cycling science

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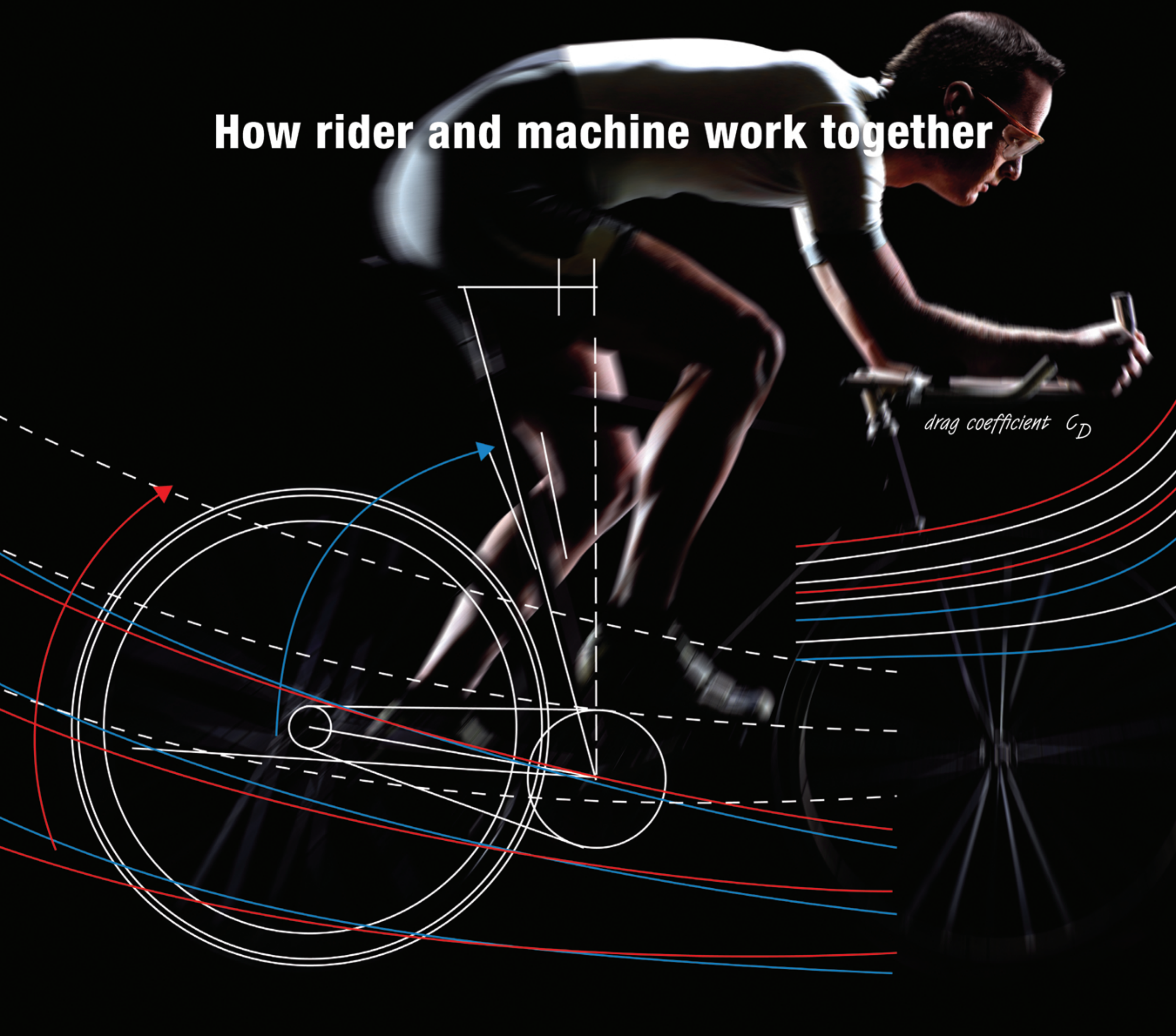
How rider and machine work together



How can I calculate the stresses of riding?

What kind of load can my bike take?

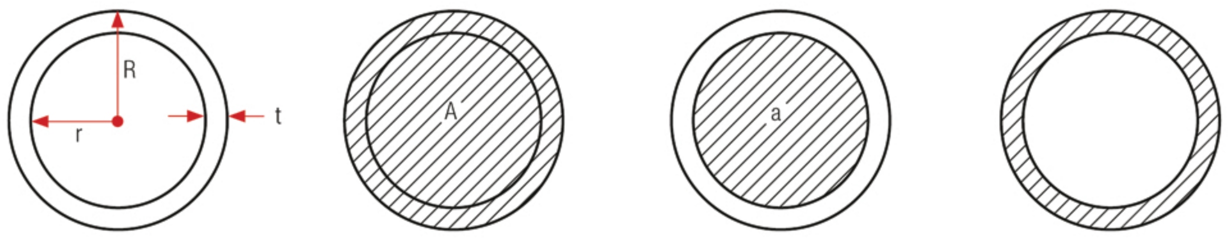
Compared to the structures used in other kinds of transport, bicycles give the impression of being frail, with a lot of fresh air triangulated by slender tubes. This is often deliberate; one goal targeted by some racing bike designers is to make their machines look insubstantial. If a frame appears light, it can offer psychological appeal to riders anxious to shave seconds off their best time. Whether or not a faster ride is the result, a spare, sleek cycle does beg the question—how does it support a full-grown human adult, six times heavier than it is and pumping the pedals with legs like pistons?

