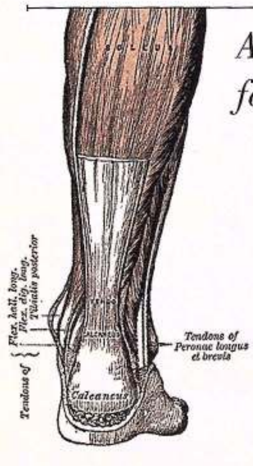
THE SPRINTER'S FOOT

An examination of an elite athlete has led to a rethinking of the way the fastest runners accelerate—and how all of us walk. By Stephen J. Piazza



Athletes move with amazing grace and speed. They perform perfectly coordinated movements in which contracting muscles pull on tendons, which in turn pull on bones to produce joint rotations.

In my research I try to understand how joint structure influences the capacity for movement in order to help those whose movements are impaired, and sometimes this is best accomplished by studying elite athletes who operate at the extremes of human performance. While science and engineering have certainly helped to improve performance in athletes, I have also heard it said that, "We have more to learn from athletes than they do from us."

STEPHEN J. PIAZZA

At Penn State we are used to going to see great athletes perform. Our football stadium seats 107,282, and home football games always sell out. So those of us in the Penn State Biomechanics Laboratory were excited one day in 2006 when we learned that a former Nittany Lion all-American wide receiver who had gone on to a long career in the National Football League would be coming to see *us*.

As an undergraduate at Penn State, this player completed a research project under the direction of one of my colleagues, Dr. Larry Kenney, who studies thermoregulation in athletes. It was Kenney who arranged for the receiver to spend an afternoon during the off-season undergoing various tests in our department, including assessments of body composition and reaction time.

At the time, I was working with Sabrina Lee, a graduate student in kinesiology, to measure the lever arms of tendons that cross the ankle joint. Sabrina and I had just completed a study in which we measured how likely certain ankle muscles are to contribute to deformities affecting the gait of children with cerebral palsy or older patients who have had strokes.

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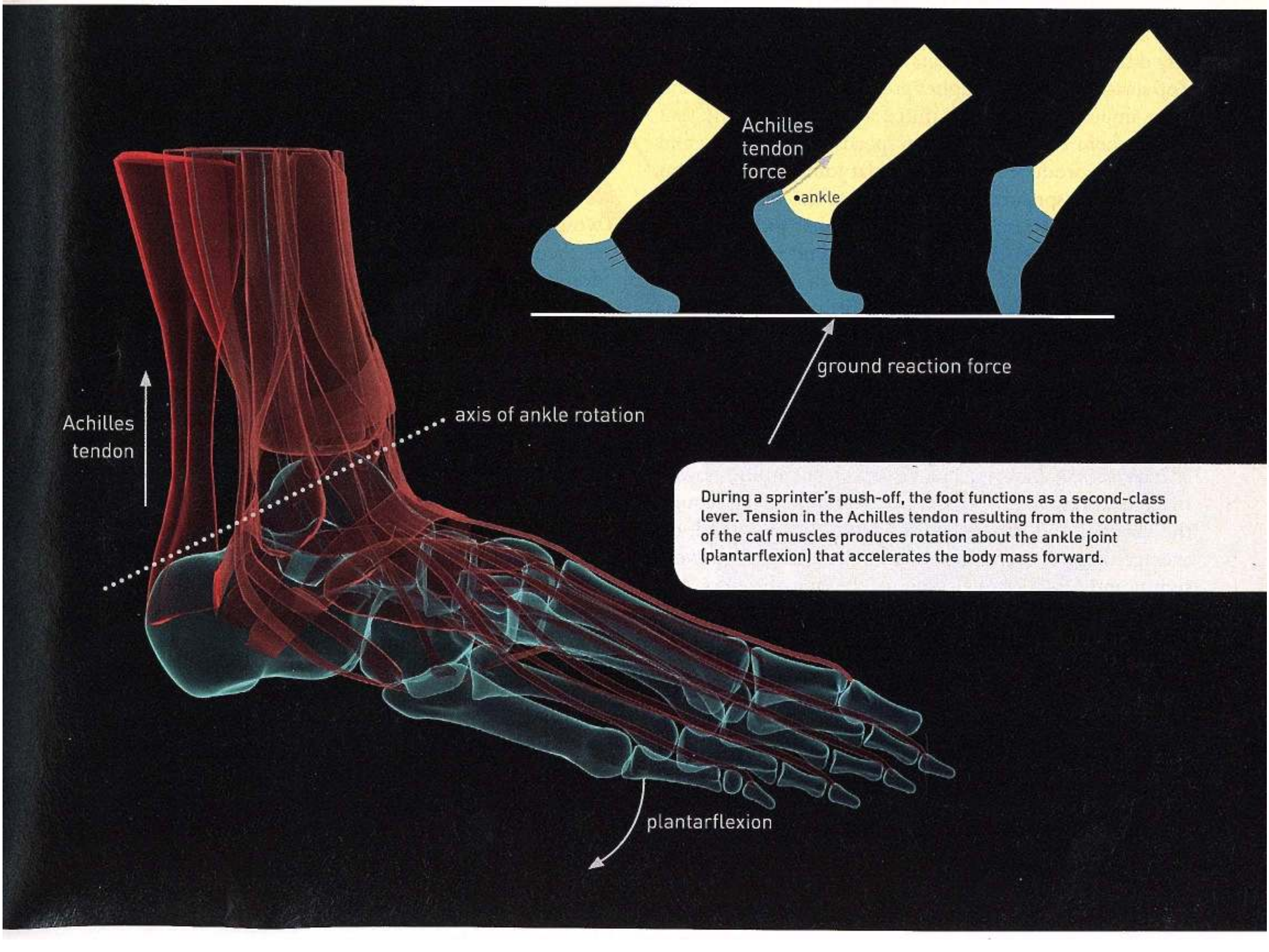
We decided to measure the lever arms of the receiver's Achilles tendons so that we might learn how effective his calf muscles were at producing a plantarflexion moment about the ankle for a given force. Ankle plantarflexion moments are produced when the Achilles tendon pulls on the heel in such a way that the toes would point if not resisted by the ground reaction force.

