands). After all, sometimes flexors must even be activated in phases where an extension is still required in the joint involved. But nature has deployed unique actuators for this from which engineers can still learn a lot, namely muscles that do not cross one but two joints. There are such bi-articular muscles on both sides of the upper leg: the rectus femoris on the front side and the hamstrings at the back side of the upper leg. In the task performed in fig. 3a the rectus femoris is actively involved, thus resisting the extending torque of the gluteus maximus and increasing the net torque of the knee, while the hamstrings bring about a reversed distribution of net torques [Ingen Schenau et al, 1993]. Without bi-articular actuators this steering in the direction of the pedalling force would only be possible on the basis of a considerably less efficient use of muscles. To name an example: in the task of fig. 3b the powerful knee extensors are not supposed to be active. On the contrary, a knee bender should become active while the hip extensors should push the knee further to the stretched position against the working of these muscles. So considerably less power would be delivered and a part of the power delivered by the hip extensors would be converted into heat in the knee bender that is to be elongated. For this same reason the robots equipped with torque motors in the joints are inefficient for such jobs and hard to control [Gielen and Ingen Schenau, 1992]. Thanks to the bi-articular muscles man can steer the force on the pedal efficiently and effectively. But it is certainly not true that the optimal production of power and transfer to the pedal will be achieved if we succeed in minimizing F_N from fig. 2. In the first place it must be pointed out that one should not consider F_N a wasted force, let alone suggest that the fraction F_a/F_N would have anything to do with some sort of efficiency of the drive. Just as in technique, in biological systems one is easily deceived by a consideration of forces. After all, mechanically speaking F_N does not perform work and since the muscles generating F lost their activation energy (energy needed to get the muscle active) already anyway, there

is hardly any difference with the mechanical consideration that F_N has no energetical meaning. F_N comes with F almost without any metabolic energetic expense. Energetically speaking the only relevant question is how we can reach an optimal generating of power on muscular level, dependant of F_e/F_N, and an optimal transfer of this power to the pedal. Well, a complete steering with F in the direction of F_e calls for such a disproportionably large load of the rectus femoris and hamstrings that these muscles will tire prematurely compared to the other muscles. This could be solved by tensioning the mono-articular less strongly, but that implies a decline in the power delivered. That is why cyclists seem to learn themselves to steer along just a bit (roughly according to the directions shown in fig. 3) but this certainly doesn't lead to a minimizing of F_N. The optimal relation F_e/F_N mainly concerns the optimal distribution of the load over all muscles involved. Here too theoretical grounds (for example by using simulating models) do not yet enable us to check and see if what the practice shows after a learning process is really optimal. Therefore many questions remain to be answered in the light of all contemplations dealt with in this contribution. Couldn't we do much different and better with a different moving technique and/or alternating drive systems? To answer this question at least slightly, in the next paragraph some comparisons with differing movements will be made.

Can we get more efficient?

If a designer of human powered vehicles is faced with the question if a profit can be yielded in the area of air resistance, then he/she will point out the fact that the drag coefficient can in theory still be reduced considerably because this coefficient is known for ideal streamlined bodies, like a falling drop of water; and this apart from the question if a decrease in value is feasible in the (far) future or not.

In this final paragraph an attempt will be made to indirectly get a grip on the direction to seek for a possible improvement of the drive system. At the beginning of this contribution it was already pointed out that in exercise physiology we use the term gross efficiency to show how much of the principally available metabolic energy benefits the mechanical energy that can be used for overcoming external forces (for overcoming resistance and for changing the kinetic and potential energy of the system). For activities like cycling this gross efficiency therefore does not only include the mechanical efficiency of the transition of metabolic energy into mechanical energy, but also all internal losses to heart and long muscles, other organs, friction, activation losses, eccentric and static muscle work, losses for accelerating and slowing down leg segments, and even the frictional losses in the drive system. So one should expect a gross efficiency not only smaller than the thermodynamically speaking maximum feasible efficiency of 30%, but also clearly smaller than the efficiency of isolated muscles, so below 26%.

In fig. 4 the gross efficiencies of a number of activities are compared to the efficiency of the contraction mechanism and to the muscle efficiency. With an average gross efficiency of 23-24% (averaged from many studies) the drive in cycling proves to come very close to the theoretical maximum. Apparently all the internal losses just mentioned are already so small that one cannot expect much progress from an alternative drive system aimed at increasing the efficiency. Regarding the question posed in the title of this contribution the following conclusion must be made: no, we can hardly expect any further improvement of effectivity at all.
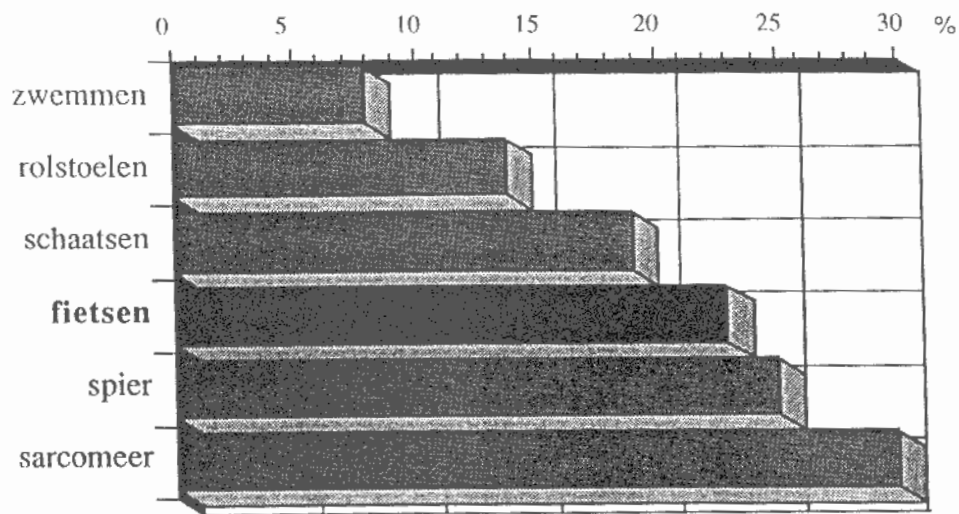
Fig 4: Gross efficiency of a number of various activities compared to an isolated muscle and the thermodynamically speaking maximum possible efficiency on the level of the contractile proteines.

