Running Shoes of the Postmodern Footwear Era: 
A Narrative Overview of Advanced Footwear Technology

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The modern era of running shoes began in the 1960s with the introduction of simple polymer midsole foams, and it ended in the late 2010s with the introduction of advanced footwear technology (AFT). AFT is characterized by highly compliant, resilient, and lightweight foams with embedded, rigid, longitudinal architecture. This footwear complex improves a runner’s efficiency, and it introduced a step change in running performance. Purpose: This review serves to examine the current state of knowledge around AFT—what it is and what we know about its ingredients, what benefits it confers to runners, and what may or may not mediate that benefit. We also discuss the emerging science around AFT being introduced to track-racing spikes and how it is currently regulated in sporting contexts. Conclusions: AFT has changed running as a sport. The construction of AFT is grossly understood, but the nature of the interacting elements is not. The magnitude of the enhancement of a runner’s economy and performance has been characterized and modeled, but the nuanced factors that mediate those responses have not. With these knowns and unknowns, we conclude the review by providing a collection of best practices for footwear researchers, advice for runners interested in AFT, and a list of pertinent items for further investigation.

Keywords: running economy, midsole, foam, super shoes

The victory of Abebe Bikila in the 1960 Rome Olympic Games and the victory of Eliud Kipchoge in the 2016 Rio Olympic Games may serve as appropriate bookends for the “modern” era of running shoes. Bikila, iconically and obviously running barefoot through the streets of Rome, represented the last hurrah for an age where the shoes would go on to repeat his Olympic victory and set another world record in Rome in 1964, but this time Bikila did so wearing the Onitsuka Tiger Marup, a shoe that had the structural elements would appear, but these essential ingredients linked the Onitsuka Marup that Bikila wore to victory in 1964 with the shoes used by Stephen Kiprotich to win the gold medal in London 2012 and those used by Dennis Kimetto to set the world record in 2014.

In 2016, Kipchoge, subtly and covertly running in prototypes of the Nike Vaporfly—initially in the London Marathon and then during his first Olympic gold-medal run in Rio later that year—ushered in a new era of shoes. Advances in polymer foams and their regulated in sporting contexts. AFT has changed running as a sport. The construction of AFT is grossly understood, but the nature of the interacting elements is not. The magnitude of the enhancement of a runner’s economy and performance has been characterized and modeled, but the nuanced factors that mediate those responses have not. With these knowns and unknowns, we conclude the review by providing a collection of best practices for footwear researchers, advice for runners interested in AFT, and a list of pertinent items for further investigation.

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The energetic benefits of these “postmodern” shoes in running have been robustly demonstrated in laboratory studies. An understanding of how their benefits translate to performance improvements is less robust, but it has been modeled and is continually developing as performance data sets grow. However, the precise mechanism of benefit and individual characteristics that mediate response are still unclear. This narrative review examines the current state of knowledge regarding advancements in footwear technology, including the necessary elements and construction of advanced footwear, the degree and nature of its benefit to running economy (RE) and performance, changes in biomechanics associated with the new footwear, the migration of the new footwear technology to track racing spikes, and the regulation of footwear in competitive distance running. A list of best practices is provided for researchers along with a list of questions and pertinent topics for investigation. Finally, we provide recommendations for runners interested in this advanced footwear.

Definition and Construction

What constitutes “postmodern” footwear? The recipe for this advanced footwear technology (AFT)—the suggested scientific lexicon and term to which it will be, henceforth, referred—was established by the original Nike Vaporfly (AFTVFL). The shoe was novel in 2 interacting and multifaceted elements: a highly resilient, compliant, and lightweight midsole foam with embedded, rigid, curved longitudinal architecture (eg, a plate; Figure 1). How each of these independently contribute to the benefit has yet to disentangled, but suffice it to say, the novel foam and embedded plate likely behave in a synergistic fashion and are the necessary conditions for a shoe to be considered “AFT.”