Measurements of tendon lever arm were made using a well-established but indirect technique called the tendon excursion method. Rather than measuring the perpendicular distance from the center of joint rotation to the line of action of the muscle-tendon unit, we move the joint through a known rotation while measuring the sliding of the tendon beneath the skin using an ultrasound scanner. The ratio of tendon excursion to joint rotation can be shown to be equivalent to the average lever arm of the tendon, and this method has the advantage of eliminating the need to identify the center of rotation, something that is difficult to do experimentally.

Never having tested an elite athlete before, we fully expected him to have very long Achilles tendon moment arms. Football wide receivers are specialists at rapid acceleration that would surely be enhanced by a large plantarflexion moment during push-off, we thought. To exert a maximal plantarflexion moment, one would need to



During a sprinter's push-off, the foot functions as a second-class lever. Tension in the Achilles tendon resulting from the contraction of the calf muscles produces rotation about the ankle joint (plantarflexion) that accelerates the body mass forward.

have a large plantarflexion moment arm.

When Sabrina measured his Achilles tendon excursion, however, she got a surprise: the ultrasound scans showed that his Achilles tendon excursion was only about half of what she had seen in similar measurements made in relatively nonathletic graduate student volunteers for the same joint rotation. This meant that rather than being abnormally large, the wide receiver's Achilles tendon lever arms were substantially smaller than normal. We made the same strange observation for both his right and his left legs, and a non-athlete that we tested the next day was found to have tendon excursions that were much larger and consistent with what we had measured before.

We were left wondering: Why would someone with world-class speed have ankle joints that put the largest ankle muscles at a mechanical disadvantage?

The Cheetah's Toes

Very little is actually known about how human musculoskeletal structure determines sprinting performance. Previously published research has shown that sprinters have longer fascicles (fiber bundles) in their calf muscles that may permit those muscles to do more work. Enhanced power generation would help a sprinter to reach top speed quickly from a standing start, and research tells us that the best sprinters are those who accelerate most rapidly during the first 30 meters of a 100-meter sprint race. Top sprinters generate higher propulsive ground reaction force impulses during the initial acceleration phase that enable them to reach their top speeds more quickly and do, in fact, produce higher muscular joint moments than merely good sprinters. We know that the best sprinters have larger leg muscles that have a higher proportion of fast-twitch muscle fibers, but we found no studies documenting differences in tendon paths or joint structure that could help us understand the short muscle lever arms we measured.

