What does the evidence show?

SWEAT SCIENCE

How Do Nike's Vaporfly 4% Shoes Actually Work?

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Unraveling how a carbon fiber plate and space-age foam combine to make a more efficient shoe turns out to be trickier than expected

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Alex Hutchinson
(/1745511/alex-
hutchinson)

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Unraveling how a carbon fiber plate and space-age foam combine to make a more efficient shoe turns out to be trickier than expected

A few weeks ago, Grand Valley State University researcher Kyle Barnes (https://twitter.com/coachkylebarnes) published a study (https://www.ncbi.nlm.nih.gov/pubmed/30374945) which concluded that Nike's controversial Vaporfly 4% shoe gives runners an efficiency edge of 4.2 percent compared to Adidas's state-of-the-art marathon racing shoes, the Adizero Adios 3. I checked in with my editor to see whether I should write about the new results, but she was lukewarm about it. After all, the 4-percent claim isn't news—it's right there in the name of the shoe, was confirmed by peer-reviewed external testing at the University of Colorado (which I already wrote about last year (https://www.outsideonline.com/2262486/researchers-confirm-nikes-4-marathon-shoe-claim)), and backed up by a *New York Times* analysis (https://www.nytimes.com/interactive/2018/07/18/upshot/nike-vaporfly-shoe-strava.html) of half a million marathon and half-marathon race times posted to Strava.

In other words, we already pretty much know that it's true. To be fair, there are a bunch of interesting new wrinkles and twists in the Grand Valley study. Crucially, unlike the Colorado study, it wasn't funded by or affiliated with Nike, Adidas, or any other shoe company. It also found that the Vaporfly was 2.6 percent more efficient than Nike Zoom Matumbo track spikes, and observed an average improvement of 1.90 percent in 3,000 and 5,000-meter track times—new territory for a shoe that's mostly been marketed to marathoners. But the basic claim that the Vaporfly allows you to burn significantly less energy to run at a given pace is now pretty widely accepted.

Instead, the debate has moved on to two trickier questions. First, how exactly do the shoes work? And second, should they be allowed? Those two questions are tightly intertwined, because of the perception that the curved carbon fiber plate embedded in the shoe's midsole acts as a spring. But there's been surprisingly little consensus, even among the shoe's designers, about how the Vaporfly's various components actually work. So that makes another new study, from the same Nike-funded University of Colorado team that tested the original 4-percent claim, an intriguing read.

The study, which appears in the journal *Sports Medicine* (https://link.springer.com/article/10.1007%2Fs40279-018-1024-z), used three-dimensional biomechanical stride analysis and force-plate measurements in an attempt to unravel what makes the Vaporfly so efficient. The shoe has two novel components. One is a super-thick cushioned midsole made of a new foam that Nike calls ZoomX. The foam is ultralight, allowing the heels to be 31 millimeters high at the heel, which is about 50 percent thicker than comparable shoes, without being heavier. It's also exceptionally compliant (you can squish it) and resilient (it springs back to its original shape, returning most of the energy you applied to squish it). In a sense, every shoe with a midsole has a "spring" in it; this one just happens to be particularly springy.

The second novel component is a curved carbon fiber plate embedded within the midsole. This is where a lot of the controversy comes in. One school of thought is that the plate is simply a spring, bending as your foot lands and then catapulting you forward as it springs back into position. Back in 2016 when rumors about the shoe first began to circulate, a Nike patent (https://patents.google.com/patent/WO2016179265A1/en) for a "footwear sole structure including a spring plate" began to make the rounds (https://twitter.com/stevemagness/status/811213903116075009?ref_src=twsrc%5Etfw%7Ctwcamp%5Etweetembed%7Ctwterm%5E811213903116075009&ref_url=https%3A%2F%2Frunningmagazine.ca%2Fsec files-shoe-spring-patent%2F), fueling rumors that Nike had a spring-loaded shoe. This patent turned out (https://www.runnersworld.com/gear/a20849486/nikes-magic-shoes-what-if-they-really-work/) to be for a different (and so far unreleased) shoe design, but the idea stuck. Most people now assume the Vaporfly is powered by its carbon fiber spring.

