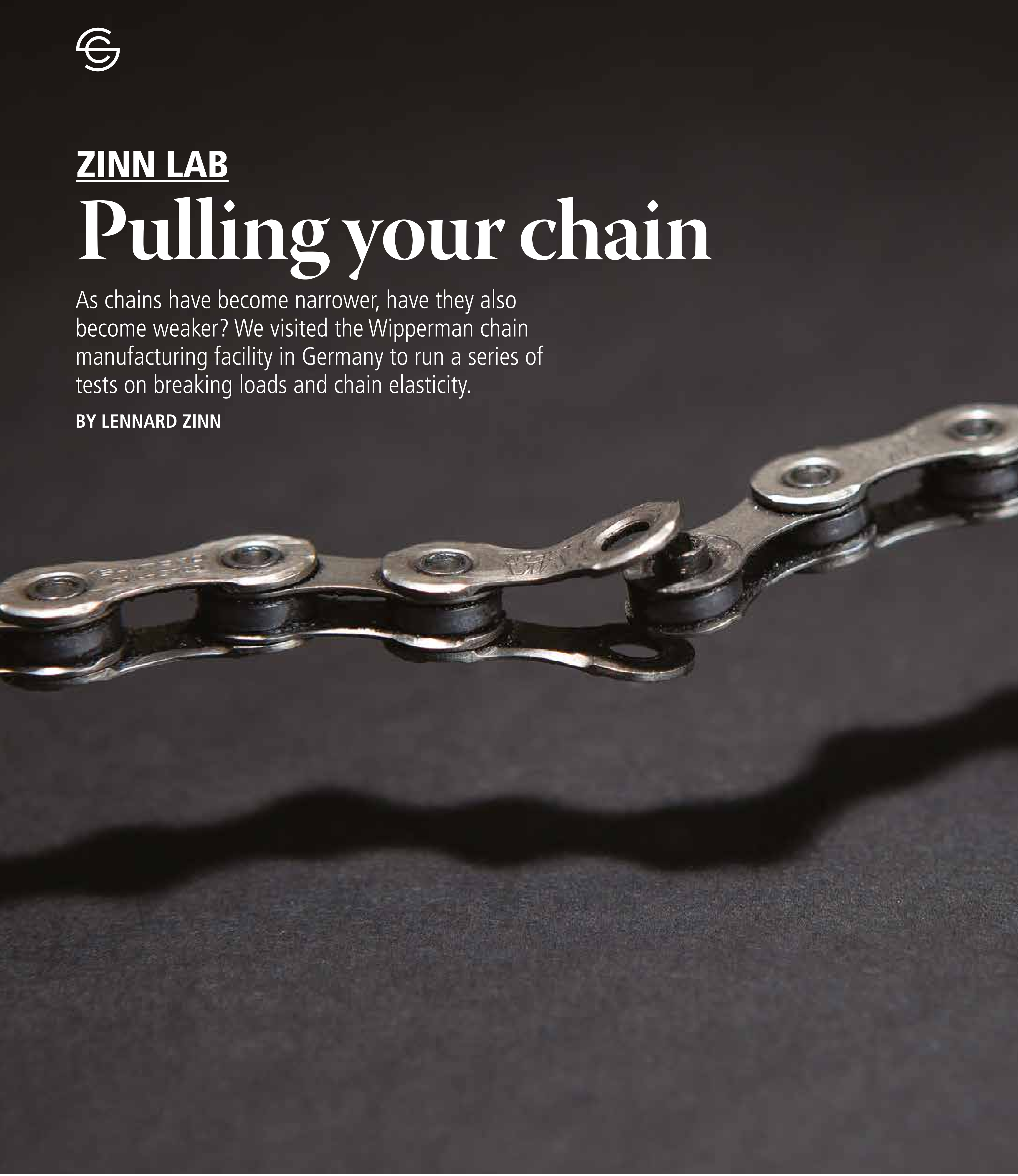
ZINN LAB

Pulling your chain

As chains have become narrower, have they also become weaker? We visited the Wipperman chain manufacturing facility in Germany to run a series of tests on breaking loads and chain elasticity.

BY LENNARD ZINN



BRAD KAMINSKI

Breaking a chain can ruin your day. Your crotch clonks onto the top tube, and your foot hits the ground. My only broken chains have come on the mountain bike, and only during front shifting under load, which can pry a chain plate off of its pin. How likely are you to break a chain from the sheer force of a pedal stroke? I traveled to Germany to find out.

When riding a road bike with a derailleur, broken chains from simple pedaling load are actually quite rare. In the 1970s and 1980s, broken chains usually were caused by faulty maintenance, since you simply pushed a rivet in and out. Chain plates on derailleur chains used to be like those on track chains—they were flat with two straight holes. The pins protruded quite far.