The first factor to understand about bike frame strength is stress, which is a measure of how an applied load (force) is distributed over a section of material. When a material—this could be a frame tube, a spoke, a chain link—is subjected to an external force, it adjusts itself until this force is balanced out. A liquid or gas can flow until this happens, but, in fact, solids can respond in a similar way. The soft part of a saddle or a suspension spring changes shape until internal forces balance out the external ones. Components we think of as "rigid"—such as frame tubes—do much the same thing, but the changes they undergo before internal and external forces balance out are so microscopic that they are unnoticeable by us.

The stress each part undergoes is the average force per unit area of the component. To complicate matters, components such as frame tubes often do not have a consistent thickness or shape throughout—they are engineered to optimize a combination of specific characteristics such as weight, stiffness, and impact-resistance. Stresses also fluctuate rapidly in response to hard braking, bumps, and sharp turns, so a margin of safety also needs to be built in.

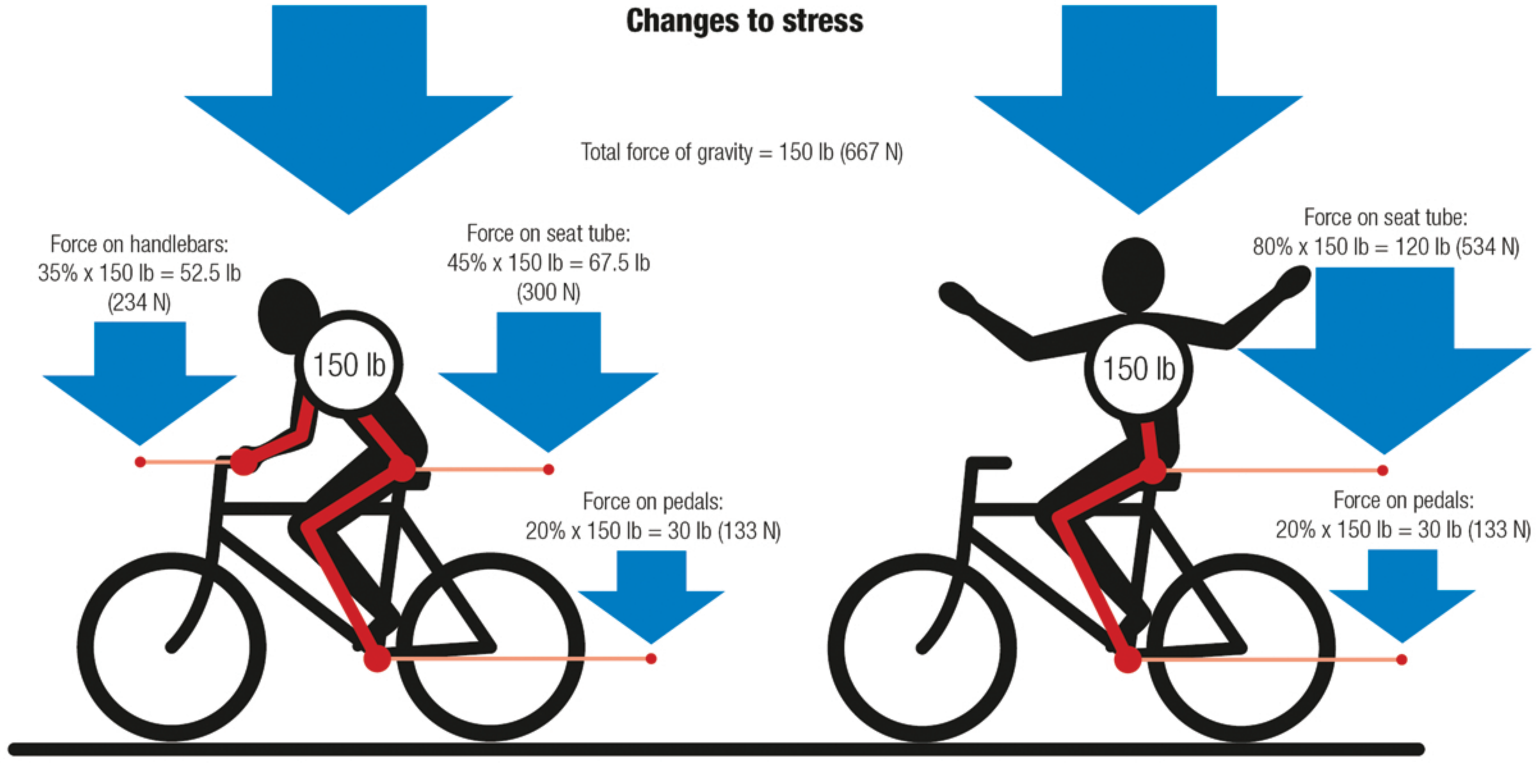
▼ ***Area code*** *Stress is the external force divided by the area to which it is being applied. The material of a flat pedal experiences stress in proportion to the area of the shoe in contact with it. Likewise, the stress on a saddle depends on the breadth of the rider's backside. The stress on the hollow tubes from which a bicycle frame are made is related to the cross-sectional area of their walls. Imagine a cross section of your frame tube. The ring of material that bears the stress lies between the outer radius (R) and the inner radius (r). Its thickness is* $t = R - r$. *Its area is equal to the outer area* ($A = \pi \times R \times R = \pi R^2$) *minus the inner area* ($a = \pi \times r \times r = \pi r^2$). *The constant π (pi) is about 3.1416. So, for example, the cross-sectional area of a tube with an outer diameter of 1 in (R = ½ in) and thickness t = ⅛ in is about 0.344 in² (about 0.000222 m²).*

