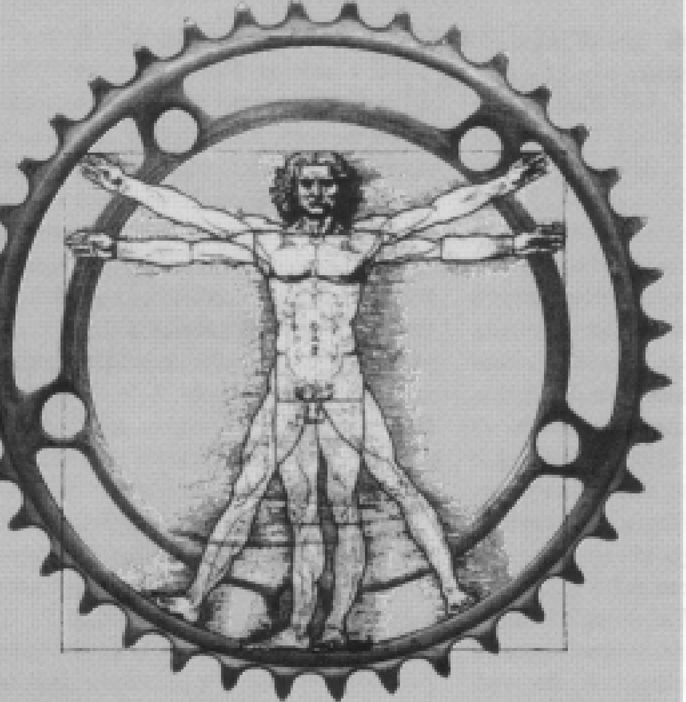

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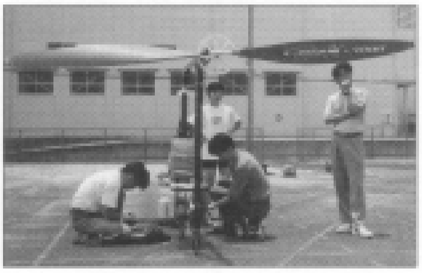
Measurements of the Power Required at the Take-off Run of HPA

CHicK-2000 Project Team
"Active Gals"



Toshiaki Yoshikawa Asanuma Corporation
Project Manager and Chief Engineer
Hiroshi Kusumoto Maruhuku Engineering
Yasushi Yamamoto Minolta Co.,Ltd.
Shinsuke Sakamoto Mitsubishi Electric Corp.
KoToNo Hori ToTo Co.,Ltd.
Takashi Hattori Nagoya University
Kouta Sata Nagoya University

This paper was originally presented at the 6th Sky Sports Symposium in Tokyo, Japan on 12/8/96 by Kotono Hori

Abstract
HPAs consume a great deal of energy to become airborne. The pilots must get up enough speed in as short a distance as possible. The system of using a propeller in conjunction with a rope drive is common. The ability of this system to generate enough speed is tested.

Key Words: Take off Run, Required Power, Human-Powered Aircraft

Introduction

Flying: A Woman's Natural Advantage
"Active Gals" is an HPA team in Japan that started HPA activities in 1991. Because women have the advantage of lighter weight in human-powered flight we designed our plane for a female pilot. Our estimations reveal that it takes a continuous output of 346 W for the average male to fly. We selected Kotono Hori because she was 154cm (5ft) tall and weighed 43 kg (97 pounds) (!). We estimated if she could maintain an output of 283 W for IO seconds she could fly—an 18% reduction in power required over that for the average male. Lacking a grant we can conduct only a few flights a year. Kotono Hori, the pilot, succeeded in human-powered flight for the first time for a Japanese female in 1992. That airplane, the KoToNo-Limited, has been displayed at Kakamigahara Aerospace Museum since 1994.

Kotono Hori, the pilot, gives a lecture at 6th Sky Sports Symposium

Kotono Hori, pilot
Date of birth 1967/11/8
Height: 154 cm (5 ft)
Weight: 43 kg (97 lbs)

In 1994 our goal was to fly using only 160 W of power at a velocity of 8.0 m/s in a 360 degree circle with a radius of 200 m. To fly with such low power, we adopted a long wing aspect ratio (AR) of 43.7. To overcome the twisting load on both sides of the wing during banking we built our plane, the CHicK-2000, using a "stress-skinned" carbon fiber reinforced plastic (CFRP) structure. On most planes the wings are constructed by forming a skin over a frame latticework, or extended spar. In some military planes the skin cover is a stress-bearing member, much like a hollow tube. This reduces spar weight, making the plane one-third lighter.

Six years later, we succeeded in a straight flight on 4th Nov. 2000. During that time we conducted experiments and took measurements to obtain basic data for the design of new airplane. We developed techniques to make CFRP, new flight techniques and control methods at the same time.

There were three accidents, including crashes as well as the plane collapsing in midair. As a result of our repairs the airplane became too heavy to fly in a 200 m circle as originally planned. Below we describe some of our results, experiences and techniques we gained in making our attempt.

Power Requirements
In human-powered flight, high power is required to become airborne. However, with an efficient take off the pilot still has enough power to make a powerful climb and subsequent stable flight.

Measurement of physical strength

We designed our plane to fly with minimal power requirements. What we sought was to become airborne with minimum distance, time and power loss. This is what we investigated below.

It is very hard to measure accurately the required power in taking off for several reasons such as friction between the wheel and the ground, the efficiency and thrust of the propeller, and the lift and drag at low Reynolds numbers (Re). The exact power required during take-off not being clear we estimated the required power as 208 W, a 30 percent increase of the power required for steady flight. Knowing this allowed us to maximize efficiency which is especially important in high-power training. Because the maximum power required was during take-off we used this as the index for training. The data acquired were useful in designing the cockpit frame, seat and drive unit.

Drive system

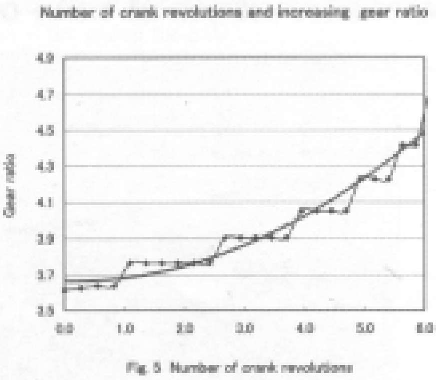
A Dual drive was adopted. This is when pedalling spins both a propeller and drives a bicycle wheel to achieve enough speed to get airborne.

