For years, shoes have been made around the same stock designs without an appreciation of the forces during walking and running that are related to lower extremity injury—including debilitating knee osteoarthritis. And while for the last 30–40 years especially, the typical cushioned athletic shoe has been heavily marketed as protecting the joints in the leg and the associated muscles and tendons, only recently have peer-reviewed studies demonstrated that such cushioning in fact increases the peak forces on the joints, most notably and concerning, the knee. Specifically, biomechanical studies show that most shoes, as currently made, increase forces about the knee that are associated with the development and progression of knee osteoarthritis. Fortunately, the same biomechanical studies that have demonstrated flaws in shoe design have shown us something else as well: how to build a better, healthier shoe. Now the challenge is for shoe companies to innovate new materials and manufacturing processes to actually make them.

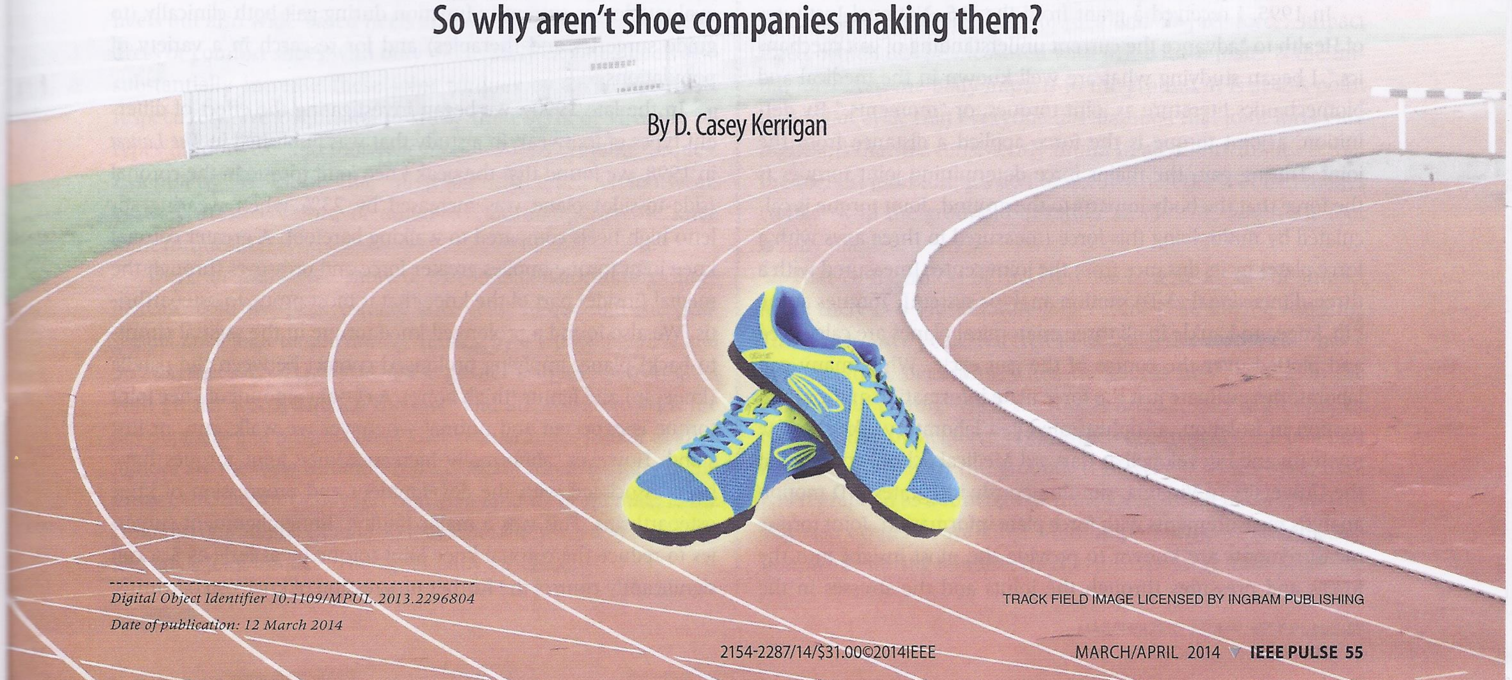
For many years, shoes (including athletic, comfort, and casual styles—not just dressy women's high-heels) have been designed with an elevated heel, some type of arch support, and a curvature or foot conforming "cradle" running side to side in the sole. These design features have been marketed as being healthy. In addition, for the last 30–40 years, athletic shoes have been built around the assumption that the initial force that occurs when the foot first strikes the ground, called the "impact" force, causes the greatest forces through the joints and the associated muscles and tendons. While Nike was one of the first companies to introduce and market shoes that cushion impact force, essentially all of the major athletic shoe companies have followed suit and have been making shoes with this same design.