But that's the not the theory I heard when the shoe was finally released and I started calling around to ask shoe biomechanists what they thought. It turns out that researchers (and other shoe companies) have been playing around with carbon fiber plates since at least the 1990s. The most direct precursor to the Vaporfly's plate is Adidas's ProPlate, which appeared in the early 2000s and was developed by University of Calgary researcher Darren Stefanyshyn. (One of Stefanyshyn's former Ph.D. students, Geng Luo, led the design of the Vaporfly and appears on the patent (https://patents.justia.com/patent/20170095034).)

Back in 2006, Stefanyshyn published (https://www.ncbi.nlm.nih.gov/pubmed/16540846) his explanation for the how the carbon fiber plate works. When you run, you spend some energy bending your main toe joints. Unlike your ankles and foot arch, which bend and then spring back into position, you don't get any energy return from your toes—it's wasted. Stefanyshyn showed that a stiff carbon fiber plate keeps your toes straighter, saving that energy and improving running economy by about 1 percent.

But there's a problem with this approach, Luo explained to me when I was reporting on the Breaking2 project last year. A stiff plate keeps your toes straight, but it forces your ankle to do more work, counteracting some of the overall efficiency benefits. The solution Luo and his team came up with was a plate with a more exaggerated bend in the forefoot, allowing the toes to roll forward without adding work for the ankle. This is the explanation Nike provided in their patent filing: a stiff plate to save wasted energy from toe-bending was already known, but their innovation was curving the plate to reduce forces at the ankle.

That's not the only possible explanation, though. Another group, at the German Sport University in Cologne, led by an ex-decathlete named Steffen Willwacher, started studying carbon fiber insoles long before the Vaporfly was released. Their explanation of how this type of insert works, published in 2014 (https://www.ncbi.nlm.nih.gov/pubmed/24882222), is that the stiff plate basically changes the length of the lever between your ankle and where your foot pushes into the ground. That, in turn, changes the "gear ratio" between the internal lever arm of your muscles and tendons and the external lever arm of your ankle and foot, giving you a mechanical advantage in much the same way that the gears of a bike do. That's not an explanation that's easy to wrap your head around (at least it wasn't for me), but it's one I heard from a bunch of different biomechanists.

The new experiment, from Wouter Hoogkamer, Shalaya Kipp, and Rodger Kram of the University of Colorado's Locomotion Lab, involved 10 runners who ran five-minute trials in three different shoes: the Vaporfly, Nike's Zoom Streak 6, and Adidas's Adizero Adios Boost 2, the latter two being state-of-the-art traditional marathon racing flats. Each runner had 44 reflective markers taped to their body and shoes for three-dimensional analysis of their running motion; they ran on a special treadmill that measured the forces as their feet hit the ground. This enabled them to calculate the angles, forces, and work done for each joint.

The properties of the shoe were also measured separately by a "rotational axis material testing machine" that bent the shoe lengthwise while simulating a running motion to estimate its bending stiffness. By combining the stiffness of the shoe with the forces hitting the treadmill and the relative movement of the reflective markers, the researchers could estimate exactly how much the shoe (and the stiff plate inside) compressed and bent—and, consequently, how much energy was stored and returned with each stride by different components of the shoe.

The results were somewhat unexpected. The bending of the carbon fiber plate stored and returned energy at a rate of 0.007 watts per kilogram with each stride. In comparison, the squashing and unsquashing of the thick ZoomX foam returned 0.318 W/kg—more than twice as much as either of the other shoes, and about 45 times more than the plate. So the shoe definitely functions like a spring, but in this analysis it's the foam midsole rather than the stiff plate that makes almost all the difference in the shoe's contribution to energy savings.

As for the other theories, running in the Vaporfly did indeed seem to save some energy that would otherwise be lost to toe-bending. But the magnitude of the savings was small enough that Hoogkamer and his colleagues don't think it makes a major contribution to the 4 percent boost in running economy.

Instead, there seem to be more significant energy savings at the ankle joint—but not quite in the way they expected based on the "gear ratio" theory. The theory predicts that the Vaporfly will produce a larger rotational force at the ankle; the data, in contrast, showed a smaller rotational force. There are some long passages in the paper that explore why the result was the opposite of what they expected yet still produced an energy savings. I'll summarize those passages loosely as follows: They're not sure what's going on.