In pedaling an HPA, it is important to improve the propeller's efficiency by smoothing the oscillation due to pulse acceleration caused by pedaling. The propeller spins most efficiently with continuous power as opposed to the pulse accelerations caused by alternate pedal thrusts of the legs. During the initial acceleration before lift-off the peak power shifts are great as the legs alternate pushing because large torque is required. During that time, the propeller blade alternates between cycles of acceleration and deceleration, and as a result its efficiency decreases greatly. At low speeds (under 5–6 m/s) the drag of the propeller is considerable and acceleration by driving a conventional bicycle wheel is more efficient. Also, a variable-pitch mechanism that adjusts the propeller angle automatically is needed.

At around 5–6 m/s, the wing begins generating lift decreasing the weight on the driving wheel and the ability of the wheel to propel the plane. Just before lift-off the bicycle wheel drops in efficiency due to tire slip and the efficiency of the propeller drive increases. When this happens the drive powering the bicycle wheel shifts into propeller drive. This is thus a very efficient drive unit.

We used a 2800 mm diameter propeller and a rotational speed of 140 RPM. The efficiency was estimated to be 90%. The propeller was driven by a twisted chain connected to a conventional chainwheel assembly, 1200 mm between axes. The bicycle wheel was a tubular (sew-up) tire as used in bicycle races and velodromes.

At the cranks, the Kevlar rope was wound onto a 235 mm diameter front drum between two closely spaced, large, flat discs (see Fig. 7) and a 65 mm diameter drum attached to the rear wheel (see Fig. 13) As a result, each turn of the pedals increased the diameter of the crank-arm drum onto which the rope was wound and decreased the size of the rear hub drum the rope was unwound from. As a result each revolution of the pedals increased the gear ratio (see Fig. 5).



Number of Crank revolutions and Increasing Gear Ratio

What we sought was to determine the optimal rate of gear ratio increase as well as the optimal time for shifting to all propeller drive.

Method

For our experiments we made a full size replica of the cockpit frame (i.e., without wings) that the pilot could pedal like a bicycle, using the dual-drive system described above and a measurement system to study the maximum power possible. Our goal was 8 m/s.

Cockpit frame

Cockpit frame was constructed with square tubes of CFRP composites the

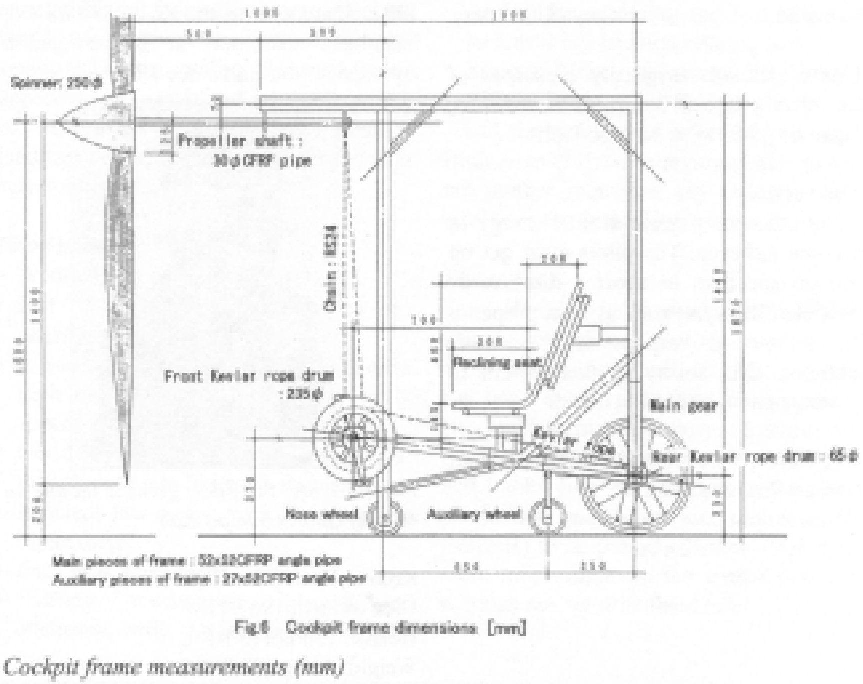


Fig.6 Cockpit frame dimensions [mm]

Cockpit frame measurements (mm)

same sizes used in the "CHicK-2000". Aluminum square tubes are used as mould to pile up the prepeg sheets. After which the prepreg sheets are heated and cured by the tape wrapping method. CFRP tubes were hand-made by PYROFIL TR-340 (Mitsubishi Rayon Co., Ltd.).

Apparatus

A strain gauge located on the right hand pedal measured pedal torque and a photoelectric sensor measured rotational speed of the sprocket. Analog voltage signals caused by electrical resistance which are proportional to the strain were amplified and logged by a U-LOGGER L840 (UNIPULSE). The sampling rate was 1000/s.

A photoelectric sensor detected the passing of the sprocket teeth. When a tooth crosses the photoelectric sensor it opens a switch and transmits a +5 V output. The data logger treated these analogue signals as pulse signals. Power was derived using data from the rotational speed and the strain gauge.

A strain gauge was connected to the crankshaft by winding a suitable length of cable around a drum connected between the crankshaft and sprocket. With each test run the cable was wound up by the drum.

Data Collection

The strain gauge converted torque to voltage. The relationship between force and voltage is: force (F) and voltage (V) is related with the equation as follows.

F(kg)=-2.0705+7.6720V

A regression line was fit that accounted for 99.9% of the variance.