The advent of 9- and 10-speed chains brought the need for special connecting pins due to the minimal protrusion of the pins from the plates; 5- and 6-speed chains were about 8 millimeters wide, and 7- and 8-speed chains were around 7.3 millimeters wide. Today, 11-speed chains are 5.6 millimeters wide (5.25 millimeters for 12 speeds). The pins of 11- and 12-speed chains are very nearly or completely flush with the face of the chain plate; this is accomplished by chamfering the edges of the pin holes and mushrooming out the heads of the pins into these recesses in the faces of the plates.

Has the strength of chains been sacrificed as they have become narrower to accommodate more gears? This question is not new. On stage 4 of the 2001 Giro d'Italia, the chain of featherweight Mexican climber Julio Perez (Panaria), who had attacked on the climb to the Montevergine di Mercogliano, snapped with only four kilometers to go. At the time, pundits wondered whether the failure was due to improper maintenance, or due to ever-thinning chains. That debate arose again in 2008 when David Millar snapped his chain in the final meters of the Giro d'Italia's stage 5.

Still, powerful sprinters like Marcel Kittel, Andre Greipel, and Peter Sagan regularly churn 1,500 Watts through their 5.6-millimeter wide, 11-speed chains without failure. As it turn out, the European ISO standard of 8,000 Newtons of minimum breaking force for a chain offers a good margin of security.

The chains I tested in Germany all performed far beyond that barrier without breaking. Great success, right? Well, during the testing process, I noticed a separate phenomenon. The chains stretched some before breaking. So I decided to investigate further.

About the testing facility

I toured the Wippermann chain factory years ago and ogled at its huge chain-production and heat-treating capacity. I also was enthralled by its chain testing equipment, including the durability-testing machine that upholds the company's claim to producing the longest lasting chains. I traveled back to Wipperman this June to test 11-speed chains, and to perform tensile-strength tests on other chains.

The 125-year-old privately-held chain manufacturer is in its fifth generation of the Wippermann family. In addition to making Connex chains for all types of bicycles, including e-bikes and track bikes, and chains for other vehicles, Wipperman produces industrial roller chains and fat, multi-plate "leaf" chains that lift the forks on fork lifts and shipping containers onto tall cargo ships.

Wippermann manufactures in Germany, where labor costs are high, some of the world's most stringent environmental regulations and restrictive building codes apply, and a high tax structure supports a social welfare and health care system that takes care of everybody. The factory is located in a lush, green valley in Hagen, in the Ruhrgebiet of west central Germany. It uses a lot of water and detergent to clean off all of the oil required in the process of stamping and rolling and shaping all of its steel chain parts, yet when that water leaves the factory, it is certified as drinking-water quality.

In-house, Wippermann continually tests its chains as well as those of competitors with a wide variety of testing infrastructure. An enormous 100-ton tensile-strength-testing machine tests foot-long chains for failure; enormous chunks of metal fly when the links break. Another long-running machine continually tests a chain's durability. Staff also examine the chains under microscopes. The tests are important—a broken bicycle chain can lead to a dangerous crash, and a broken industrial chain can cause unfathomable destruction. Before each chain is packaged, a machine tugs it with a load of 2.5 metric tons, and cameras inspect every link for defects. Wippermann guarantees each chain will last 15,000 hours, a staggering figure relative to what we bike riders expect to get out of bicycle chains.

BREAKING-LOAD TEST RESULTS

The force, in Newtons, at which a given model of chain broke (averaged over five samples), from high to low

Connex 11sX	**10,700.36**
Connex 11sB	**10,105.29**
KMC X11 93	**9,945.73**
Connex 11 s0	**9,886.30**
SRAM PC1130	**9,858.96**
Campagnolo Chorus	**9,846.76**
KMC X11SL	**9,663.58**
Shimano CN HG9	**9,640.50**
SRAM PC1110	**9,618.04**
KMC X11SL Gold	**9,561.53**
SRAM PC XX1	**9,388.51**
Shimano CN HG 7	**9,331.11**
SRAM PC1170	**9,232.42**
Campagnolo Record	**9,226.04**

Breaking-load test

For this test we used 14 different chains, which were cut into five, 13-link pieces.

With a pin through the chain's end hole holding it in place, the ends were mounted into the upper and lower heads of a Shimadzu tensile-strength-testing machine (above).

The two heads of the machine slowly moved apart, producing a graph of pulling force versus extension in millimeters.

When the chain broke, the machine automatically stopped.

The results above show that all samples of the 14 chains went well over the 8,000-Newton ISO breaking-force resistance standard; in fact, all of them tested beyond 9,100 Newtons before breaking. Wippermann's internal standard is 9,500-11,000 Newtons of breaking force for its bicycle chains, and they achieved that; some of the others fell short of that.