So that's where we stand for now. There are several other studies in the pipeline from Barnes and others that will give us further insights on how these shoes work. For now, we can say two things. One is that the shoes change how efficiently you're able to lever force into the ground, in some way that's not yet clear. The other is that the shoes act as a spring—but only in the way that virtually all shoes act as a spring, by having a soft midsole. Kram's back-of-the-envelope guess that the foam midsole gives a 3 percent boost, and the carbon plate adds another 1 percent. But the math may not be that simple: there may be some synergy between the foam and plate that makes the whole greater than the sum of its parts.

The ideal test would be to try a Vaporfly with no carbon fiber plate and see what happens. Would it be like running on giant floppy marshmallows, or would it be just as good as the real thing? "We have wanted to test this for quite some time, but haven't been able to get such prototypes," Hoogkamer told me in an email. "I personally think that a big, thick ZoomX stack without a plate would be a lot less stable, specifically taking 90-degree turns at Kipchoge speed (https://www.outsideonline.com/2344696/eliud-kipchoge-berlin-marathon-world-record). I don't think it will be too soft, but hard to say without testing it."

As for other big question of whether they should be banned, the Colorado study makes an important point. It's not enough to say "Shoes shouldn't have springs in them, so we should ban springs," because you have to define what you mean by springs. If it's really the ZoomX foam that makes the biggest difference, then banning carbon plates will miss the mark. If it's the angle and shape of the carbon plate that provides the magic, then setting an upper limit on midsole thickness or resilience will also miss the mark. To figure out what you need to ban, you have to have a clear idea of what it is that's objectionable—beyond the mere fact that the shoes seem to work.

My new book, Endure: Mind, Body, and the Curiously Elastic Limits of Human Performance (https://amzn.to/2GMlFWo)*, with a foreword by Malcolm Gladwell, is now available. For more, join me on Twitter* (https://twitter.com/sweatscience) *and Facebook* (https://www.facebook.com/sweatscience1)*, and sign up for the Sweat Science email newsletter* (http://alexhutchinson.us10.list-manage1.com/subscribe?u=16b257be614b5f18187d3b50a&id=4111e620a3).

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How to Fuel for a Solo, Unassisted Antarctic Crossing

Colin O'Brady thinks it's possible—but just barely—to haul enough calories to traverse the continent. Here's how.

Alex Hutchinson (/1745511/alex-hutchinson)

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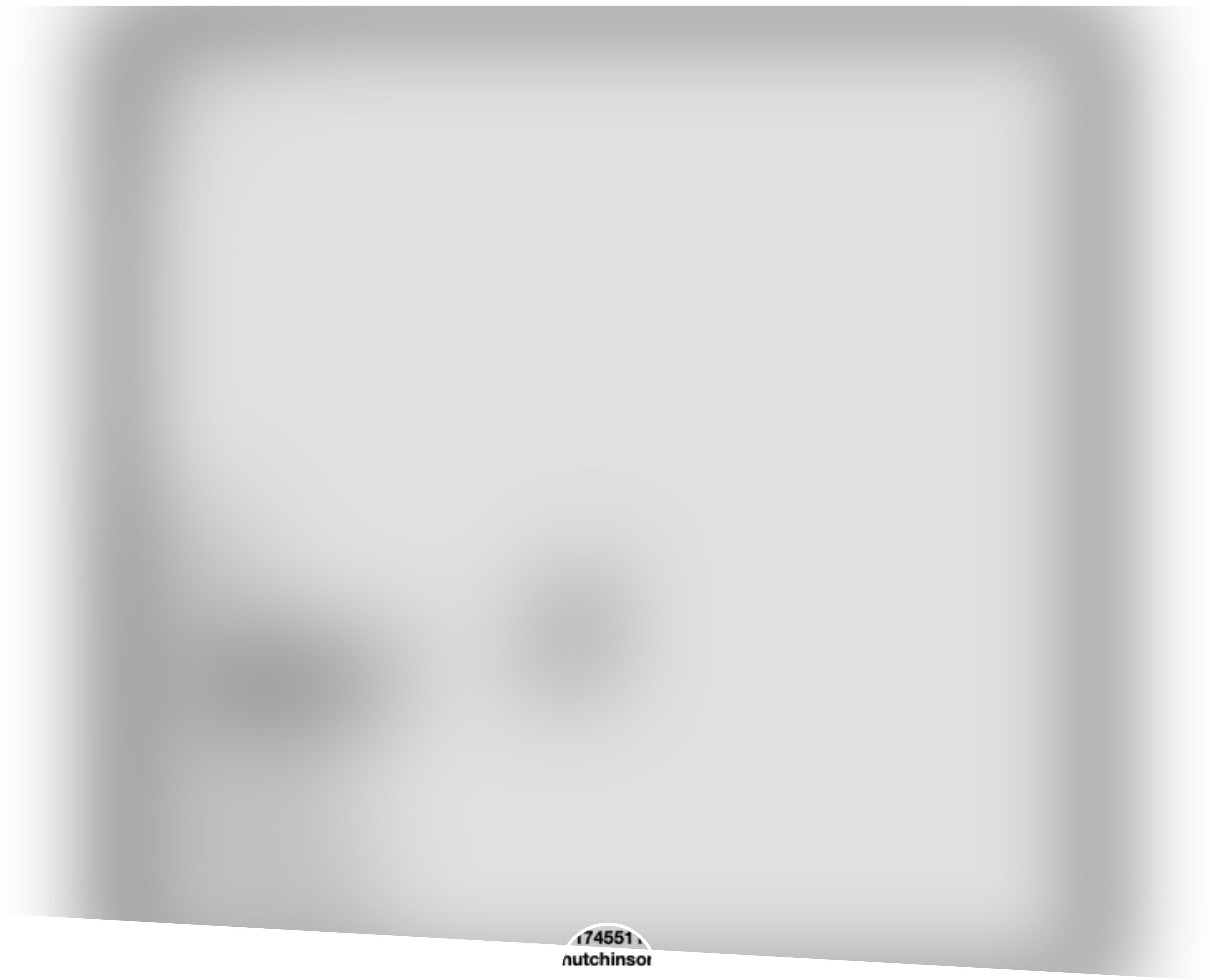