We subsequently performed a study in which we quantified the musculoskeletal architecture of the lower leg in 12 collegiate sprinters and jumpers and 12 non-sprinters (a paper describing this study will appear soon in the *Journal of Experimental Biology*). The results of our study showed that our earlier finding was not an aberration. Even though the sprinters and non-sprinters were height-matched, on average the sprinters' Achilles tendon moment arms were significantly smaller than those of the non-sprinters. We made another interesting discovery in this study, that the toes of our sprinter subjects were significantly longer than the non-sprinters' toes.

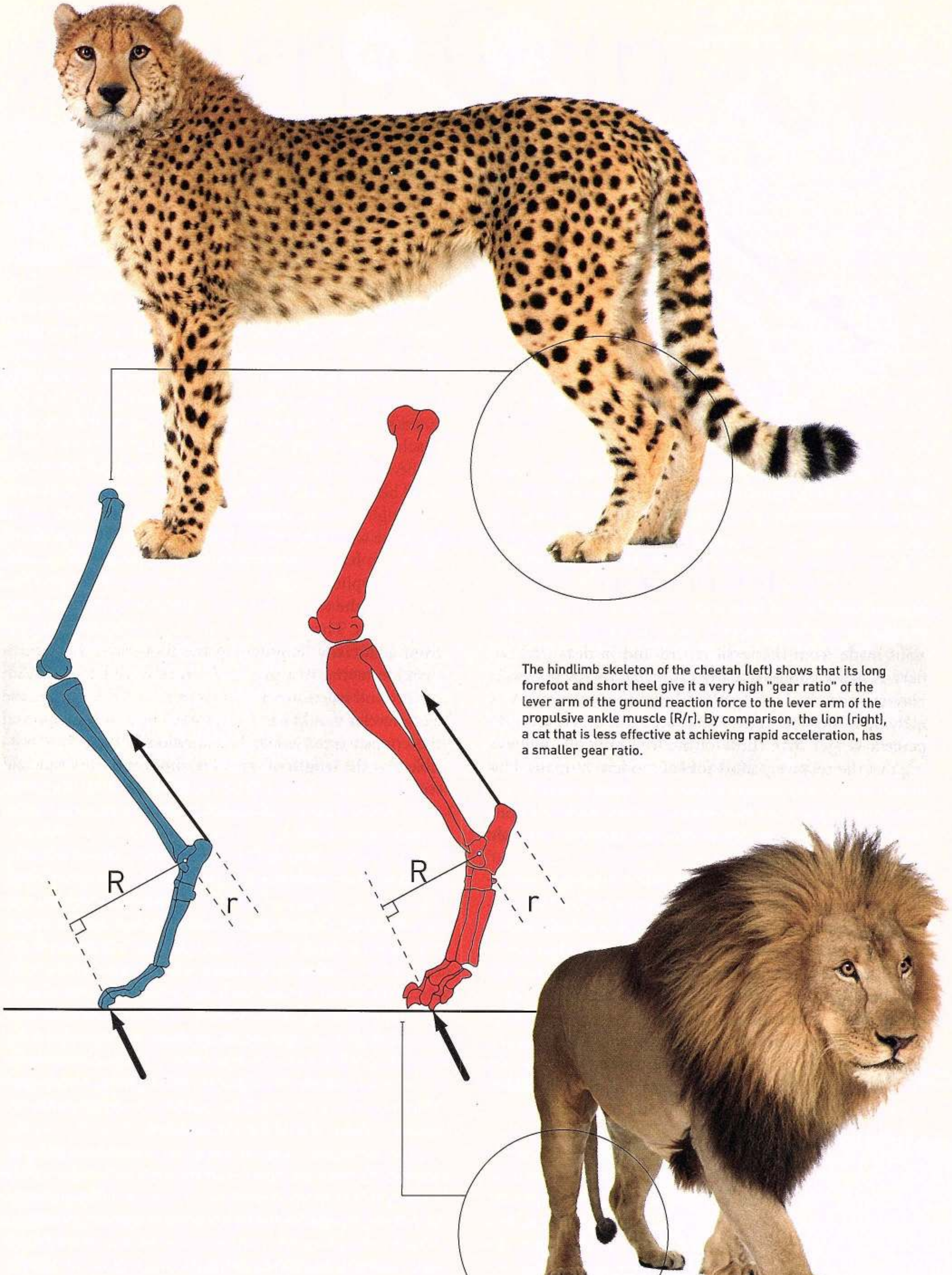
We found clues that helped to make sense of our results in the anatomy of the best animal sprinters. Cheetahs are the best sprinters on earth, reaching speeds of nearly 70 miles per hour in about three seconds. Biologists who specialize in comparative functional morphology have noted that cheetahs and other fast runners are adapted for speed in several ways. One of these is that cheetahs have a higher ratio of the lever arm of the ground reaction force about the ankle joint divided by the lever arm of the propulsive extensor muscle about the ankle. Cheetahs have long toes (with claws that only partially retract, effectively lengthening the toes even more) and have short heel bones, which combine to yield a very high value for this "gear ratio." While a high gear ratio does place the muscle at a mechanical disadvantage in terms of its lever arm, this is more than compensated for by the fact that a high gear ratio permits higher muscle forces to be generated.