The Foam

The foam used in the previous “modern” running footwear—henceforth, simple footwear technology (SFT)—was ethylene
vinyl acetate (EVA), a random copolymer that is quite soft and light relative to the rubber soles of antiquity. Importantly, it is easy to manufacture and manipulate. While it provided beneficial cushioning,\textsuperscript{10,11} it acted as a dampener, typically returning 60\% to 75\% of energy under compression.\textsuperscript{1,12,13} Other foams emerged, such as the thermoplastic polyurethane foam used by Adidas as their “Boost” foam that provided more favorable resilience (75\%–79\% of energy returned)\textsuperscript{1,14} and demonstrated a small enhancement (\textasciitilde1\%) of RE.\textsuperscript{14}

The foam in the first AFT—the AFT\textsubscript{NVE}—was polyether block amide (PEBA),\textsuperscript{1} a block copolymer that was previously used as a rigid plastic, providing structure in ski boots or spike plates in sprint spikes alike. When foamed, the chemical becomes a material that is both very compliant (“soft”), highly resilient (“returns a lot of energy”), and has the potential for a very low density (“light”).

\textbf{Resiliency}

Hoogkamer et al\textsuperscript{1} compared the AFT\textsubscript{NVE} PEBA material properties with EVA foam in the Nike Zoom Streak (SFT\textsubscript{NVS}) and the thermoplastic polyurethane foam in the Adidas Adios Boost (SFT\textsubscript{ABB}) and observed 87\% resilience compared with 66\% in the SFT\textsubscript{NVS} and 76\% in the SFT\textsubscript{ABB}. We have observed similar resilience values (82\%–84\%) for the AFT\textsubscript{NVE} as well as other AFT models using PEBA (or similar) foams, including the Nike AlphaFly (AFT\textsubscript{NAF}), Saucony Endorphin Pro (AFT\textsubscript{SEP}), Asics Metaspeed Sky (AFT\textsubscript{AMS}), and Adidas Adizero Adios Pro (AFT\textsubscript{AAP}).\textsuperscript{15} Although the relative timing of the energy return has been the subject of some question, the AFT foams appear to return their energy across a spectrum of compression and decompression times suitable for typical running dynamics. It was initially demonstrated that 86\% of energy was returned in the AFT\textsubscript{NVE} over a 185-ms cycle time—similar to a complete period of ground contact at faster speeds—and 82\% to 84\% in the aforementioned AFT models over a 100-ms cycle time—similar to the time course of heel compression and decompression during heelstrike.\textsuperscript{16}

\textbf{Compliance}

In addition to the improved resiliency, the second facet of the advanced foam that is beneficial to a runner is its greater compliance—its deformation under a given load—as compliant surfaces have been shown to be ergogenic for running provided that they have substantial resilience.\textsuperscript{13} The AFT\textsubscript{NVE} deformed \textasciitilde12 mm under 2000 N of load, twice as much as the SFT\textsubscript{NVS} and SFT\textsubscript{ABB} (\textasciitilde6 mm).\textsuperscript{1} This allowed it to store twice as much mechanical energy with each compression, and due to its greater resilience, it would return most of it to the runner. In examining the material stiffness (the inverse of compliance) of the midsoles of other AFT models (Figure 2), we observed most, including the AFT\textsubscript{NVE}, AFT\textsubscript{NAF}, AFT\textsubscript{AMS}, and AFT\textsubscript{AAP}, to have low material stiffnesses (45–59 kN/m) compared with a traditional SFT, the Asics Hyper Speed (SFT\textsubscript{AHS}), with a stiffer and less compliant midsole (96 kN/m).\textsuperscript{15} This corroborates the initial AFT findings with regard to compliance and indicates that AFT from several manufacturers can be up to twice as compliant as traditional SFT.