Calculating cross-sectional area



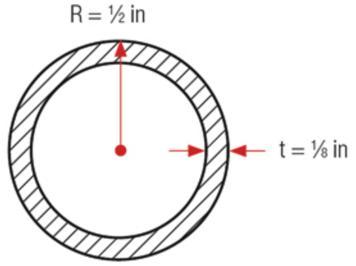
$r = R - t$ | $A = \pi R^2$ | $a = \pi r^2$ | Cross-sectional area = A – a

Changes to stress



Stress on seat tube $= \dfrac{67.5 \text{ lb}}{0.344 \text{ in}^2} = 196$ psi (1.35 MPa)

Stress on seat tube $= \dfrac{120 \text{ lb}}{0.344 \text{ in}^2} = 349$ psi (2.41 MPa)



Cross-sectional area = 0.344 in²

▲ ***Stress raiser*** *The stress levels that the parts of a bicycle experience are always changing because the rider doesn't sit still for long. A cyclist changes position frequently to improve comfort, balance, steering, and pedaling efficiency. Each movement changes the distribution of loads on the three points of contact with the bicycle—the saddle, the pedals, and the handlebars. Every time the load changes, the stress on a component also changes. This diagram shows how the stress on a hypothetical seat tube can increase when a 150 lb (68 kg) rider takes their hands off the handlebars. Sudden impacts such as potholes can multiply stresses on key components such as rims, spokes, and pedals many times over.*

Need to know

This formula gives the so-called "normal stress":

$$\sigma = \frac{F}{A}$$

where:

σ = stress (psi or Pa)

F = external force (lb or N)

A = area (in² or m²)

Stress is typically expressed in pounds per square inch (psi) or, in SI units, newtons per square meter (N/m²), also known as pascals (Pa). A 1 pound (1 lb) force applied over a 1 in² area results in 1 psi of stress (in SI units, a force of 1 N applied to an area of 1 m² produces a stress of 1 N/m², or 1 Pa; the unit megapascals, MPa, representing a million pascals, is frequently used). 1 psi is equal to about 6,900 Pa, or 0.0069 MPa. Stress has the same units as pressure.

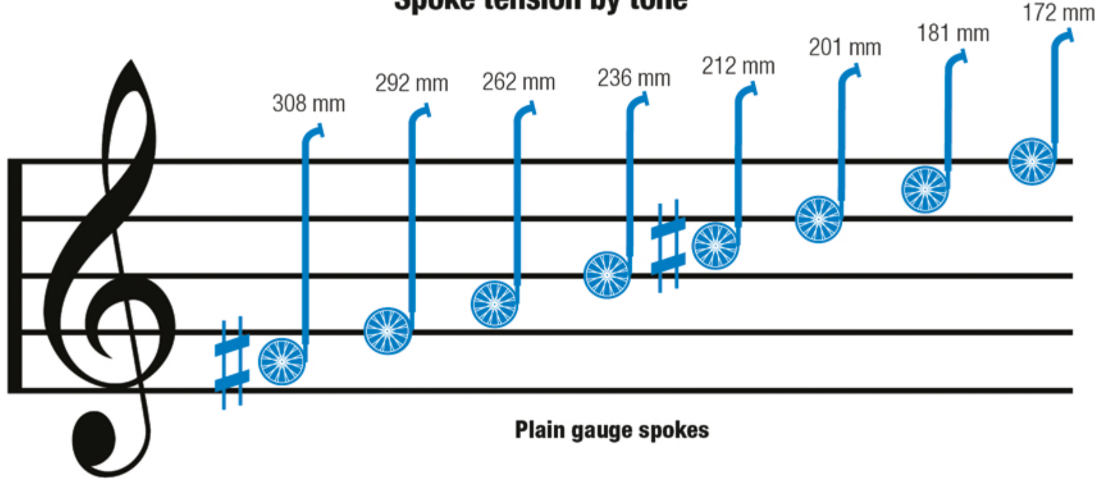
How do tensioned spokes make the wheel work? → Can I make my spokes work in harmony?