Christopher McDougall's book *Born to Run*, published in 2009, raised public awareness to the idea that the typical cushioned running shoe is increasing, rather than decreasing, injuries in runners. Providing biomechanical support that the traditional running shoe design is flawed, my research team and I published a study in 2009 showing that peak joint forces, particularly at the knee, are substantially increased when wearing traditional running shoes compared to running barefoot [1]. A month later, Lieberman et al. reported that impact force, measured with a force plate, is absent in runners who habitually run barefoot [2]. Our study, along with Lieberman's, is often cited in supporting that running barefoot is best. While our study indeed supports that running barefoot compared to running in traditional running shoes is better, it simultaneously provides biomechanical

The Race to Build a Better Shoe

Biomechanists now know how to build a healthier shoe. So why aren't shoe companies making them?

By D. Casey Kerrigan



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From Scientist to Entrepreneur

Shoe Manufacturers Wouldn't Respond to Casey Kerrigan's Research, So She Built Her Own Shoe Factory from Scratch

I never imagined building a factory or owning a shoe company. But in many ways, running a factory is like running a laboratory. You strive to have the very best equipment, and you design and even build your own. You are always working on new ideas and are constantly experimenting. And you love to teach, inspire, and be taught and inspired by all the people with whom you work. Of course, I realize that my factory is unique. But that is exactly why and how I built it.

For years, I had been studying and learning the detrimental effects of traditional footwear on the body. That led to clear ideas for how shoes ought to be constructed. I tried to get the large shoe companies interested in my work. But what I requested—a complete overhaul in how shoes are currently being made—seemed to be too much to ask. The large shoe makers are already heavily invested in the manufacturing and marketing of traditional shoe design. Most of their marketing is based on cushioning and arch support—both of which features we showed to have detrimental effects on the body. The highly responsive, noncushioning sole that I envisioned could not be made with their current manufacturing processes. Developing such a sole would require research and development that was beyond the scope of the industry. Ultimately, I realized that I would need my own factory with equipment and machinery not common to shoe manufacturing.

The challenge was that I had no clue how to build a factory. Starting with the university engineering library, I checked out every book pertaining to injection molding, filament winding, and all the types of materials that I considered using. I got comfortable with *Machinery's Handbook* and taught myself computer-aided design. I relied on the Internet for information on just about everything from hydraulic presses to Teflon paste (which seems to work better than tape). A friend taught me how to weld. I got very acquainted with our local hardware store, which I sometimes visited three times a day. I built oven presses and converted an old pizza oven into a postcure oven. We bought a computer-numerical-code (CNC) waterjet saw and a CNC-controlled three-axis milling machine and machined all sorts of metal parts. And after a long search, I found just the right injection molding machine and modified it further so it would inject the way I needed it to. A group of engineering students and I built all sorts of jigs and supports and designed and built a cooling system that runs off of a refurbished industrial water chiller.

We make all but the fabric sock uppers, which we import from overseas. Unlike most factories, we also make all of our own tooling and molds. That means that we can continuously experiment and refine different and more efficient ways to inject material in our factory in Charlottesville, Virginia. Also, we can continuously evaluate the effects of different material compositions, temperature, pressure settings, etc. The excitement I get when I try on the first pair of a new launch of shoes is similar to the excitement I used to get in evaluating research results. You are the first to see them. And you can't wait to share them with everyone else in the world.