Alex Hutchinson (/1745511/alex-

Nov 14, 2018

Colin O'Brady thinks it's possible—but just barely—to haul enough calories to traverse the continent. Here's how.

Two days before Colin O'Brady flew to Antarctica to attempt the first solo, unassisted crossing of the earth's most inhospitable continent, I asked him about the definition of a perfectly planned expedition. He was frantically dashing around his hometown of Portland, Oregon, checking off the final logistical details of a project he'd been obsessing over for most of the year, so the topic resonated.

"I've asked a lot of people this question," he said. "Is it a successful expedition if you get to your very last day and you're eating your last day of food? Or is it a successful expedition if you get to the end of your project and you've got, like, five to seven days of food left on your sled? And it's funny, because people come really strongly down on either side."

August 2018: O'Brady's tent on expedition, crossing the 400 mile Greenland icecap in preparation and training for the Antarctica crossing. (Colin O'Brady)

This isn't an abstract debate about the aesthetics of a beautifully planned trip. In the Antarctic, the nuances of exactly how much you pack dictate success or failure, and sometimes life or death. On November 3, a Twin Otter dropped O'Brady off on the Ronne Ice Shelf. Over the next two months, he'll be trying to make it 921 miles across Antarctica, via the South Pole, to the Ross Ice Shelf, roughly approximating the route that British adventurer Henry Worsley was trying to complete when he died (https://www.outsideonline.com/2051151/word-explorer-henry-worlsey-onward), 900 miles into his trek, in 2016. (You can track O'Brady's trip here (https://www.colinobrady.com/theimpossiblefirst); one of Worsley's former expedition mates, Louis Rudd, is currently attempting a similar feat (https://shackletonlondon.com/blogs/blog/expedition).)

Others have crossed the continent in teams, or with the aid of animals or sails or machines. But a solo, unassisted trip is a different matter. "It's straight-up impossible to take enough calories with you to get across the continent of Antarctica," a *Wired* article (https://www.wired.com/2016/02/people-cross-antarctica-all-the-time-its-still-crazy-hard/) asserted after Worsley's death. O'Brady's training, fitness, and psychological resilience will undoubtedly be pushed to their limits in the coming weeks. But in some ways, his biggest challenge is much more fundamental: it's thermodynamics.