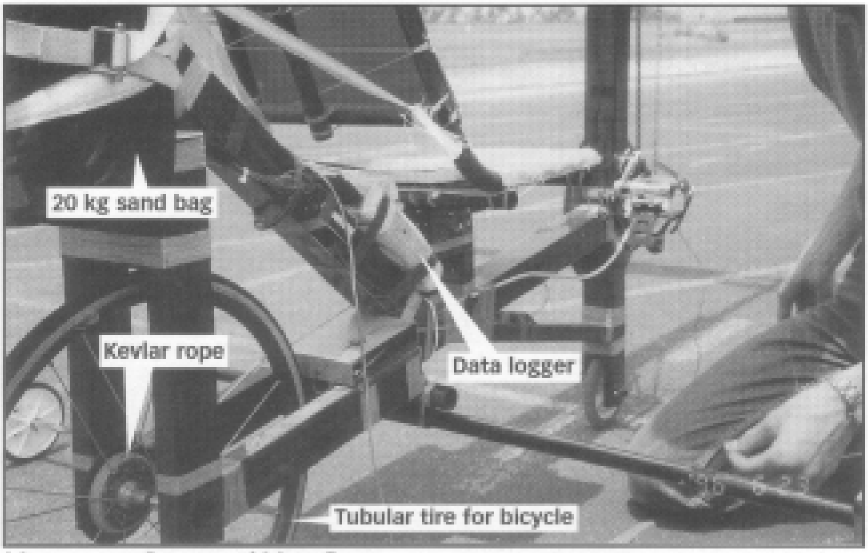
Torque was obtained by multiplying force (F) and the crank arm length (l)

l=175 mm
T=Fkg *lm

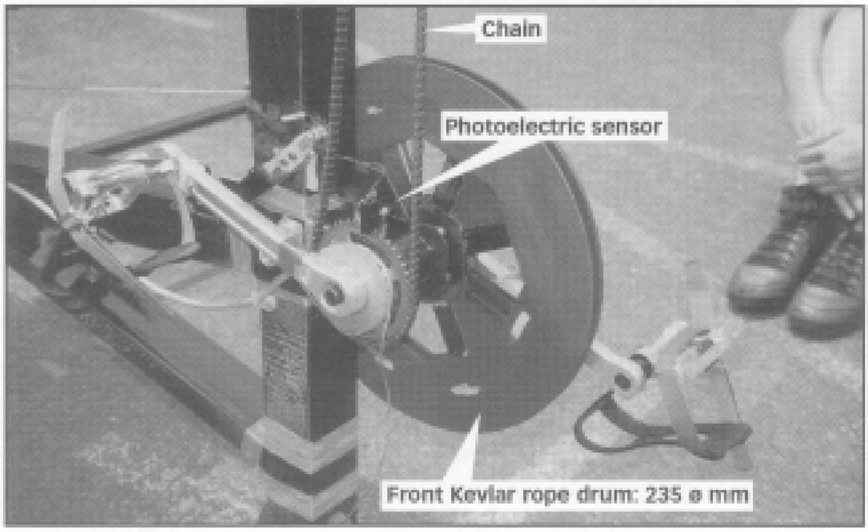
Data were stored in a data logger (U-LOGGER L840) and uploaded to a PC where the strain gauge and photoelectric sensor data were separated. Pulse signals obtained by photoelectric sensor were converted into rotational speed by a FORTRAN 77 program.

Experiment I

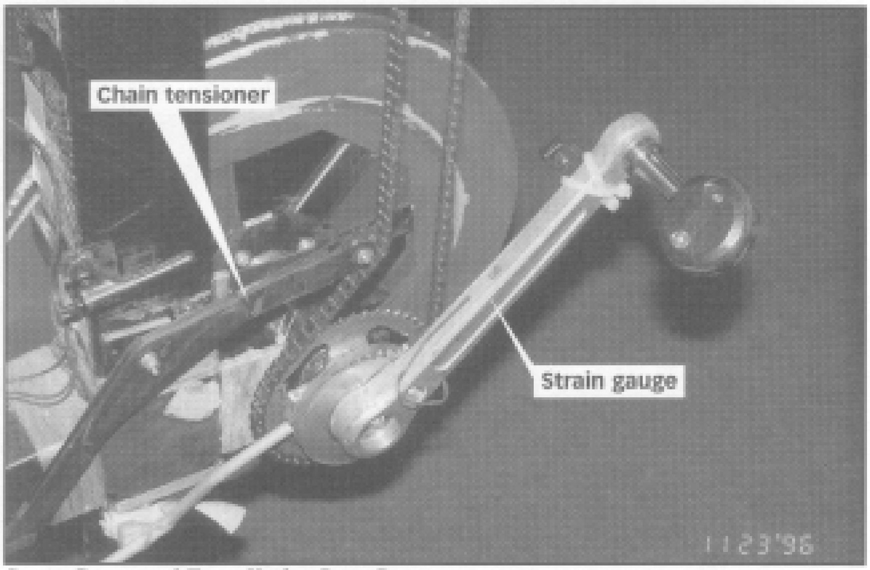
Experiment I consisted of two



Measurement System and Main Gear



Front Kevlar-Rope Drum



Strain Gauge and Front Kevlar-Rope Drum sessions. The first session was on 6/23/96 and consisted of 5 trials, or runs, and the second session was on 9/8/96 with one trial. Both sessions were conducted on the track at Osaka University of Health and Sport Sciences under the direction of Prof. Huchimoto.

Test runs were conducted on a Tartan™ track made from synthetic rubber and used at the Olympics. It was thought that the coefficient of friction between the tire and track was large enough so that the driving wheel would not slip.

Runners guide but do not push the cockpit

Each run was conducted under less than 2 m/s of wind velocity. Each run was 30 m, and we adjusted the length of Kevlar rope so that the distance using both propeller and rope drive (DUAL drive) was 20 m. The last 10 m was under propeller drive only. We attached a 20 kg sandbag to the back of the seat so that the weight of the cockpit frame was the same as the complete airplane.

Results of Experiment I
Our results are shown in Tables I–IV.