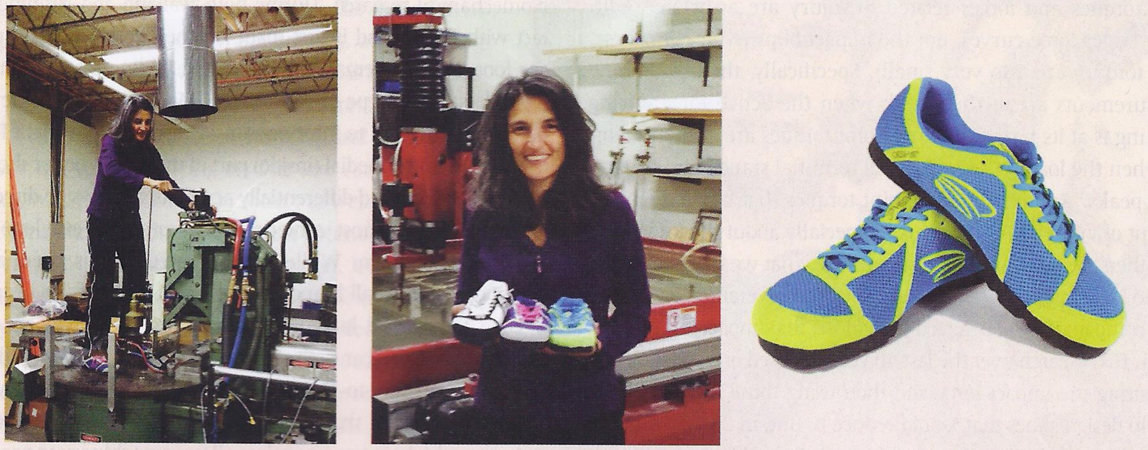
We've been making and selling shoes now for three years. With not much advertising other than word of mouth, we've been growing exponentially. There are now thousands of pairs of OESH shoes being worn around the world (Figure S1). Most importantly, we are profitable. That means I no longer rely on grant funding to do something that I greatly enjoy. True, as we grow, I'm finding myself delegating more and more, but again, that is the nature of success in research as well. I remain committed to teaching and will be sure to continue hiring students and apprentices, which I know will continue to make it fun.

Looking back, I don't think I'd do anything differently. I believe I had to try working with the big companies first. All that time, even in the trips to China, I was learning the existing shoe industry. In fact, the visits to China helped fully convince me that innovating a new manufacturing process is best done here in the United States. If you are a scientist who has an idea for a better product requiring a

data to inform the construction of a new, altogether different shoe that is truly healthy.

In 1995, I received a grant from the U.S. National Institutes of Health to "advance the current understanding of gait mechanics." I began studying what are well known in the medical and biomechanics literature as joint torques, or "moments." By definition, a joint torque is the force applied a distance from the joint. During gait, the major force determining joint torques is the force that the body imparts to the ground. Joint torque is calculated by multiplying this force (measured in three axes with a force plate) by its distance from the joint center [measured with a three-dimensional (3-D) motion analysis system]. Torques at the hip, knee, and ankle in all three anatomical planes are calculated and plotted over the course of the gait cycle. While many gait laboratories evaluate just the force plate information and/or joint motion in isolation, a sophisticated gait laboratory, like the one my team and I developed at Harvard Medical School and then at the University of Virginia, simultaneously integrates 3-D motion analysis measurements with force plate information. Joint torque measurements are known to provide the most insight into the forces and pressures through the joints and the stresses in the associated muscles, ligaments, and tendons. In fact, joint torque measurements have been used now for a number of years to evaluate lower extremity function during gait both clinically (to guide surgeries and therapies) and for research in a variety of populations.

In the late 1990s, we began investigating the effect of different types of footwear. In a study that was published in *The Lancet* in 1998, we found that the peak knee joint torque in the coronal (side-to-side) plane was increased by 23% when wearing stiletto high heels compared to walking barefoot. A greater coronal knee joint torque implies greater force and pressures through the medial (inside) part of the knee that is most prone to osteoarthritis. We also found a prolonged knee torque in the sagittal (front-to-back) plane, implying prolonged contact between the patella (kneecap) and femur (thigh bone). A certain amount of knee joint torque is expected and normal whenever we walk, run, or just stand. However, abnormally increased knee joint torques have been associated with the development and progression of knee osteoarthritis. This was a major finding. Bone alignment surgeries to reduce the coronal knee joint torque by as little as 5% can significantly control the further progression of knee osteoarthritis.