A bike wheel is built by connecting the rim to the hub with tensioned wire spokes. They pull the hub and the rim toward each other, and each is under a predetermined tension so that they pull equally and keep the wheel in a true circle. This means the rim is kept a constant distance from the hub and can support the total load of rider and frame on any part of its circumference.

The loads the whole wheel can carry are impressive for a structure which can weigh as little as 18 oz (500 g). A wheel with wire spokes tensioned to 225 lb (1000 N) can support about 900 lb (400 kg), far greater than the weight of any cyclist and frame. The rim of a standard bicycle wheel experiences a compression force of about half a ton from its 36 tensioned spokes. If the spokes are kept at the right tension, a wheel will fail catastrophically only if it hits a massive bump at high speed while carrying a heavy load. For front wheels, the spokes on each side of the hub leave the hub flange at identical angles on their route to the rim. It's different on the rear wheel of a bike equipped with derailleur gears, because the cassette of sprockets must be accommodated; the flange on the gear side of the wheel is closer to the midpoint of the hub and the spokes must follow a path to the rim that is steeper than on the other side of the wheel. This means they have to be under greater tension to keep the rim in equilibrium.

Although developed initially by trial and error, virtual models of bike wheels have been put through finite element analysis (FEA) since the development of computers. These help pinpoint the strains and stresses on spokes as the wheel rolls. Despite the results of FEA, a vigorous debate continues about whether the hub hangs from the top spokes or is supported by those below. On one hand, FEA shows that while the stress is reduced in the five lowest spokes when the wheel is on the ground, this is balanced by a slight stress increase in all of the remaining 31 spokes, taking up the slack in varying amounts. Although this might imply that the hub is held in suspension by the spokes, the counterargument is that the lowest spokes provide 95 percent of the lift experienced by the hub. The debate continues.