First experimental session

Table I. Maximum and averaged speed of take-off run Table II. Torque and required power in take off run

Second experimental session

Table III. Maximum and averaged speed of take-off run
Table IV. Torque and required power in take-off run

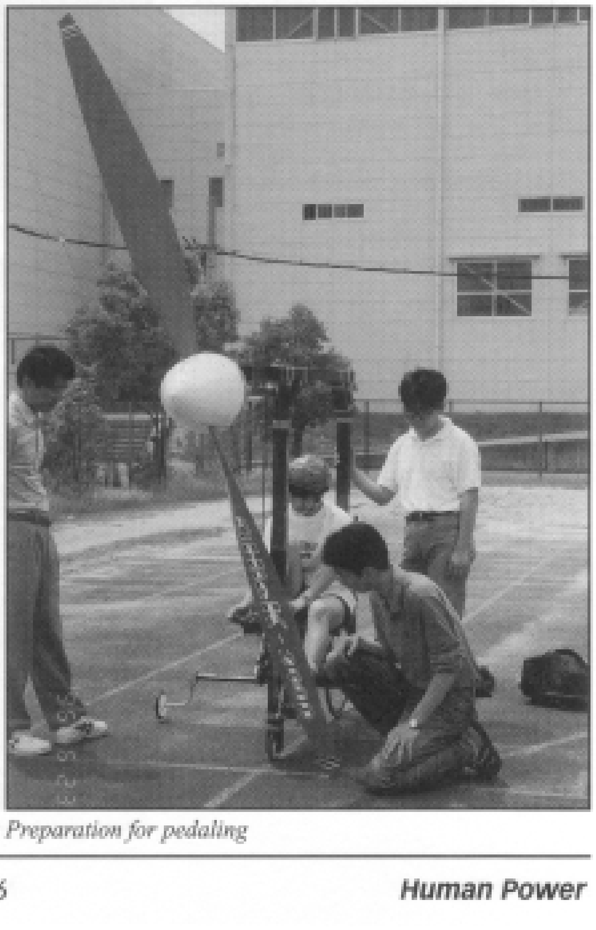
Figs 16–19 depict data summarized in Tables I & II.

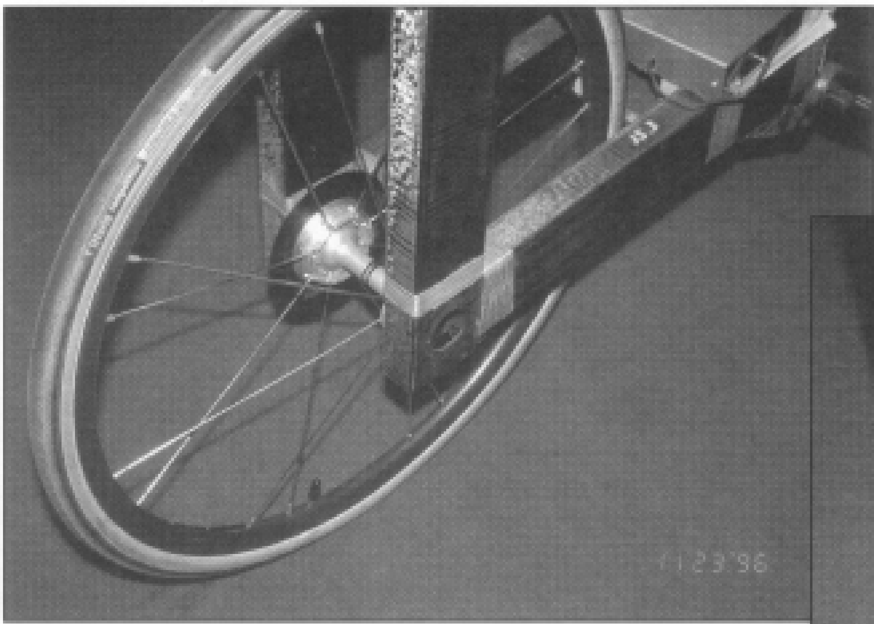
Unfortunately, we where unable to achieve our goal of a cockpit speed of 8 m/s using video analysis. The average maximum chainwheel velocity (n=6) for the first experimental session was 7.53 m/s. The highest maximum velocity of the single run of the second experimental session was 9.02 m/s. Unfortunately, no video analysis to determine cockpit speed was possible for this final run.

Discussion
The maximum chainwheel velocity is the chainwheel speed during a pedal stroke at the moment of the pilot's maximum thrust on the pedals. The average chainwheel speed in one stroke of pedaling is about half of the maximum speed.

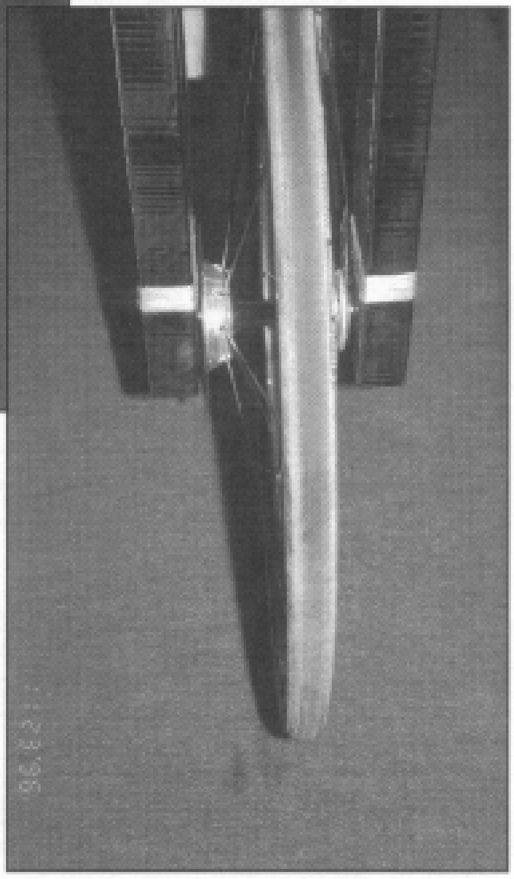
The maximum spocket speed during any single rotation of the pedals when the pilot exerts maximum thrust in extending the leg is about 12 m/s, and the minimum sprocket speed during any single rotation of the pedals is about 3m/s. The average speed is the midpoint of the maximum speed and the minimum speed.