I first met O'Brady at a hiking event (https://29029everesting.com/past-events/2018-vermont-everesting-ascent/) in Vermont last month. As it happened, I'd just returned from visiting a cousin of mine who has spent the past ten years designing a single-stage rocket with the goal of setting a new altitude record. As my cousin showed me his trajectory simulations, I'd asked a dumb question about why he didn't just add more fuel. That would add weight and also require a bigger rocket, he patiently explained, so the rocket would actually reach a *lower* peak altitude. Same thing if you took away fuel to lighten the load. The reason he'd spent a decade designing the rocket was to find that perfect optimum where either adding or subtracting fuel made things worse.

As I chatted with O'Brady while we ambled up Mount Stratton, I realized that he was wrestling with exactly the same challenge. The more food you bring with you, the heavier your sled becomes, the more calories you burn pulling it, and the slower you move, meaning that you have to bring even more food to cover the extra days. Conversely, a lightly laden sled allows you to move more quickly and efficiently, but you'll run out of food sooner. Somewhere in the middle is a theoretical optimum—a peak range, like the rocket's peak altitude—where either adding or subtracting a single energy bar from your sled will reduce the distance you're able to cover. The question that has remained unanswered so far is whether that peak range is greater than the width of Antarctica.

October 2018: Receiving the specially designed bars on ice, packed and shipped from the Nutrition Innovation Center. (Jenna Besaw)

While there is plenty of accumulated lore about how to maximize your range on polar man-hauling expeditions, O'Brady is taking a dramatically different approach compared to those who have gone before him. He's been working closely with a "whole food supplement" company called Standard Process (https://www.standardprocess.com/), regularly visiting their Nutrition Innovation Center (https://www.standardprocess.com/About-Us/Innovation#.W-XiXzFReUk) in North Carolina for batteries of tests to figure out exactly what combination of foods will fuel him most efficiently. The result: a bespoke 1,150-calorie creation, tailored to his unique metabolic and physiological needs, known as the Colin Bar, that will supply more than half of his 8,000 daily calories. It's the size and shape of a gold brick, and it comes in one flavor (a subtle hint of chocolate, which the scientists have kept as neutral as possible so that he hopefully won't hate chocolate bars for the rest of his life). O'Brady started his trip with 280 of them lashed to his sled: four a day for 70 days.

Back in 2012, a century after Robert F. Scott and four companions reached the South Pole and then died on the way back, a pair of scientists asked a poignant question in the journal *Physiological Reviews* (https://www.physiology.org/doi/full/10.1152/physrev.00031.2011): with modern knowledge and equipment, could Scott and his team have survived? In exhaustive detail they analyzed the challenges facing would-be Antarctic explorers, and what we know now that Scott didn't. It's not just the cold, which frequently hovers around -40 degrees Fahrenheit even in the summer, and forces the body to consume precious calories just to stay warm. There's also the vicious wind, and the desert dryness that forces travelers to drink around five liters of water per day. And the Antarctic plateau has an average elevation of about 7,500 feet above sea level, which in terms of oxygen content feels like more than 9,000 feet due the effects of extreme cold and wind on atmospheric pressure.

There are innumerable details that could have been improved on Scott's expedition, but the fundamental problem was that they were woefully short on calories. Scott's rations added up to between 4,200 and 4,600 calories per day. No one really knew how many calories a polar expedition like this burns until Mike Stroud—one of the authors of the 2012 paper—and Ranulph Fiennes made a two-person unsupported 1,600-mile crossing of Antarctica in 1992 and 1993. Careful measurements of energy consumption using isotope-labeled water showed that they were burning an astounding 7,000 calories a day for 96 days. During one ten-day period while they ascended the plateau, they averaged 11,000 calories a day. Even though they were eating 5,000 calories a day, they lost 48 and 54 pounds respectively during the trip.

The solution—take more calories—seems obvious, but the problem once again is the weight of additional food. Stroud and Fiennes tried to maximize the amount they could carry by relying on calorically dense fat. Stroud's description of their diet (https://books.google.ca/books?id=L24t58739VIC&pg=PT578&lpg=PT578&dq=mike+stroud+ranulph+fiennes+%22butter%22&source=bl&ots=5QlH4_a4lb&sig=Eo8R0kGwIb "porridge fortified with butter in the morning, soup with added butter during two brief stops in the day, a flapjack with butter after stopping in the tent, and a freeze-dried meal with butter in the evening." It still wasn't enough.