The lever arm affects the capacity to generate force through the force-velocity property of muscle. It is well known to biomechanists that muscles generate less force the faster they are required to shorten. This happens because a certain amount of time is required for cross-bridges to form between the sliding contractile protein filaments found within muscle fibers. When a muscle-tendon unit has a high gear ratio, its muscle fibers will shorten less for a given joint rotation. If the rotation has the same duration, the resulting reduction in shortening velocity permits the muscle to generate greater force. Having a high gear ratio becomes advantageous when this increase in muscle force overcomes the loss of mechanical advantage that follows from having a short muscle lever arm.

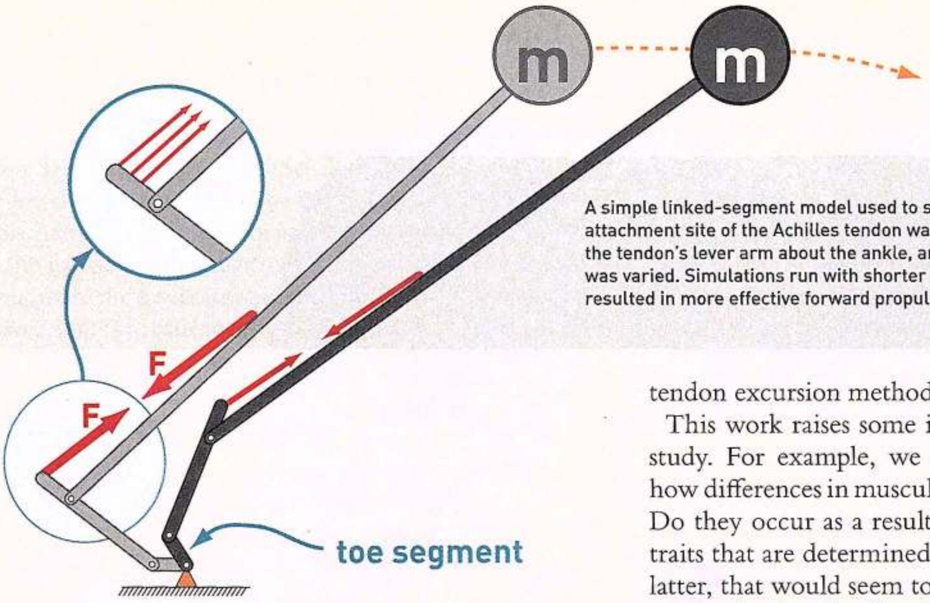
Variations in morphology across species were suggestive of an explanation for the differences we measured between sprinters and non-sprinters, but we wanted to see if variations similar to differences we measured would benefit sprint performance. Would the advantages theoretically conveyed by having short Achilles tendon lever arms and long toes be evident during a human sprinter's push-off?

Making alterations to the toes and ankles of living humans is a difficult proposition, so we constructed a mathematical model for this purpose. We tried to create the simplest possible anthropomorphic model that would allow us to answer our question, with revolute joints between the ground and toes, between the toes and the rest of the foot, and between the foot and the body. We used parameter optimization to find the excitation control histories for muscle-tendon actuators that produced the greatest possible forward impulse during a simulated push-off.