For reference, compare the minimum measured breaking load to that applied by a 198-pound (90-kilogram) rider standing on the pedal attached to a 175-millimeter crank at the 3 o'clock position. The highest chain load is with the smallest chainring: a 22-tooth on a mountain bike triple crankset, which has a radius of 1.76 inches (45 millimeters). To calculate chain load, think of a teeter-totter with its fulcrum 175 millimeters from the end the load is applied, and 45 millimeters from the end that the force is transferred to.

The force on the pedal is 90kg x 9.8m/s^2 (rider mass times the acceleration of gravity). The load on the chain is then that force times 0.175 meters (the crank length) divided by 0.045 meters (the radius of the 22-tooth chainring), or 3,500 Newtons, which is well below the 9,100 Newtons that all of the chains withstood.

With the same crank and pedaling load with larger chainrings, the peak chain load is only 2,283 Newtons with a 34-tooth chainring and 1,472 Newtons with a 53-tooth chainring. Peak forces for road pros are in the 3,000-4,000 Newton range. Even a 300-pound rider standing on a 200-millimeter crank with the chain on a 22-tooth chainring is only applying 6,044 Newtons on the chain, still well below the ISO standard of 8,000 Newtons and more than 50 percent below the 9,100 Newtons that all of these chains exceeded.

These results show that, with a properly assembled chain, Kittel, Greipel, and Sagan need not worry about their chains breaking in a sprint. If they were using a 53-tooth chainring, they would have to stomp on the pedal with 5,564 Newtons of force to reach the 9,100 Newton load on the chain. This is equivalent to a 1,252-pound Kodiak bear standing with all of its weight on the pedal!

On chains without link cutouts, breakage occurred at the end of an outer link; the outer link either broke at the hole or pried off of the pin. On chains with cutouts, breakage occurred at the middle of a link, right across the cutout. Nonetheless, the chains with cutouts (KMC X11SL Silver and KMC X11SL Gold) all withstood at least 9,535 Newtons of load before breaking.

After our test I watched some Wippermann industrial multi-plate leaf chains being broken on a much bigger test machine. I watched one withstand 917,000 Newtons of pull before breaking—100 times as much as bicycle chains can take. You should have heard the noise it made when it broke.

Chain elasticity test

I noticed during the breaking-load test that the chains tended to elongate by at least

6 millimeters before breaking, with those with cutouts in the chain plates elongating considerably longer than those with solid plates. I set about quantifying the elasticity of these two types of 11-speed chains.

Using the same Shimadzu tensile-strength-testing machine, three lengths of chain were gradually pulled 100 times with 6,000 Newtons of force. This is a force approximately equal to what a world-class kilo rider applies on the first couple of strokes from the start. This is a much higher load than road riders are ever likely to apply to the chain. After each tug on the chain, it was allowed to relax with zero Newtons of force pulling on it before being pulled on again.

One chain had solid link plates, while the other two chains both had cutouts in the inner and outer link plates. Each chain section was 31 links long, with an inner link on either end to engage the Shimadzu machine's jaws. As bicycle chains have a ½-inch pitch, each link is 12.7 millimeters long, giving a calculated length of 393.7 millimeters, approximately equal to the chainring-to-cog length on a road bike with a short rear end.

After settling in following 10 or so pulls, the solid chain stretched up and down over an approximate range of 3.5 millimeters, while both chains with cutouts stretched up and down over an approximate range of 4.7 millimeters. Clearly, all of us are constantly stretching our chains on every pedal stroke, and if we have chains with cutouts, they are stretching a bit more.

If the chain behaves like a perfect spring with no energy lost as heat, then all of the energy is returned to the system. It's returned, however, in a way that provides no additional power. In other words, the chain stretches when the chain is fully loaded on the pedal downstroke and stores this as elastic potential energy. Then, when the pressure reduces with the feet at the top and bottom of the pedal stroke, the chain contracts back in length. The chain's contraction pulls the cog forward, but the equal and opposite reaction at its other end is to pull back on the chainring, slowing the passage of the feet over the top and bottom of the stroke. And by stretching on the downstroke, the chain allows the foot to drop down through the power stroke slightly faster.

If the chain were as stretchy as a rubber band, the bike would obviously get nearly nowhere; the foot would fall very quickly through the downstroke and transfer minimal power. Clearly, less chain stretch is more efficient than more chain stretch.

