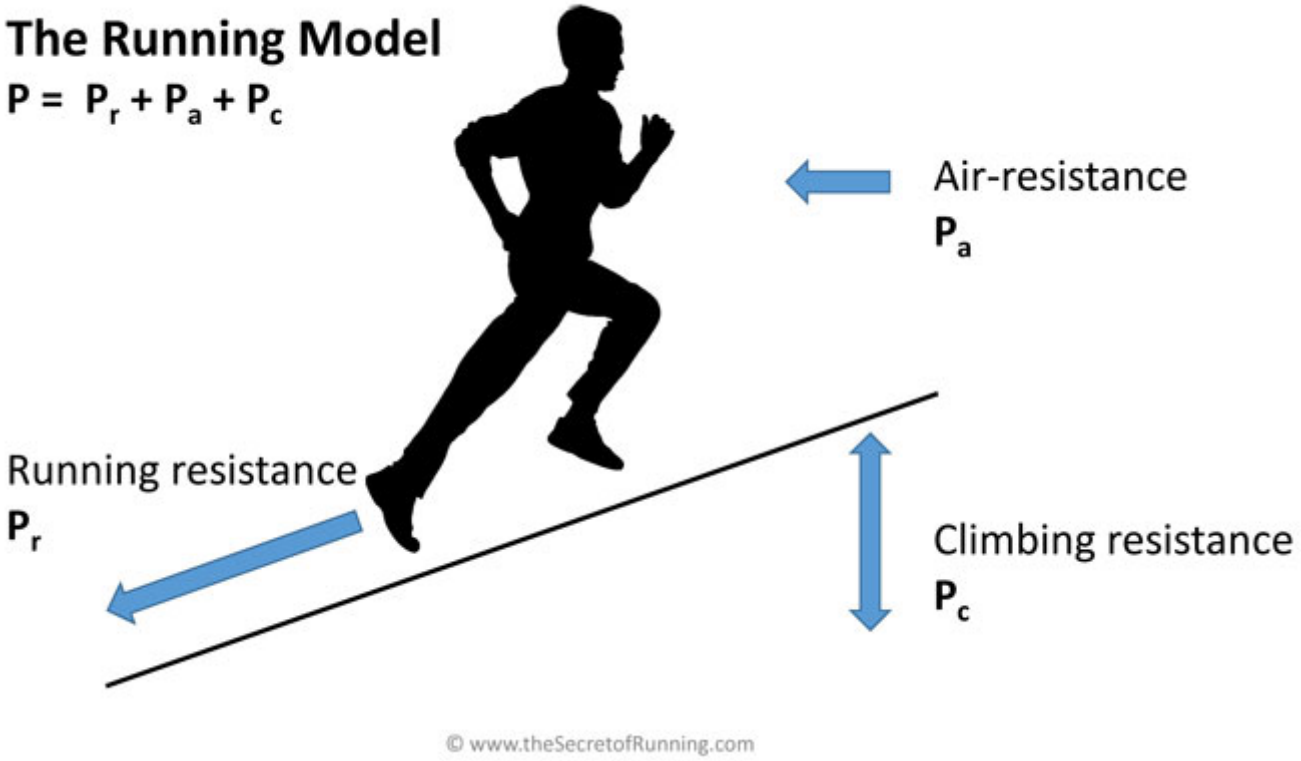
Running With Power: What It Can Tell Us About Our Human Limits

model is based on the premise that the power produced by the “human engine” (i.e. the leg muscles and the heart-lung system) must be equal to the sum of the power required to surmount the running resistance **Pr**, the air-resistance **Pa** and the climbing resistance **Pc**, as indicated in the figure below.



environmental conditions (wind, temperature, altitude, air-pressure, hills, footing).

In this paper, we will briefly describe the model and some interesting results. Meanwhile, we have tested the model in many situations (running, cycling and both in the lab and in races) and found the results very convincing and consistent. Finally, we have observed that the Stryd power data match our model calculations perfectly.