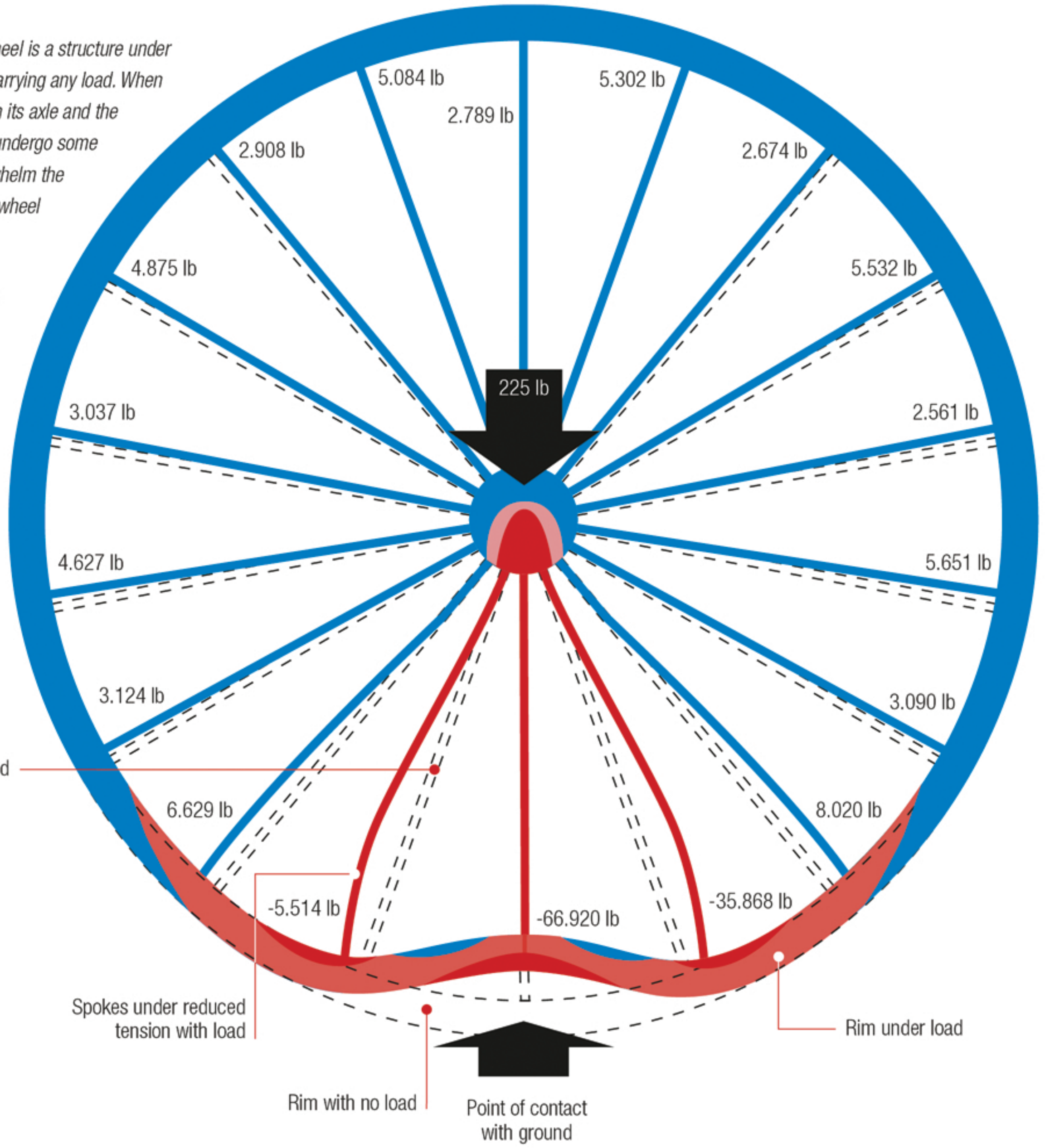
Spoke tension by tone



◀ ***Ringing spokes*** *Wheel builders check that spokes are under the same tension by plucking them so that they ring like a guitar string. Those with the same pitch are equally tensioned. With a set of pitch pipes or a tuning fork, it is possible to check by ear if a wheel has spokes tensioned to the recommended optimum. The notes shown here are the optimum for a selection of plain gauge spokes.*[16]

Spoke tension

▶ ***In suspense*** *A wire-spoked bicycle wheel is a structure under tension throughout its life, even when not carrying any load. When a load of 225 lb (1000 N) is applied through its axle and the wheel is on the ground, the lowest spokes undergo some compression, although not enough to overwhelm the original tension that was introduced during wheel building. Nevertheless, the rim deforms, increasing the tension in spokes on both sides of the contact area. When the wheels are rotating, the tension in the spokes is constantly increasing and decreasing. (The distortions are exaggerated here for clarity. The values are an average of the tension in two spokes of a 36-spoke wheel superimposed on a reproduction of a finite element analysis [FEA] of an 18-spoke wheel.)*[17]



Need to know

The tension in spokes can be measured with a tensiometer, or assessed by plucking them so that they ring like a guitar string—when they all play the same note, they are in equal tension. The expression for the fundamental vibration of a tensioned spoke is:

$$f = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

where:
- **f** = fundamental frequency (cycles per second)
- **L** = length of the spoke (ft)
- **T** = tension of the spoke (lb)
- **μ** = mass per unit of length (slug/ft)

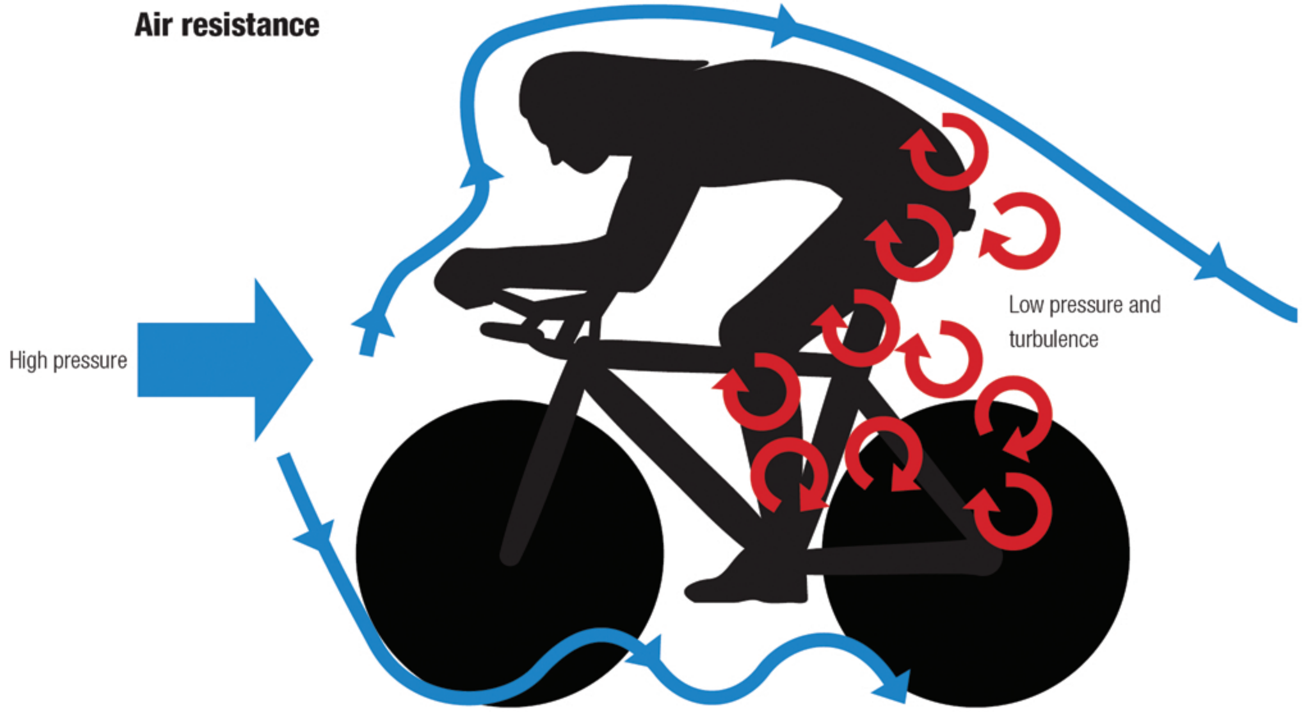
Why bother with aerodynamics? ↷ Why is the wind always against me?