Beyond quantity, the type of calories also matters. After all, Henry Worsley still had plenty of food when he finally called for help, leaving some uncertainty about what killed him. In a general sense, he'd pushed himself beyond the limits of his endurance. In a specific sense, the cause of death was massive organ failure secondary to a bacterial infection in his abdominal lining. What sequence of steps connects those two facts? "We think it was a poor immune system response that affected his gut function," says John Troup, vice president of clinical science for Standard Process, the company behind the Colin Bars, "so that's part of what we're trying to stabilize with Colin."

One of first things the scientists at Standard Process did was run a series of tests on O'Brady's blood samples to determine his response to various foods, looking not for overt allergies but for subtle variations in the inflammatory response they triggered in him. They came up with a list of about 20 foods to avoid, with the most significant being ginger, tuna, beef, oranges, peanuts, and flax seeds. "If he's going to be really stressed out there, it's going to be because he's hyper-inflamed and couldn't recover from it," says Troup. "More simply stated, it's a reflection of immune response." Since butter and other dairy foods are also among O'Brady's triggers, the Colin Bar is laden with coconut oil and filled out with nuts, seeds, dried fruit, and other whole-food ingredients that his system responds well to.

July 2018: Testing at the Standard Process Nutrition Innovation Center. (Mike McCastle)

His overall diet will be high in both fat and carbohydrates, with 40 percent of calories from fat, 15 percent from protein, and 45 percent from carbohydrate. In comparison, Scott's rations during the hardest part of his trip were 24 percent fat, 29 percent protein, and 47 percent carbohydrate. Stroud and Fiennes opted for 57 percent fat, 8 percent protein, and 35 percent carbohydrate. You can quibble about the relative pros and cons of these various macronutrient breakdowns, but the biggest different is simply the the sheer quantity. While Scott maxed out at 4,600 daily calories and Stroud and Fiennes took 5,000, O'Brady is taking 8,000 calories per day, including oatmeal in the morning and Alpineaire freeze-dried meals in the evening.

That means starting out with a sled weighing 375 pounds (Worsley's, in contrast, weighed 330 pounds). Unlike Worsley, he's not bringing cigars or a bottle of Royal Brackla Scotch whiskey to toast his progress. In fact, he admitted, "I'm not bringing a second pair of underwear." That ruthlessly pragmatic approach contrasts with the swashbuckling tradition of polar exploration pioneered by the British —but this particular challenge, O'Brady believes, simply doesn't allow any margin for whimsy. The starting load of food was about 245 pounds, with another 55 pounds of fuel, which is needed to melt the necessary five liters of water daily, and 75 pounds of equipment and clothing.

Four days into his trek, O'Brady acknowledged in an Instagram post (https://www.instagram.com/p/Bp22_45F76o/) that the sled's weight was pushing him to his limits: "Today was the first day I haven't cried into my goggles," he wrote. Still, as he'd explained to me before he left, this was a calculated risk: "I'm banking on the fact that, by actually feeding myself enough calories, the slightly additional weight that I'm putting in my sled is made up for by the fact that my body doesn't break down as quickly."

As for the great debate about how you should finish a perfectly planned expedition, O'Brady falls in the cautious camp. He hopes to reach the Ross Ice Shelf after about 65 days, with five days of food still tucked in his sled. But he knows that Antarctic conditions, and how he responds to them, will be almost impossible to predict until he's in the thick of them. His mega-calorie approach does give him some wiggle room. He fared reasonably well on 5,500 calories a day during a recent expedition in Greenland. "If it starts to look like it's going to take 80 days to do this expedition," he says, "I do think that I have the ability to switch some of those calories and stretch the expedition to 75 or 78 days." After all, most Antarctic travelers before him made do with less. And some of them even survived.

My new book, Endure: Mind, Body, and the Curiously Elastic Limits of Human Performance (http://amzn.to/2GMlFWo)*, with a foreword by Malcolm Gladwell, is now available. For more, join me on Twitter* (https://twitter.com/sweatscience) *and Facebook* (https://www.facebook.com/sweatscience1)*, and sign up for the Sweat Science email newsletter* (http://alexhutchinson.us10.list-manage1.com/subscribe?u=16b257be614b5f18187d3b50a&id=4111e620a3).

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