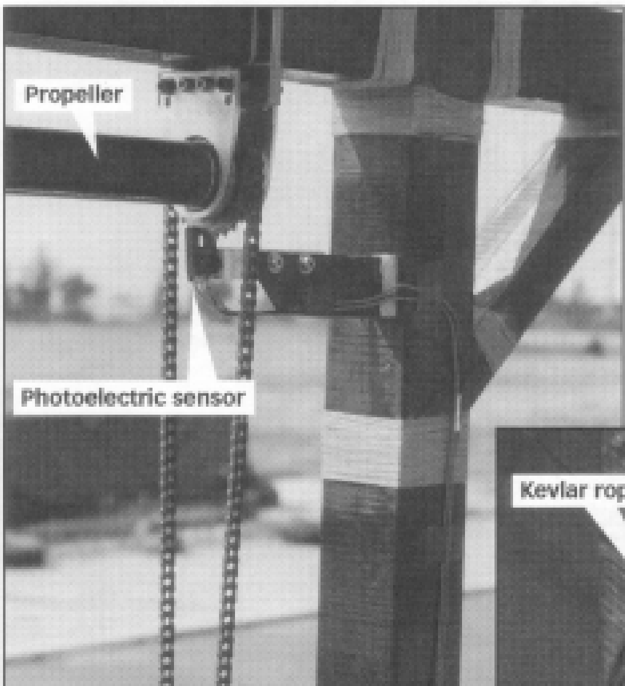
In pedaling a bicycle, the differences between the maximum and minimum values are attenuated by the inertial force of the combined bicycle and rider weight. In pedaling an HPA the propeller is so light that there is no flywheel effect and the power oscillation of alternating pedal thrusts is great. This led to Experiment II.


Preparation for pedaling

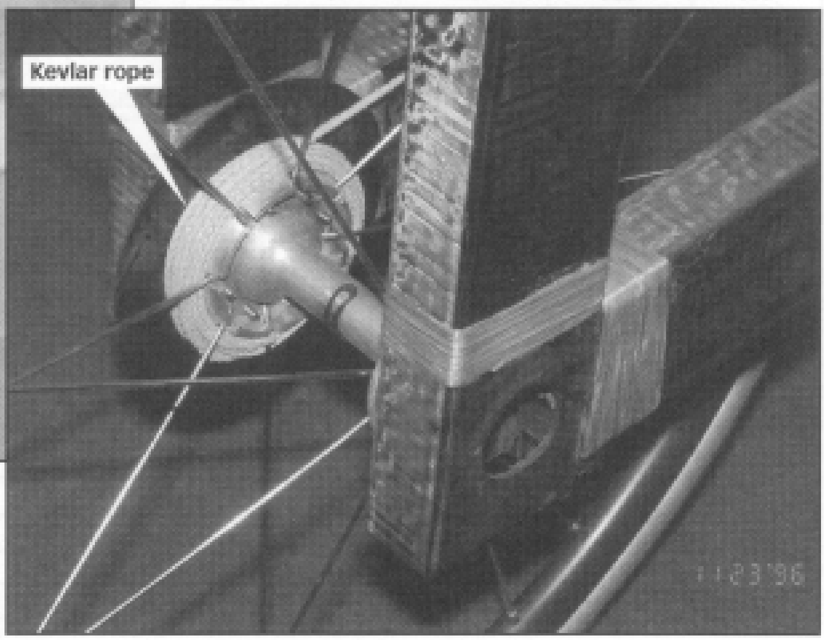


Rear hub





View of the photoelectric sensor equipped with the cockpit



View of the wound-up rope

TABLE I
Experiment I—First Experimental Session
Maximum and Averaged Speed of Take-off Run

Trial	Averag chainwheel Velocity m/s (rpm)	Maximum chainwheel Velocity m/s (rpm)	Cockpit frame Velocity by video an analysis m/s	Notes	Figures
1	4.50 (51.1)	7.34 (83.3)	5.77	No data in changing driving method	
2	4.83 (62.2)	7.82 (133.0)	5.45	–	Fig-16,17
3	5.09 (63.4)	7.82 (133.0)	5.88	–	
4	5.10 (65.4)	7.82 (133.0)	6.25	–	Fig-18,19
5	4.74 (59.4)	7.34 (121.0)	5.77	–	
AVERAGE	4.85 (60.3)	7.63 (120.7)	5.82		

TABLE II
Experiment I—First Experimental Session
Torque and Required Power in Take-off Run

Trial	Averag crank Torque kg·m	Maximum crank Torque kg·m	Required Power Averaged watt	Required Power Max watt	Notes	Figures
1	4.41	12.9	227	812	No data in changing driving method	
2	3.90	12.7	239	875	–	Fig-16,17
3	3.85	12.8	240	930	–	
4	3.80	12.3	248	920	–	Fig-18,19
5	3.89	12.9	228	907	–	
AVERAGE	3.97	12.7	236	889		

TABLE III
Experiment I—Second Experimental Session
Maximum and averaged Speed of Take-off Run

	Averag chainwheel Velocity m/s (rpm)	Maximum chainwheel Velocity m/s (rpm)	Cockpit frame Velocity by video an analysis m/s	Notes
1st	5.27 (59.9)	9.02 (103.0)	–	–

TABLE IV
Experiment I—Second Experimental Session
Torque and Required Power in Take-off Run

	Averag crank Torque kg·m	Maximum crank Torque kg·m	Required Power Averaged watt	Required Power Max watt	Notes
1st	6.82	19.1	431	1232	–

Experiment II

The second experiment was a single experimental session on September 8, 1996 that consisted of three trials and was conducted in a brick-powder track. Compared with a rubber track used in the previous measurement, it had a much larger slip ratio. We made the following changes.

Changes made before the second experiment.

1. During the first two runs we noticed the chain was loose, increasing the power alternations between pedal thrusts, further decreasing the efficiency of the propeller due to power alternation (described above). To reduce the oscillation of the chain we re-tensioned the chain and improved the efficiency.

2. The drum on the rear wheel which the kevlar rope was wound around as tapered going from 50 mm to 65 mm. This increased the gear ratio 30% as the rope unwound. In such a way the gear ratio increased from 3.616 to 4.700.

3. Because we could not reach the take-off speed of 8m/s during the last 10m of the previous runs using propeller drive only we lengthened the rope from 20 m to 30 m so the cockpit frame was powered by DUAL drive throughout the run. In this way we hoped to reach 8 m/s.