The physics of running

We have applied the laws of physics to running and derived the equations, presented in the box:

The physics of running

Running resistance: $P_r = cmv$

Air-resistance: $P_a = 0.5\rho c_d A(v+v_w)^{2*}v$

Climbing resistance: $P_c = img\eta v$

Running formula:

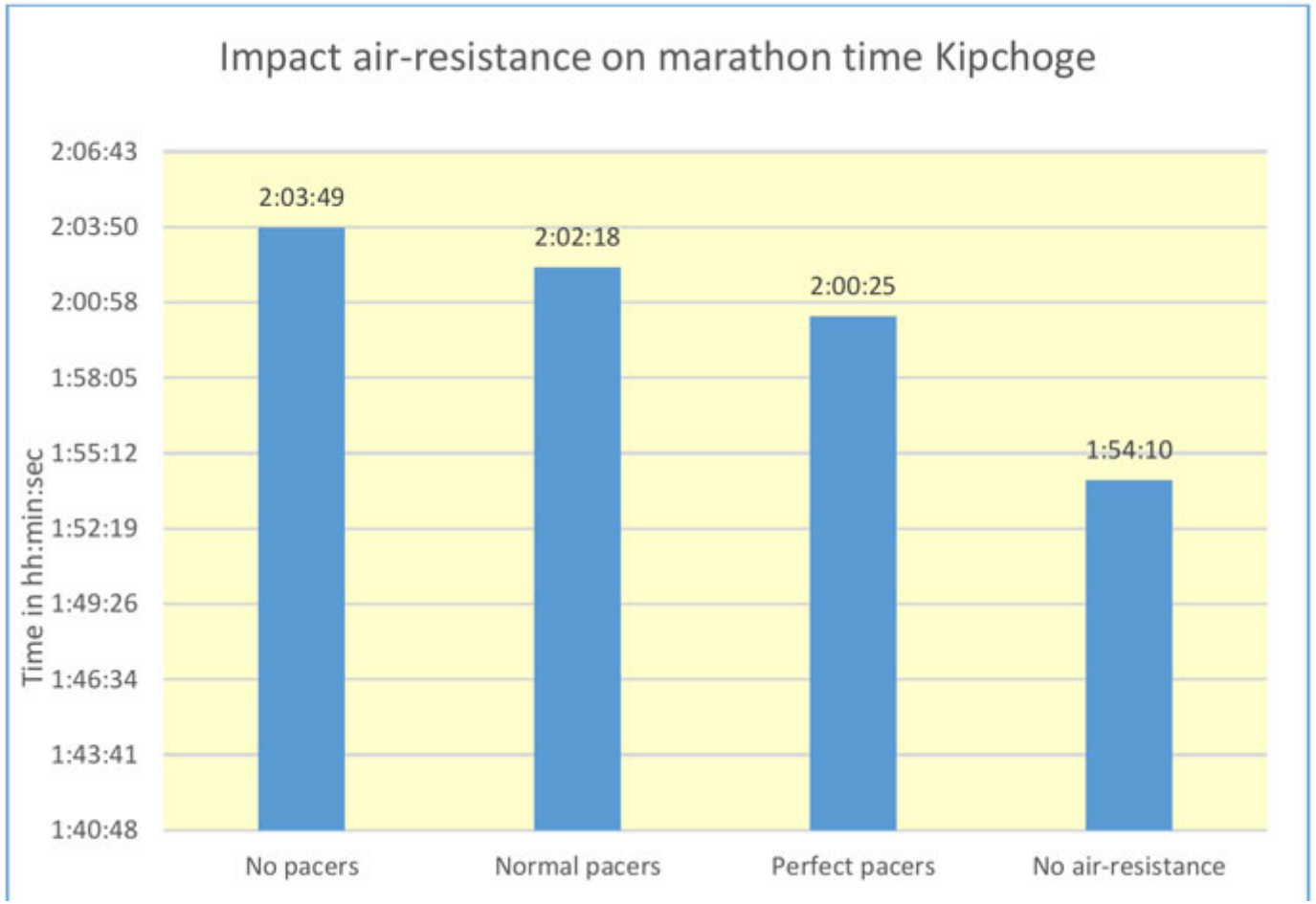
$$\mathbf{P = cmv+0.5\rho c_d A(v+v_w)^2 v+img\eta v}$$