The simulation results showed that a model with the sprinters' Achilles tendon lever arms produced substantially greater propulsive impulse than the impulse generated using the non-sprinters' lever arms. Longer toes resulted in only slightly higher propulsive impulses, but permitted contact with the ground to be sustained. It is somewhat counterintuitive that longer contact times



The hindlimb skeleton of the cheetah (left) shows that its long forefoot and short heel give it a very high "gear ratio" of the lever arm of the ground reaction force to the lever arm of the propulsive ankle muscle (R/r). By comparison, the lion (right), a cat that is less effective at achieving rapid acceleration, has a smaller gear ratio.



A simple linked-segment model used to simulate a sprinter's push-off. The attachment site of the Achilles tendon was modified in order to prescribe the tendon's lever arm about the ankle, and the length of the toe segment was varied. Simulations run with shorter tendon lever arms and longer toes resulted in more effective forward propulsion.

would enhance sprint performance, but sustained contact should be a benefit during the acceleration phase, when forward velocity must be rapidly increased and ground reaction force is the only means for doing so.

An Ancestor's Stride

Our hypothesis that long toes are useful for rapid acceleration during human sprinting is supported by observations made from the fossil record and in distance runners. A paper published earlier this year by researchers at Harvard and the University of Massachusetts noted that early hominids like Australopithecus had toes that are 40 percent longer than those of modern humans, suggesting that the relatively short toes of modern humans must hold some evolutionary advantage. Experiments conducted in a gait laboratory showed that the work done by the toe flexor muscles of distance runners increased with toe length.

"The results from sprinters and our work suggest there is a tradeoff between toe length and muscular effort during running: longer toes require greater muscle effort, and are thus less economical over endurance distances," said Campbell Rolian, lead author of the Harvard study. "At the same time, however, longer toes allow more propulsive force, permitting greater acceleration in sprinting. The fact that our toes are considerably shorter than those of our ape relatives and fossil ancestors implies that the need for endurance and economy may have outweighed the need for rapid accelerations in our ancestors."

While we are excited by our findings because they potentially provide a means for explaining how musculoskeletal structure determines functional performance, we still regard these findings as preliminary. The next steps for us will include a more detailed examination using magnetic resonance imaging of the internal structure of the feet and ankles of sprinters. Location of the joint center of rotation and tendon line of action with MR imaging can also be used as an alternative to the tendon excursion method to assess lever arms.

This work raises some interesting questions for future study. For example, we are interested in determining how differences in musculoskeletal structure come about: Do they occur as a result of sprint training, or are they traits that are determined by genetic makeup? If it is the latter, that would seem to lend credence to the old track coaches' axiom that "sprinters are born and not made."

The spiked shoes worn by sprinters give some of the same benefits that we would expect to follow from having long toes. The spikes themselves increase traction in the same way that a cheetah's claws would, but sprinters' shoes also have a stiff plate under the forefoot. This plate permits application of the ground reaction force closer to the tips of the toes, effectively giving the sprinter slightly longer toes. There would clearly be diminishing returns from artificially lengthening the foot using footwear – imagine trying to run a sprint race wearing skis. With the ground reaction force so far in front of the ankle, the calf muscles would be at a tremendous disadvantage and the contact time would be ridiculously long. It is possible that the length of sprinters' shoes and the shape and stiffness of the forefoot plate could be tuned to optimally suit the toe length and other aspects of a sprinter's musculoskeletal structure.

We are now turning our attention to a different group of people for whom speed is important: older adults. With advanced age comes a decline in walking velocity that may be attributed to many causes, including age-related muscle wasting and impairments to nervous and circulatory function. If we can find musculoskeletal structural characteristics that serve as markers for reduced mobility, we may be able to identify those older adults who could benefit most from targeted strength training programs. The characteristics that enable seniors to maintain gait velocity are likely to be different from those possessed by elite sprinters, since elderly gait is not marked by rapid movements and force-velocity effects would thus be minimal.

This is an important problem because mobility is perhaps the most significant determinant of quality of life among the elderly. When one sees Terrell Owens dashing down the sideline or Usain Bolt exploding during a 100-meter sprint, it's easy to believe that we engineers and scientists have little to teach them. But, amazingly, what they have to teach us could very well improve the lives of the growing population of elderly Americans. ■