Air is the cyclist's strongest opponent. It takes more energy to overcome this invisible foe than all of the other resisting forces—even on a flat road and at a modest speed, on a day when there is no hint of a wind. It is air that prevents cyclists from riding at highway speeds. Elite riders at their peak may look as if they're flying, but they are struggling continually against the atmosphere. Humans on bikes are simply the wrong shape when it comes to aerodynamics.

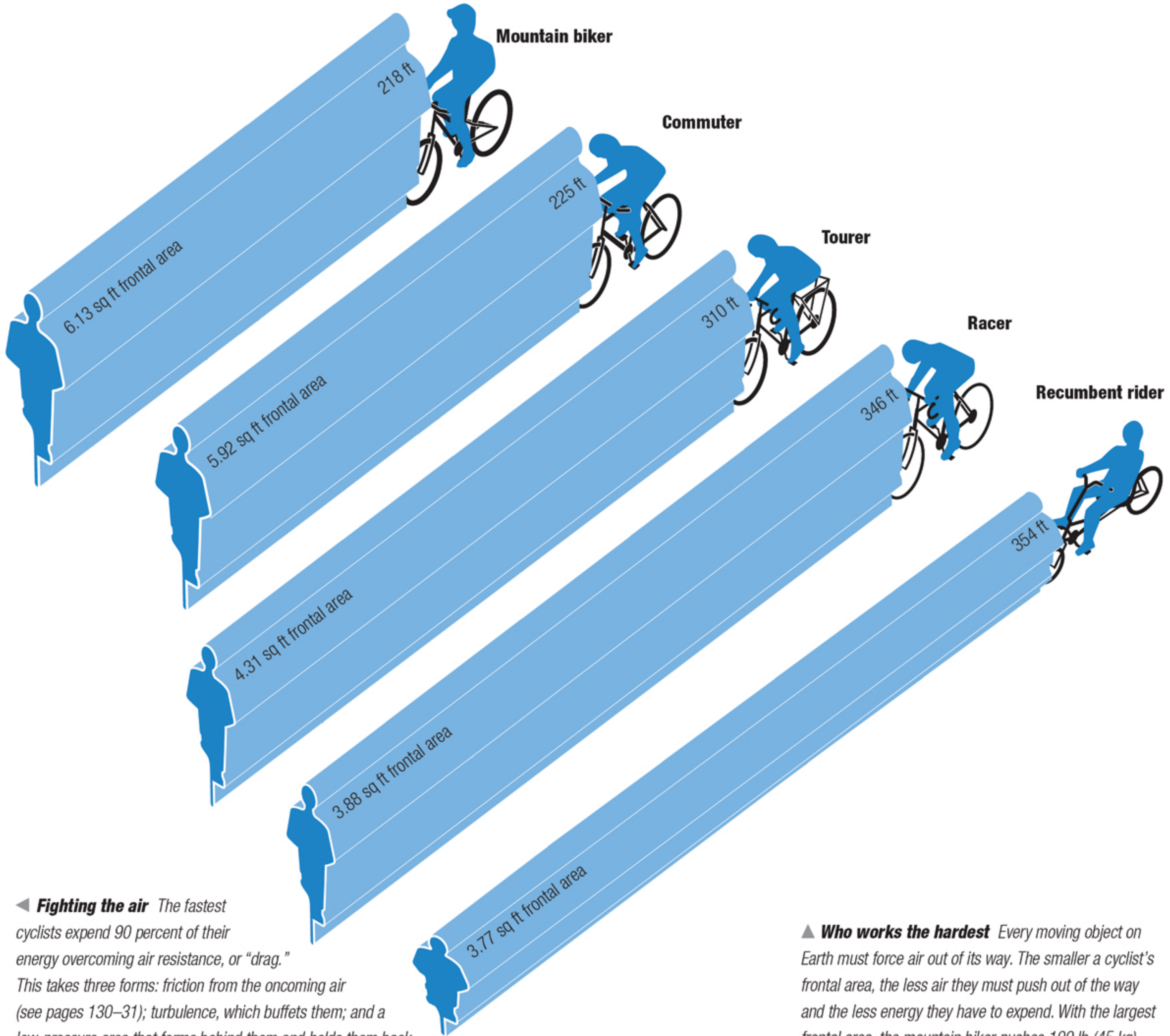
The problem is that air isn't weightless, although it's just thin gas. At sea level and a temperature of 68°F (20°C), a cubic foot of dry air weighs about 1¼ oz (35 g). It may not be solid and is less viscous (sticky) than water, but every rider has to work to push it out of his or her way. The science of aerodynamics examines how air moves around objects (rider, bike) and can help produce better bike designs that make bikes more slippery and reduce the work a rider has to do. Aerodynamics has had a profound impact on cycle sport in the last three decades. Riders now know which rims, wheels, frames, helmets, and riding positions will slice through the air to the finish line most easily. Aerodynamics has affected the results in classic races, world records, and championship titles and has resulted in cycling's governing body, the Union Cycliste Internationale (UCI), changing its rules several times.