This means that even at a level course (so Pc = 0), and in windless weather, some 7 percent of the power of the runner is lost due to the air-resistance. In record attempts pacers are frequently used to shield the elite runners and reduce the air-resistance (by some 20 percent). We have used our model to calculate how big the advantage of pacers is for world record performances.

According to our calculations, Kenenisa Bekele owes some 21 seconds of his phenomenal 10,000 m world record to the reduced air-resistance from his pacers. The air-resistance is eliminated altogether on a treadmill, so in theory Kenenisa Bekele could run even two minutes faster at the 10,000 m on a treadmill! The table below shows the present world records and the results of our calculations without pacers (so with increased air-resistance) and on a treadmill (so without any air-resistance).

World Records: Men				
Distance	Time	Name	Calculated time without pacers	Calculated time on treadmill
1,500 m	00:03:26	Hicham El Guerrouj	00:03:29	00:03:07
3,000 m	00:07:21	Daniel Komen	00:07:27	00:06:44
5,000 m	00:12:37	Kenenisa Bekele	00:12:48	00:11:38
10,000 m	00:26:17	Kenenisa Bekele	00:26:38	00:24:23
15 km	00:41:13	Leonard Komon	00:41:41	00:38:26
20 km	00:55:21	Zersenay Tadese	00:56:03	00:51:43
21.1 km	00:58:23	Zersenay Tadese	00:59:03	00:54:30

and the wind-breaking time screen on the car) was virtually perfect at 37.5 percent. According to our calculations, his 2:00:25 is equivalent to 2:02:18 in a normal race (which would be still an impressive new world record).



The physiology of running

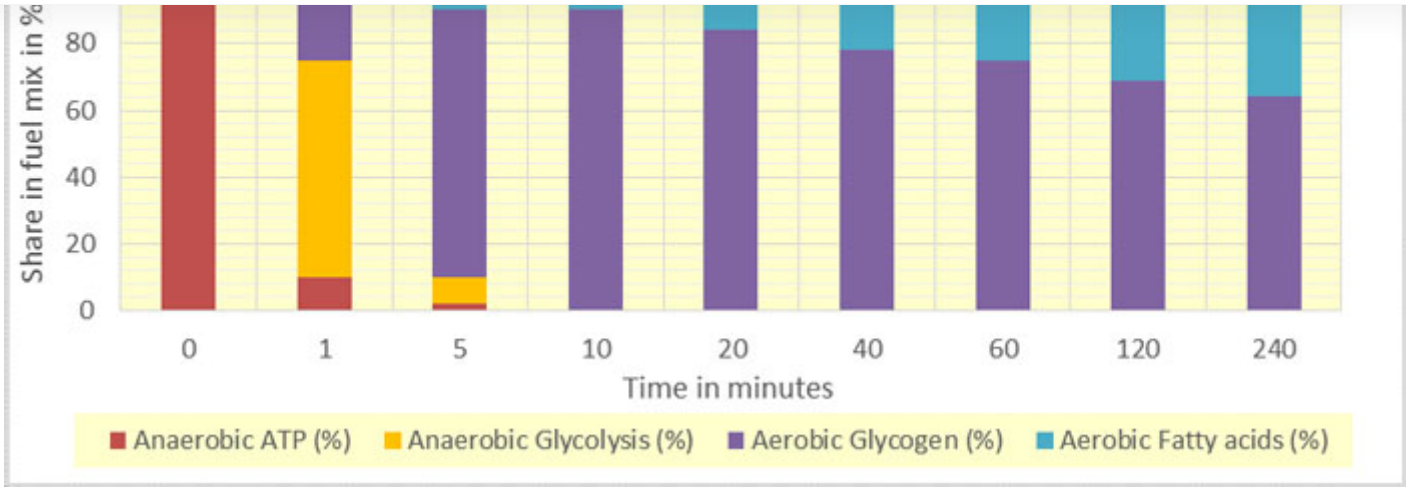
We have applied the laws of physiology to running and derived the table below that specifies the power limits of the four power producing processes in the human muscles. We consider these numbers as the maximum of human power for male elite athletes (who have very little body fat, for women the numbers are some 11 percent lower due to their higher fat percentage).