(a) (b) (c)

FIGURE S1 Designed for the whole body, OESH is the only shoe founded on ground-breaking, peer-reviewed medical and scientific research. With patented and proprietary technology, the OESH sole is uniquely designed to respond to the body's natural movement. (a) Dr. Kerrigan adjusting the clamp on an injection molding machine in her factory, (b) Dr. Kerrigan showing shoes manufactured in her factory, and (c) the 2014 OESH La Vida Fiji's. (Images courtesy of Casey Kerrigan.)

different manufacturing process, my advice is to figure a way to make it yourself. As far as preparation goes, I think all you really need is a strong willingness to learn. But very quickly, by trial and error, you will become the expert in many things. An expert in carbon fiber (who wrote one of the books I checked out of the library) asked if he could interview *me* for a chapter in his next edition. I was astonished with 1) how much I knew and 2) how little he was able to add to my knowledge base. And, once, I wrote an informative blog post on how to loosen stubborn nuts from bolts. This might seem trivial, but loosening stubborn connections is key to being able to refurbish manufacturing machinery. There is much used, but solid manufacturing machinery just sitting in warehouses in the United States (mostly Detroit) that is just waiting to be refurbished and brought into the 21st century—for the price of not much more than just shipping the machinery to your facility.

Although currently there are not a lot of women in manufacturing, I believe women have an advantage in some ways. I suspect that there are many women like me who have grown up not knowing which way to turn a wrench. However, I think the key, regardless of being a man or a woman, is the willingness to learn.

— D. Casey Kerrigan, CEO of OESH Shoes

And here we were showing that just a shoe, albeit with a 2-in stiletto heel, affects joint torque by 23%.

In 2001 and 2005 [3], we found that not only 2-in stiletto heels but also wide-based heels and so-called sensible women's dress or comfort shoes with only moderately elevated heels also substantially increase these joint torques by 26% and 19%, respectively. We continued to study the effects of virtually all types of footwear and footwear modifications on joint torques. Essentially, we found that all traditional types of footwear, be they dress, comfort, or athletic, abnormally increase knee joint torques.

Then, in 2009, we showed that traditional running shoes increase both the peak coronal knee joint torque and the peak sagittal knee joint torque during running by a whopping 38% and 36%, respectively [1]. Again, these greater torques are associated with greater forces through the knee and are associated with the development and progression of knee osteoarthritis. Insofar as knee injuries are the most common and significant running injury in the lower extremity, our study received a fair amount of attention in the running community. Of note, in that same study, we also found hip and ankle joint torques to be significantly increased.

While these studies have received much press coverage (e.g., *The New York Times*, ABC's *20/20*, BBC, NPR, etc.), what hasn't been well covered is our more obvious finding regarding the relationship between joint torques and impact force. Impact force, which can be measured with just a force plate, is the initial force that the body imparts to the ground. It is at this point in the gait cycle that everyone has assumed that joint forces are highest. What we consistently found in all of our studies is that the highest joint torques do not occur when the foot first makes contact with the ground, but rather much later, when the foot is fully planted.

That is, regardless of the presence or absence of the impact force, there is a substantially larger force peak during running. This larger force peak, referred to as the active force peak, has a long duration, beginning when the foot is first planted on the ground and ending when the foot is lifted from the ground. In contrast, the impact force peak, which occurs when the foot first makes contact with the ground, is of very brief duration and, when graphed as a function of time, looks much like a blip. This blip also occurs in walking. More importantly, for this discussion, while during running there is just one large force peak (the active force), in walking there are two major force peaks (called the loading response and terminal stance force peak).

Of critical significance, it is clear from our studies that the joint torques and forces related to injury are associated with these larger force curves, not the impact blips (when of course, joint torques are also very small). Specifically, the joint torque measurements are at their peak when the active force during running is at its peak. Similarly, joint torques are at their greatest when the loading response and terminal stance forces are at their peaks. And it's the high joint torques that correlate to the instant of vulnerability to injury, especially about the knee.