We can quantify the worst-case scenario, where all of the potential energy stored in the stretched chain is lost when it relaxes. Then, Hooke's Law says that $F = -kx$ and $PE = 1/2kx^2$, where k is the spring constant for the chain, x is the amount of stretch, F is the force to stretch it, and PE is the potential energy stored in the chain. Ignoring the negative (which indicates directionality), the spring constant for the no-cutout chain is:

$$\mathbf{k = F/x = 6000N\ /\ 3.5mm = 1{,}700{,}000\ N/m\ (no\ cutouts)}$$

Similarly, the spring constant for the chain with cutouts is:

$$\mathbf{k = F/x = 6000\ N\ /\ 4.7mm = 1{,}300{,}000\ N/m\ (with\ cutouts)}$$

Now that we have the spring constant for each chain (and assuming it is indeed a constant for a bicycle chain, which I'm not sure is the case), we can use it to estimate the chain stretch under different loads. We saw above that the peak chain load for a 198-pound rider simply standing on the pedal of a 175mm crank with a 34-tooth chainring is 2,283 Newtons. So, the displacement for the no-cutout chain at that load is:

$$\mathbf{x = F/k = 2283N\ /\ 1{,}700{,}000\ N/m = 0.0013m = 1.3mm\ (no\ cutouts)}$$

And the displacement for the chain with cutouts at the same load is:

$$\mathbf{x = F/k = 2283N\ /\ 1{,}300{,}000\ N/m = 0.0018m = 1.8mm\ (with\ cutouts)}$$

Then the potential energy stored in the no-cutout chain when it is stretched under that 198-pound load on the pedal is:

$$\mathbf{PE = 1/2kx^2 = (1{,}700{,}000\ N/m)(0.0013m)(0.0013m)\ /\ 2 = 1.4\ Joules\ (no\ cutouts)}$$

And the potential energy stored in the chain with cutouts when under that same load is:

$$\mathbf{PE = 1/2kx^2 = (1{,}300{,}000\ N/m)(0.0018m)(0.0018m)\ /\ 2 = 2.1\ Joules\ (with\ cutouts)}$$

If all of that energy is lost, then the power loss is equal to the energy lost in chain stretch on each downstroke divided by the time for each downstroke. There are two downstrokes per revolution of the pedals, and there are 60 seconds per minute, so if the rider is pedaling at 100RPM with that same peak load on the pedal each revolution, then the power lost in the no-cutout chain is:

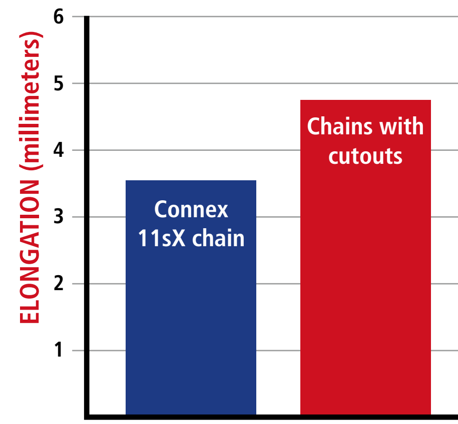
$$\mathbf{P = 2*(100/min)(1.4\ J)\ /60s/min) = 4.8\ Watts\ (no\ cutouts)}$$

And power loss for the chain with cutouts is:

$$\mathbf{P = 2*(100/min)(2.1\ J)/60s/min) = 7\ Watts\ (with\ cutouts)}$$

Chain elasticity results

Chains without cutouts were compared to chains with cutouts, in a test of elasticity



So, in this worst-case scenario, where none of the potential energy of the stretched chain is recovered as forward motion, the chain with cutouts consumes 2.2 more Watts of power than the chain without cutouts.

That extra little stretch of the cutout chain costs something each pedal stroke, while its 30-gram weight reduction (at most) gives something back when climbing or accelerating. But how do these compare? That 90-kilogram rider is putting out at least 500 Watts if he puts his full body weight on the pedals with each stroke, and plugging those numbers into bikecalculator.com, it would take him 3.12 minutes to ride a 9-kilogram bike up an 8-percent climb for a kilometer. If that rider's bike weight dropped by the 30-gram weight savings of a chain with cutouts while his power dropped by 2.2 Watts—the extra energy losses in the cutout chain versus one without cutouts—that same climb would now take 3.13 minutes, or 0.6 seconds longer. Not much. The difference would probably still be tiny if you changed the variables—the length of the climb, the weight of the rider, and so forth—to more realistic values.

Additionally, one might argue that when the chain stretches it is not perfectly engaging the last couple of teeth leaving the top of the chainring and the first couple of teeth entering the top of the cog, thus resulting in a slight increase in frictional drag. This would be hard to quantify.

In conclusion, all of the brand-name chains we tested offered a good margin of safety against breakage by sheer force. And there is no such thing as a free lunch; sometimes weight loss will cost you more in flex than it provides in the way of reduced power required to drag it up a hill.