They are based on the fundamental biochemistry of the conversion processes (i.e. the maximum conversion speed and the energy production per unit of time) and on a gross metabolic efficiency of 25 percent (i.e. 25 percent of the metabolic energy is transferred into mechanical work, this number is considered the maximum for elite athletes in running and cycling).

ATP/CP		
ATP → ADP	$C_{10}H_{16}N_5O_{13}P_3 \rightarrow C_{10}H_{15}N_5O_{10}P_2$	24.64
Anaerobic conversion of glycogen		
$C_6H_{12}O_6+3ADP \rightarrow 2C_3H_6O_3+3ATP$		13.50
Aerobic conversion of glycogen		
$C_6H_{12}O_6+6O_2+38ADP \rightarrow 6CO_2+6H_2O+38ATP$		7.76
Aerobic conversion of fatty acids		
$CH_3(CH_2)_{14}COOH+23O_2+130ADP \rightarrow 16CO_2+16H_2O+130ATP$		2.36

Next, we have analyzed the impact of endurance time on the “fuel mix” in the muscles and the power produced. Sprinters use mainly ATP, 400 – 800 m runners use mainly the anaerobic conversion of glycogen, but distance runners rely on the aerobic conversion of glycogen and fatty acids.

This means that as distance/endurance time increases, less power can be produced so the speed is reduced. We have



Running power and FTP of the world records

We have used our model to calculate the running power P to run at the speed of the world records. The table below confirms that at increasing distance and endurance time the running power P is reduced.

The table also shows the so-called Functional Threshold Power (FTP), which is defined as the power that can be maintained during one hour. We have recalculated P to FTP using Riegel's formula as explained above.