Others are also now coming to realize what we have observed. Benno Nigg, a biomechanist and advisor to several major athletic shoe companies, long believed (like most) that impact force causes injury. His research over the last 40 years focused on modeling and measuring the impact force and then using those measurements to help design shoes that would reduce it. But, in 2010, Nigg confesses in his book *Biomechanics of Sports Shoes* that the impact forces are much too small to be responsible for injuries. Thus, our studies have provided a new paradigm for how better shoes can be made.

First, shoes should not be designed around trying to reduce impact force. While a cushioned shoe may or may not be able to reduce peak impact force (at most the blip on a graph), we've shown that such footwear clearly has a negative effect on peak joint torques and the consequent period of vulnerability. If that weren't enough, it is likely that altering the impact force affects sensory input, which, in turn, affects neuromuscular control as well as balance. Moreover, there are also some very interesting data in astronauts suggesting that the impact force is important for maintaining bone density. For all these reasons, a better shoe would be one that does not attempt to interfere with impact force. Rather, a better shoe is one that is designed around the large forces that occur when the foot is fully planted, when forces and stresses through the lower extremity are at their greatest. At this point in the gait cycle when joint torques are at their maximum, the sole cannot merely absorb the force (which will only further increase joint torques) but rather it should respond, i.e., compress and release in tune with when these forces are at their maximum.

Second, a better shoe should be completely flat. We've shown that any amount of raised heel, whether it's cushioned or not, increases joint torques. Moreover, we've found that even a small amount of arch support significantly increases coronal knee joint torque. Many have suggested that an arch support weakens the foot over time and that would be another reason to not have a built-up area under the arch. Finally, the side-to-side cradle sole shape that is inherent to most current shoes similarly affects the coronal knee joint torques. Thus, a better shoe would be completely flat in all directions.

Building a better shoe with these design features requires not just new methods in shoe manufacturing but also significant investments in new tooling and equipment. (See "From Scientist to Entrepreneur.") Even just making the sole perfectly flat with no elevated heel, arch support, or side-to-side curvature requires not only new molds and tooling but also different types of machinery. For example, much of the side-to-side cradling in current shoes is necessary because of the current processes used to attach the upper part of the shoe to the sole.

Creating a shoe that responds when the major forces, including the joint torques, are at their maximum, yet does not interfere with impact force, relies again on findings obtained from comprehensive biomechanical research. During both walking and running, contact with the ground is first made on the lateral (outside) part of the foot. This is a remarkably consistent finding across all subjects regardless of foot type or gait pattern. Meanwhile, the large forces and torques related to injury occur when the body weight force is centered over the medial (inside) part of the foot. A better shoe sole, then, would respond differentially across its side-to-side direction.

The soles of most athletic shoes comprise ethylene vinyl acetate (EVA) foam. While EVA, theoretically, is adequate for cushioning the small blip of impact force, it lacks the properties needed to respond later in stance, when the forces are much greater and significant. Creating a sole that responds differentially across its side-to-side direction requires a substantially more advanced material than what has ever been used in the shoe industry, which, in turn, requires all new machinery to process it.

The biomechanical understanding to make better shoes is here. The only remaining challenge for a shoe company is to appreciate this research and actually make them. That means developing new tooling and manufacturing processes. And abandoning billions of dollars in investments already made in traditional shoe manufacturing processes. This is difficult for a big shoe company to do. It is far easier for the large companies to introduce minimalist shoes that use all their same tooling and manufacturing processes. Unfortunately, the typical minimalist shoe, often marketed as having barefoot technology, is merely a watered down version of the traditional shoe, with the same detrimental effects.

Conversely, a new company—with its major investments in biomechanics, as well as in new tooling, machinery, and manufacturing processes—may very well just have the advantage.

The race is on.

D. Casey Kerrigan (dckerrigan@oeshshoes.com) is the founder of OESH Shoes. She was the first woman tenured professor and also chair of the Department of Physical Medicine and Rehabilitation at the University of Virginia, Charlottesville (UVa), and a professor of sports medicine and of mechanical and aerospace engineering. Before joining UVa, she was an associate professor at Harvard Medical School where she founded the Harvard Motion Analysis Laboratory at Spaulding Rehabilitation Hospital in Boston.

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