Aerodynamics is a complex subject because it involves dynamic bodies, changing shape as the rider pedals, moving through a gas (air) whose own speed, direction, temperature, and density are not necessarily constant. Like all decisions in cycling, compromises have to be made in the pursuit of the optimum efficiency. This chapter explains why, how, and when those choices are made.

Air resistance



Pushing air out of the way



◀ ***Fighting the air*** *The fastest cyclists expend 90 percent of their energy overcoming air resistance, or "drag." This takes three forms: friction from the oncoming air (see pages 130–31); turbulence, which buffets them; and a low-pressure area that forms behind them and holds them back. The analysis of overall drag is made more difficult by the movement of the wheels, pedals, legs, and feet, which disturb the air and create additional complex flows. Resistance can be reduced by changes to the design of the bike (including an aerodynamic frame and wheels) and the rider's position (aero handlebars and a crouched pose), and by using a more streamlined helmet and clothing. All can contribute to a faster ride without requiring additional energy from the cyclist.*

▲ ***Who works the hardest*** *Every moving object on Earth must force air out of its way. The smaller a cyclist's frontal area, the less air they must push out of the way and the less energy they have to expend. With the largest frontal area, the mountain biker pushes 100 lb (45 kg) of air aside over a distance of 218 ft (66 m), while the sleekest recumbent rider can travel 63 percent farther before they have shifted the same amount of air. It may not seem such a large difference, but over a ride of an hour, the mountain biker will have to shift hundreds more pounds of air and will be more tired, sooner.*[1]

What are fast and slow twitch?

IIb or not IIb?

Human muscles contain two different kinds of skeletal muscle fibers—slow twitch and fast twitch. Their names say it all. Slow muscle fibers are best suited to extended periods of activity with low levels of force, such as long-distance riding. Fast twitch fibers are better suited to short periods of vigorous activity such as kicking for the line in a sprint.

Slow (red) and fast (white) fibers behave differently because they have different ways of sourcing and using energy. Slow twitch fibers can quickly access supplies of ATP, the molecule that releases energy, and this makes them able to work for longer without getting tired. They're what keep cyclists going for hours when commuting, leisure riding, or touring. Fast twitch fibers, on the other hand, get most of their ATP from a less efficient process that quickly causes pain and fatigue. That's what limits a cyclist's ability to maintain hill climb attacks and ferocious sprints. The maximum contraction velocity of a single slow twitch fiber is approximately one-tenth that of a fast twitch fiber.[13] Fast twitch fibers are more likely to be injured through strain.[14] Most muscles contain both slow and fast twitch fibers and although the ratio is thought to be genetically determined, it can be changed through training.[15] In fact, there are two kinds of fast twitch fiber—IIa, which operates both aerobically and anaerobically, and IIb, which is active for only a short time, works anaerobically, and tires sooner. Riders who want to increase their count of type IIb fast twitch fibers to help them sprint can start weight training. The process of muscle change is counterintuitive, because weight training can convert type IIb fibers to the more versatile type IIa when sprinters really want a lot of IIb. The trick, however, is to stop training a little while before competition, because then the body seems to reverse the conversions and overshoot, giving the muscle perhaps twice the level of IIb fibers as before training.[16]