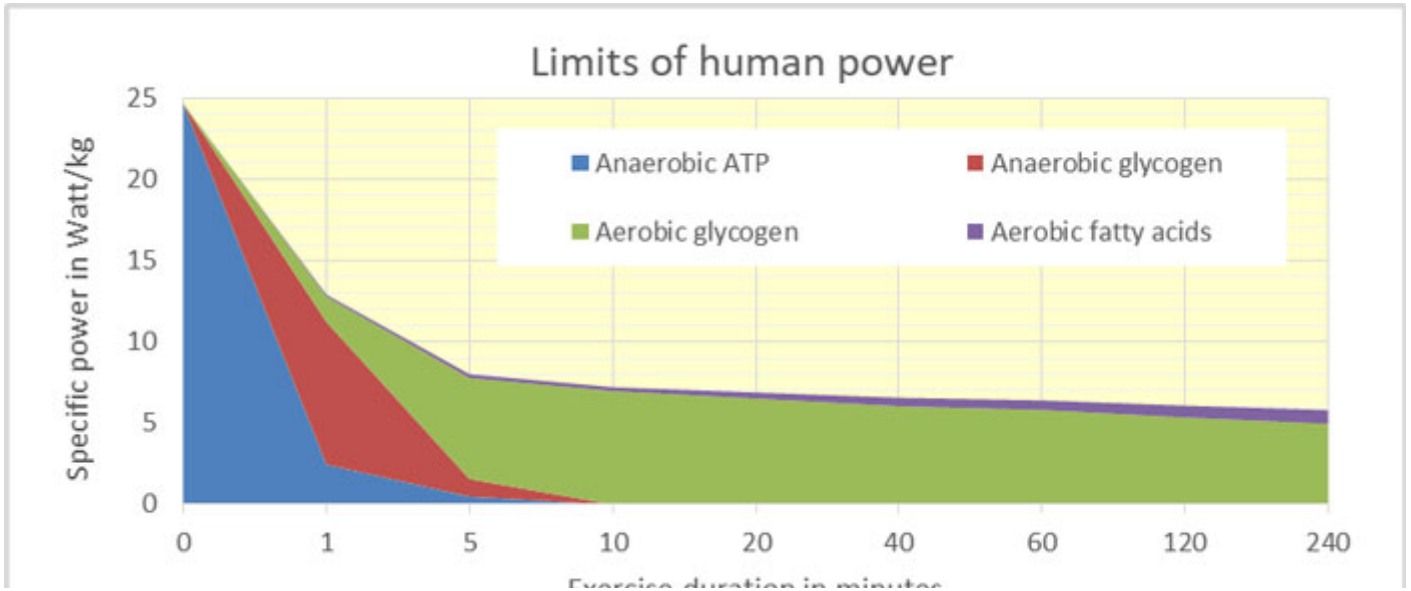
The table clearly shows that most world records are equivalent to an FTP of around 6.35 Watts/kg. The FTPs at the records at 15, 25 and 30K are a little lower, which is probably due to the fact that these distances are run much less frequent. The

3,000 m	7:20.67	Daniel Komen	7.32	6.32
5,000 m	12:37.35	Kenenisa Bekele	7.06	6.33
10,000 m	26:17.53	Kenenisa Bekele	6.74	6.36
15 km	00:41:13	Leonard Komon	6.41	6.24
20 km	00:55:21	Zersenay Tadese	6.35	6.32
21.1 km	00:58:23	Zersenay Tadese	6.36	6.34
25 km	01:11:18	Dennis Kimetto	6.14	6.22
30 km	01:27:38	Emmanuel Mutai	5.98	6.14
42.2 km	02:02:57	Dennis Kimetto	5.99	6.30

The limits of human power

From the biochemical data we have derived the limits of human power at various endurance times, see the table and figure below:

0	24.64
1	12.91
5	8.02
10	7.22
20	6.90
40	6.57
60	6.41
120	6.09
240	5.82



skating) and we have consistently found an FTP of around 6.35 Watt/kg to represent the upper limit of human performance. The only time that we got higher values were for the performances of EPO-doped cyclists.

Conclusions and outlook

We have derived a new and unified theory on running, based on the laws of physics and physiology.

Our running model can be used to calculate the speed of a runner as a function of his running power (P in Watts/kg), running economy (ECOR in kJ/kg/km) and the environmental conditions (wind, temperature, hills, air-pressure, altitude, footing). The model can also be used to analyze the limit of human performances and we found remarkable similar values of the FTP across various sports.

Meanwhile, the first running powermeters have come on the market. We have tested the Stryd footpod, both in the lab and in the field and found that the results match our model calculations perfectly.

Obviously, these powermeters provide runners now with the means to optimize their training and racing. For the first time, runners now have—on a daily basis—the numbers to try to improve their running power P and running economy ECOR and to use their running power optimally, so constantly throughout the race.

We realize that this will not be easy because for us (and for most people) running has been habituated over many years. We

www.thesecretofrunning.com.

Thank you to the co-author Ron van Megen

ABOUT HANS VAN DIJK

Hans van Dijk is professor-emeritus at Delft University of Technology and a lifelong runner. He has developed new concepts and models to analyze, predict and optimize the performance in sports. He is the author of numerous books and papers on running, cycling, speed skating and other endurance sports. www.thesecretofrunning.com | www.thesecretofcycling.com