4. Because of our changes we changed the position of the photoelectric sensor. Also, because at some points the voltage exceeded the upper limit of 10 V of the data logger, we lowered the gain of the strain gauge.

Results of Experiment II

Table V Maximum and averaged speed of take-off run

Table VI Torque and required power in take off run

Figs 20–23 depict data summarized in Tables V–VI

The mean maximum velocity of the second experiment (n=2) was 12.35 m/s. To estimate the effect of tire slip we

TABLE V
Experiment II—Second Experimental Session
Maximum and Averaged Speed of Take-off Run

	Averag chainwheel Velocity m/s (rpm)	Maximum chainwheel Velocity m/s (rpm)	Cockpit frame Velocity by video an analysis m/s	Notes	Figures
1st	5.55 (63.0)	11.7 (133.0)	4.90	–	Fig-20,21
2nd	4.98 (56.6)	13.0 (148.0)	5.00	–	–
3rd	5.53 (62.8)	10.7 (121.0)	5.20	Without 20kg of ballast	Fig-22,23
AVERAGE OF FIRST TWO RUNS	5.27 (59.8)	12.4 (140.5)	4.95		

TABLE VI
Experiment II—Second Experimental Session
Torque and Required Power in Take-off Run

	Averag crank Torque kg·m	Maximum crank Torque kg·m	Required Power Averaged watt	Required Power Max watt	Notes	Result
1st	4.04	20.6	238	1614	–	Fig-20,21
2nd	4.33	22.1	224	2334	–	–
3rd	3.38	23.0	198	1470	Without 20kg of ballast	Fig-22,23
AVERAGE OF FIRST TWO RUNS	4.19	21.4	231	1974		

Fig.16 EXPERIMENT I First experimental session, Trial 2-Chainwheel Velocity and Power

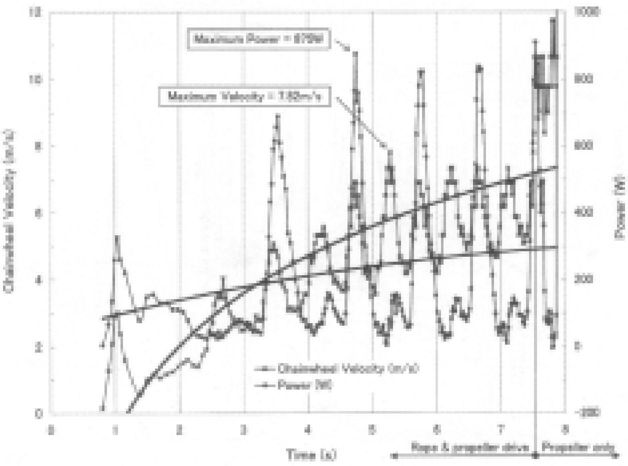


Fig.17 EXPERIMENT I First experimental session, Traial 2-Crank RPM'S and Crank Torque

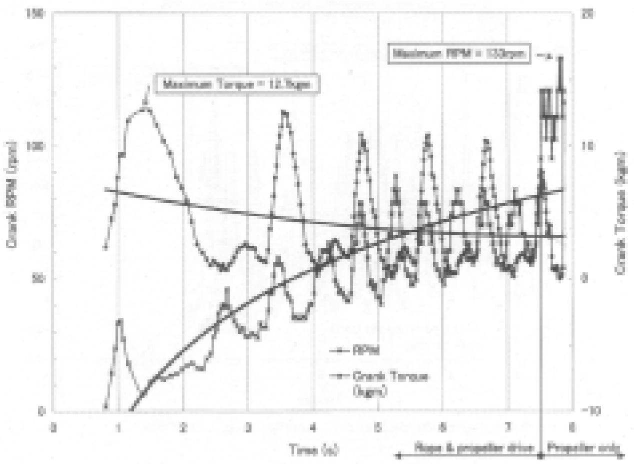


Fig.18 EXPERIMENT I First experimental session, Trial 4-Chainwheel Velocity and Power

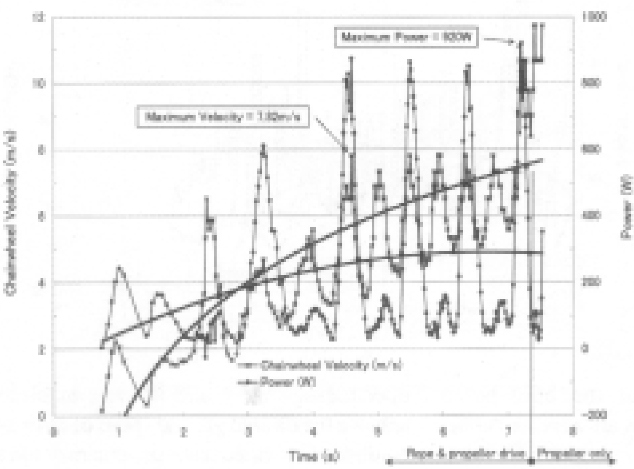
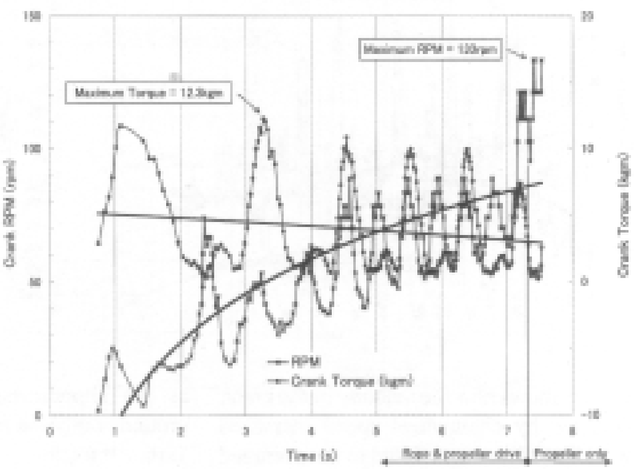


Fig.19 EXPERIMENT I First Experimental session, Trial 4-Crank RPM'S and Crank Torque



removed the 20 kg ballast for the third trial, reducing the maximum velocity to 10.7 m/s. This demonstrates that if the weight is decreased by 20 kg it requires less torque. Inspection of Table VI shows that though the ground speed velocity increased from 4.95 m/s to 5.2 m/s the average amount of torque decreased from 4.19 kg/m to 3.38 kg/m. The decrement of weight decreases the required power at take-off run.