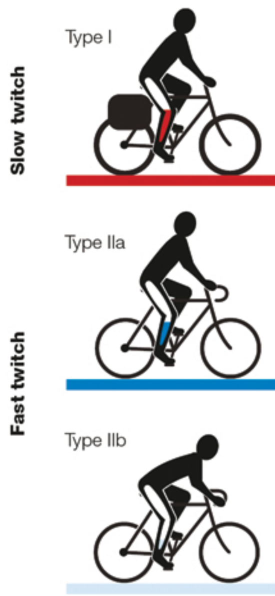
▼ ***Switch twitch*** *Training can convert one kind of muscle fiber into another, particularly the two types of fast twitch fiber, IIa and IIb. The capacity to change from fast to slow fibers is not so clear.*[17]

Slow type I
Fast type IIa
Fast type IIb

Percentage of muscle fiber types

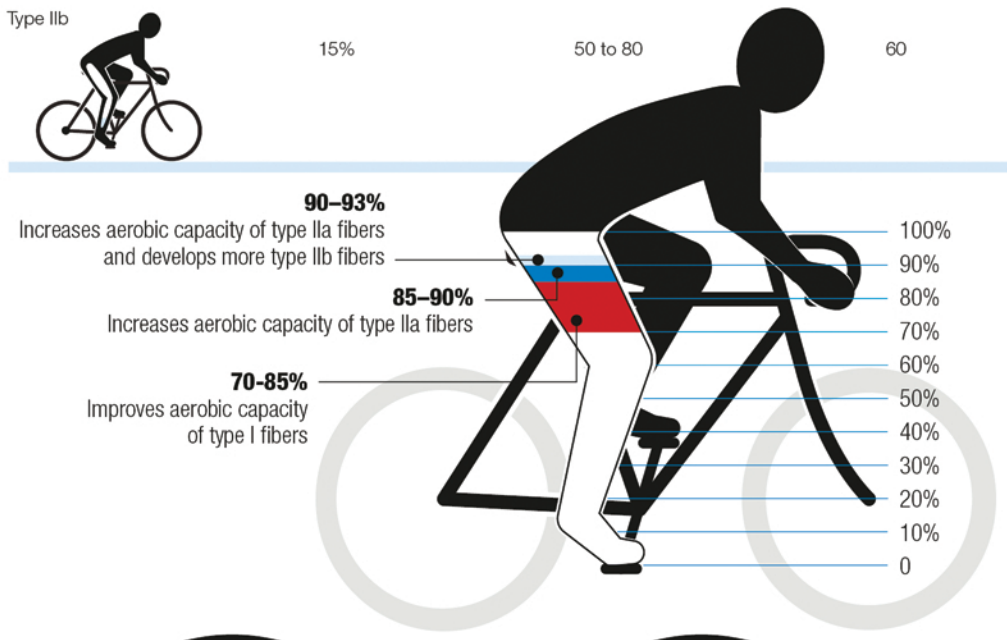
World-class sprinter | **Average couch potato** | **Average active person** | **Dedicated cyclist** | **Pro-tour domestique** | **Extreme endurance cyclist**

Speed versus distance



	Fiber percentage	Speed of contraction per second (milliseconds)	Minimum contractions per second	Activity
Type I	50%	100 to 200	16	Prolonged with low intensity
Type IIa	35%	50 to 80	60	Prolonged with high intensity
Type IIb	15%	50 to 80	60	Short with high intensity

◀ ***Which twitch?*** *We need both kinds of muscle fiber, but each has its own characteristics which can enhance or limit a cyclist's performance.*[18]



◀ ***Changing type*** *Riders who want to maximize the aerobic capacity of their type I fibers for endurance cycling train at 70 to 85 percent of their maximal steady-state heart rate. Harder training at 85 to 90 percent can improve the aerobic capacity of type IIa fibers and, at 90 to 93 percent, not only do the type IIa fibers increase their aerobic capacity but the development of more type IIb fibers is also promoted.*[19]

cycling science

What are the forces acting on a bicycle?
How much power can a cyclist produce?
Why are men's and women's bikes different?

What is the ideal frame shape?
How much energy does a frame absorb?
How does gearing help efficiency?

Does suspension make a significant difference to efficiency?
Why do road bikes have thin tires
while mountain bikes have fat tires?

How efficient is a bike chain?
Is wheel weight important?
How do tensioned spokes make the wheel work?

How does the air flow around a cyclist?
What is the biggest source of drag?
How does an aerodynamic helmet work?

How do bike gears work?
Which muscles does cycling use?
Will cycling save the planet?

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