The more muscles, the more joy

Although little progress seems to be possible on the level of efficiency and effectivity of the drive, in theory an increase in power production is certainly not inconceivable. I feel the only way in which this is possible, is to utilize more cylinders of the human engine than just those used in leg extension. This point too can be made plausible by a comparison with other activities.
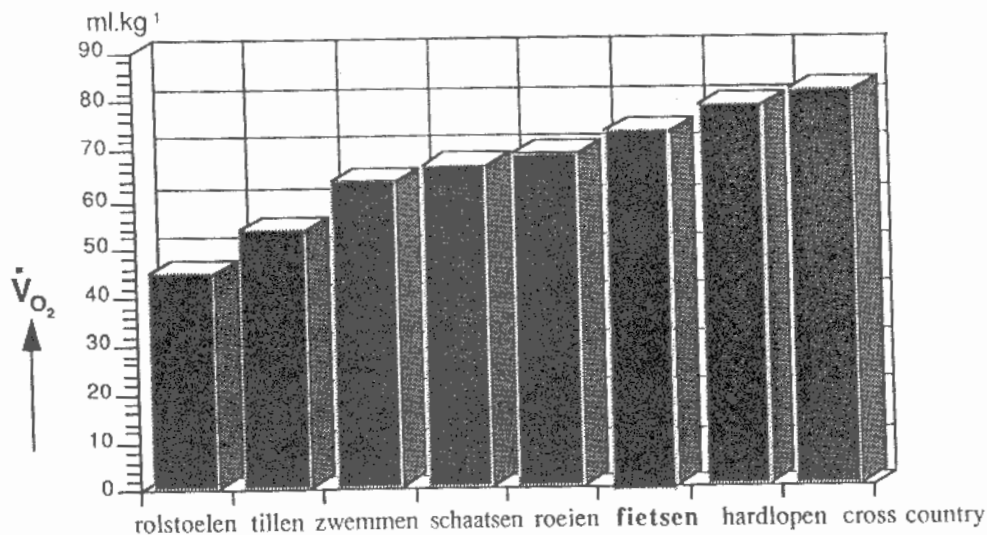
Fig 5: Maximum consumption of oxygen during a number of activities.

In fig. 5 the oxygen consumption rates measured at maximum effort are given for top athletes at the concerning activities. These maximum oxygen rates are a measure for the aerobic powers delivered in these efforts. It is often thought that the maximum oxygen

consumption rate is a fixed measure for generally quantifying the physical condition of an athlete. This aerobic condition would mainly be determined by the oxygen transporting capacity of the cardio-respiratory system (sports heart, good capilarisation of the muscles, etc.). Many studies in the last decades have shown that this is not the right way of looking at it for well trained subjects. If a rower is made to run, then his maximum oxygen uptake is generally larger during running than during rowing. The same goes for skaters. Skaters achieve a roughly 10% larger oxygen uptake on a bike than on skates. However, if they are made to run even larger values are measured. A comparison between cycling and running has been made by many research groups and all of them find larger values during running than during cycling; even with specifically trained cyclists. Averagely these differences amount to some 8-10%. By determining the consumption of glycogen from muscle biopts it was made plausible that during running much more use of calf muscles is made than during cycling with similar energy consumption of hip and knee extensors. The message seems clear: develop drive systems that allows a working participation of more muscles. On the current bicycle it is mainly the upper leg muscles that deliver the work. The other muscles are mainly active in conducting forces (calf muscles; trained is done in ankle extensions, but in practice not much can be achieved by it) or taking care of reaction forces (back and arm muscles). For example, during cross country not only the extensors of the hip, knee and ankles are used, but also the arm muscles for delivering work. That is why the largest oxygen consumption rates are measured here. So one could think of drive systems where more calf work is utilized, but also more arm work can be utilized. However it will not be easy to set up such systems so that the utilisation of extra movements will not happen at the expense of the already so well optimized power production of the leg muscles on the current bicycles. The repeatedly lifting of loads (from deep bended knee and hip joints) and the rowing contain a warning here. After all, here too arm as well as leg muscles are utilized for the delivering of mechanical work and yet the maximum oxygen consumption is relatively small. This is probably due to the fact that conducting forces must be done through the (relatively weak) back in both cases. Because we can look upon the muscles in the chain for conducting forces in an extension chain as links in a chain, weak links can lead to a smaller production of force (and therefore power) than possible, because the nerve system will primarily choose for stabilizing the system (and protection against injuries). This often takes place unconsciously.

Such problems possibly to be encountered do not take away the fact that in theory a gain of about 15-20% in power production can be made. At given frictional losses this corresponds to some 6-8% (at the most) gain in speed. This is still considerably less than the theoretically possible gain in the area of minimizing air resistance.