Discussion

Because of our changes we were able to increase the efficiency and power output so that the chainwheel velocity dramatically increased from 7.53 m/s to 12.35 m/s. For the purposes of examination Figs 24–27 are taken from previously graphed data from Experiment I, First experimental session, trial #4, which achieved the highest cockpit frame velocity (6.25 m/s) as seen in Table I and the lowest max. Torque (12.3 kgm) as seen in Table II. What we seek is the highest possible cockpit speed with the lowest maximum torque possible.

Unfortunately, the increased slipping of the tire prevented the cockpit frame from accelerating from rope drive. We wondered if the increase in chainwheel velocity was due to the increased slipping of the tire. The period of torque variation agrees with the period of pedaling so that the maximum value of the torque is during the 1st or 2nd revolution. The strain gauge located on the right hand pedal registered a peak when the right hand pedal is pressed. Fig. 24 shows the pilot's maximum torque was at the beginning.

In Fig.s 25 & 26 it can be seen that with time, crank-arm speed and chainwheel velocity increase. The maximum value of the moment is 90 RPM at 6–7 m/s. The variation period of rotation and velocity is about half of the period of pedaling.

Fig 26 shows that when the pilot pedals, the plane is accelerated. The speed of one crank arm revolution decreases from 2.1 to .8 seconds in 5 revolutions, despite the increasing gear size with each revolution. Fig. 27 shows the shape of the curve showing required power over time. The shape of the curves showing required power agrees with the shape of the curve showing the amount of torque required, Fig. 24. With time, the velocity and power increase. Inspection of Fig 24 reveals that high torque coincides with the peak power in Fig. 27, reaching a maximum during the 3rd revolution. Comparing the annular velocity of the front chainwheel (m/s) in

Fig.20 EXPERIMENT II Trial 1- Chainwheel Velocity and Power

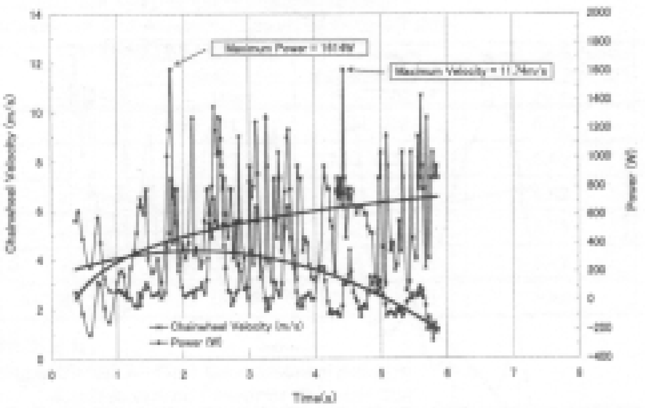


Fig.21 EXPERIMENT II Trial 1-Crank RPM'S and Crank Torque

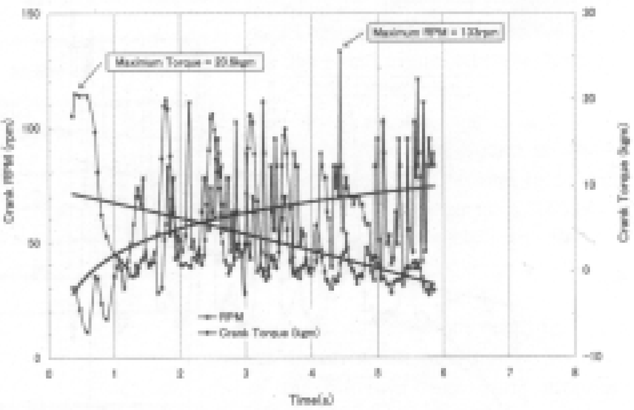


Fig.22 EXPERIMENT II Trial 3-No Ballast Chainwheel Velocity and Power

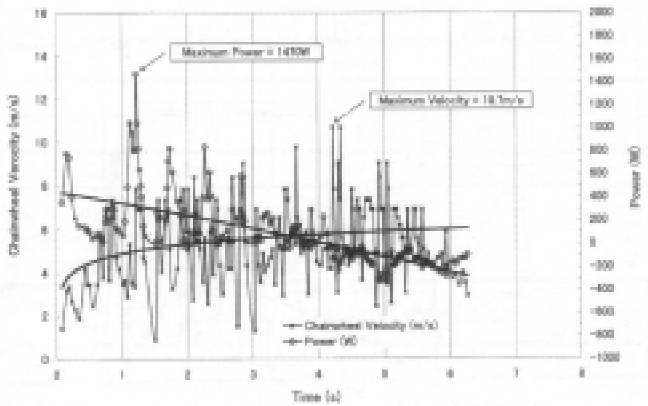


Fig.23 EXPERIMENT II Trial 3-No Ballast Crank RPM'S and Crank Torque

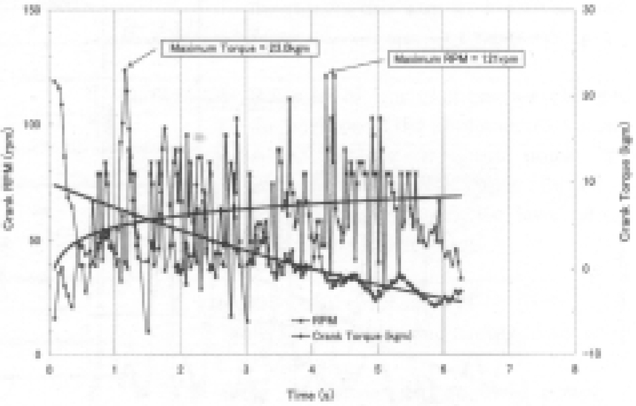


Fig. 26 shows how the velocity of the crank detected by chainwheel speed increased with time. This was related to the averaged velocity of the plane measured by video.

During the beginning of the run, the plane was propelled by both rope drive and propeller drive (DUAL drive). During the 6th revolution the rope unwound shifting all the pilot's power to the now more efficient propeller suddenly decreasing the load of the pilot and the rotational rate increased, as shown in the sixth revolution of Fig. 25 & 26.

The peak torque decreased in the second half of a run; the effect of the Kevlar rope as it unwound from the tapered drum on the rear wheel. The maximum value of torque is greater during the first half of the trial as can be seen in Figs. 17, 19, 21, 23, and 24.

In the 1st Experiment, one revolution took 1.5–2.0 s but during the 2nd this was reduced to 1.0 s, due in large part to the effect of improving the transmission efficiency of the chain-drive as well as the slipperiness of the brick-power ground compared to an all-weather rubber Tartan™ track.

The cockpit frame speed in Experiment II was slower than in Experiment I due to tire slip. After going 30 m during a real flight attempt, some lift occurs on the wing. At the beginning of a run the weight of the wings is dead weight and they hang low. When the cockpit frame has enough speed and starts to fly the wings generate lift and confirm the dihedral angle. With increased lift the cockpit frame is more likely to go straight as the force of the driving wheel decreases. This makes more power available to turn the propeller and the propeller turns faster. If 20 kg of ballast lost sand gradually during the trial the conditions would be more like those in actually taking-off.

The pilot's increased power output on the second experiment should be noted. Certainly the track was more slippery but it must be remembered that throughout the 30 m trial both the rope and propeller always operated together. While, we were unable to achieve the desired ground speed of 8m/s as confirmed by video analysis, this may have been due to a number of reasons.

For one, the cockpit frame we used had additional auxiliary wheels on either side to stabilize it that the aircraft did not. The drag from these wheels may have impaired performance. While it was difficult to balance the human-powered aircraft the stabilizing wheels may have prevented the cockpit frame from smooth acceleration. Moreover, even slight unevenness in the ground will allow the tire to imperceptibly slip.

However, we were determined to fly and finished the airplane. We took it to a very smooth runway of concrete and, without the losses incurred by stabilizing wheels on the cockpit frame, were successfully able to fly.

The pilot reported that the effort necessary for flight was the same as the experiment.

Fig.24 Crank Torque over time
Experiment I—First Experimental Session, Trial #4

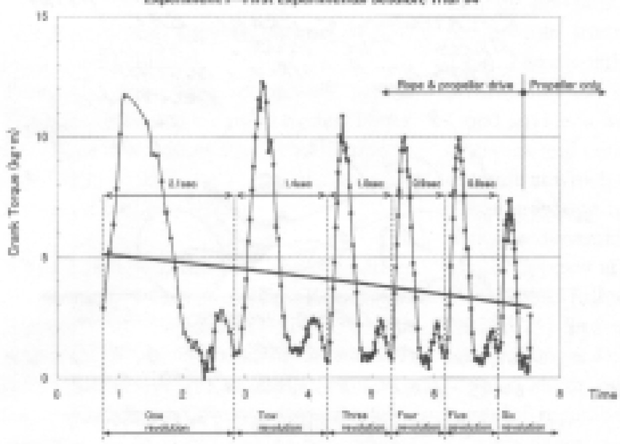


Fig.25 Crank Speed over time
Experiment I—First Experimental Session, Trial #4

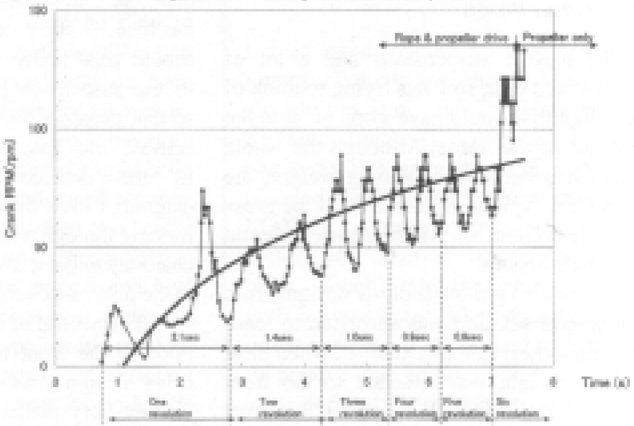


Fig.26 Chainwheel Velocity over time
Experiment I—First Experimental Session, Trial #4

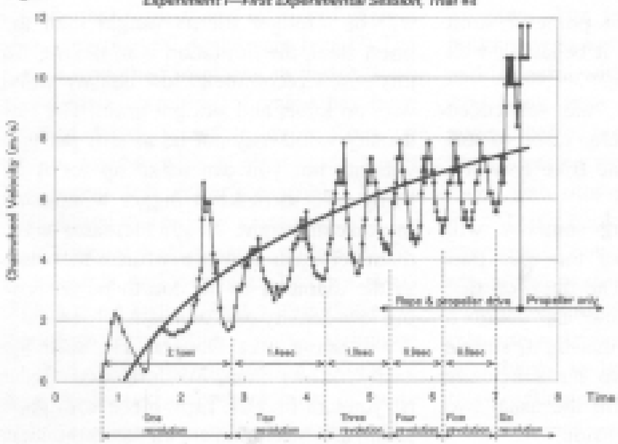
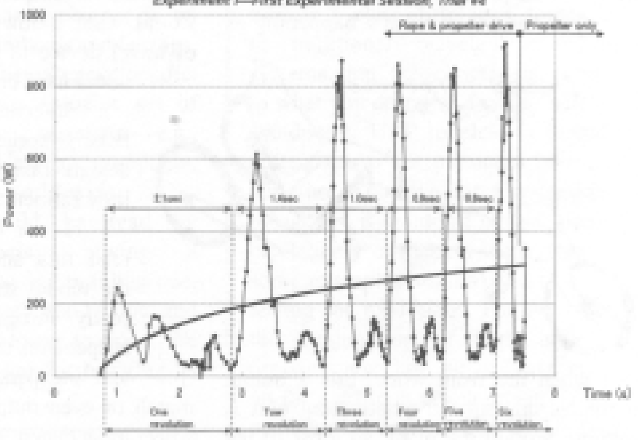


Fig.27 Required Power over time
Experiment I—First Experimental Session, Trial #4



Homepage http://www.fsinet.or.jp/~active-g/

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