\textbf{Weight}

The third facet of the AFT foams that is distinct is their low density, which makes them extremely light. Runners are typically and predictably penalized for weight on their feet, with each 100 g of added mass eliciting a 1\% decrement in RE.\textsuperscript{1,19} Kram\textsuperscript{9} estimated that the PEBA foam used in the AFT\textsubscript{NVE} and AFT\textsubscript{NAF} is \textasciitilde4\times less dense than a traditional EVA midsole foam used in SFT. Although the weight savings alone would not explain the benefit,\textsuperscript{9} it allows more of the beneficial foam to be used without penalizing the runner. That is, more of the more-perfectly elastic and compliant material can be added to the shoe to store and return more energy per step. It may also allow the material to behave in these more ideal elastic conditions before it reaches a critical strain (ie, sufficient compression) to “bottom” out and lose its compliance and/or resilience.\textsuperscript{15,20}

\textbf{Midsole Geometry}

There is an inevitable trade-off in the mechanical function of added foam volume and thickness versus the cost of weight and stability where increasing amounts are no longer fully “used” (ie, completely elastically compressed) by the runner, and the added material incurs a weight and/or stability penalty. This new ideality with AFT is currently being explored, as very thick (ie, 50 mm) AFT shoes have been shown to be unequivocally economical to similar shoes with more typical AFT foam volumes.

\textit{(Ahead of Print)}
35–40 mm thicknesses) at slower speeds (ie, average of 10.3 kph). Similarly, Bertschy et al reported that AFT with very thick (60 mm) midsoles enhanced RE compared with more standard AFT (30-mm midsoles) when matched for weight but would be inferior when factoring in the added weight. These data suggest that with current materials and embedded architecture designs, the “ideal” thickness for most may be in the 30 to 40 mm range, but the individual nature of this ideality, how it relates to speed, and how it evolves with changing materials and architectures should be the subject of continued exploration.

**AFT Foam Durability**

A final aspect of the new AFT foams that has yet to be robustly characterized is their longevity. Although there was initial public skepticism around the durability of AFT foams due to their low density and lighter weight, the block copolymer chemical structure of PEBA (the most common AFT polymer foam) typically results in stronger materials than those of random copolymers typical of SFT—for example, EVA foams. We have measured the material properties of the AFT\textsubscript{NVF} ZoomX PEBA in both unused and heavily used shoes—that is, 500 km of road running—under vertical compression with the same parameters described in Figure 2. We observed the hysteresis to be only slightly augmented—84.5% energy returned down to 82.9%—and the compliance to be similarly only very modestly reduced—42 to 45 kN/mm. These values are still substantially distinct from “fresh” EVA shoes, which may have values of 65% to 75% and 70% to 110 kN/mm. Rodrigo-Carranza et al reported that the material properties of a PEBA foam degraded more than EVA foam after 450 km of use. However, their testing was conducted using a displacement-controlled 3-point-bend test designed to assess the longitudinal bending stiffness (LBS) in the forefoot, which is not suitable to characterize the material properties of a midsole under vertical compression. It was notable that the initial energy return values reported for the PEBA and EVA shoes were similar in the unused condition (−75%), which is substantially lower than has been reported in other AFT models, though, as the authors mention, PEBA foams are not necessarily all similar. As such, further studies testing new and progressively worn shoes with the explicit models provided will be valuable to help runners better understand the longevity of commercially available AFT shoes.

**Testing Methods for Shoe Midsole Properties**

When characterizing the material properties of shoe foams—namely the compliance and resilience—it is necessary to perform some form of controlled materials testing. Typically, this is done via uniaxial vertical compressive loading on the intact shoe midsole or on an isolated sample of the foam. This characterizes the deformation of the foam under compression and decompression, allowing for the determination of the hysteresis (energy loss; the inverse of resilience) through the full loading and unloading cycle as well as the stiffness (the inverse of compliance) of the material under compression (Figure 2). Testing apparatuses range from uniform geometries, such as a simple cylinder, to bespoke constructions used to simulate a human foot. It is common practice to use a load that simulates the anticipated peak vertical forces. As such, further studies testing new and progressively worn shoes with the explicit models provided will be valuable to help runners better understand the longevity of commercially available AFT shoes.
ground reaction forces on the runner on the region of the shoe being compressed (eg, 1500–2000 N) and the time course of loading that simulates a runner’s typical ground contact time (eg, 180–260 ms).1,12,14,16,28 Though some investigators have used representative stresses rather than absolute loads,29,30 this latter approach is less common in footwear testing but is advantageous in that it is both generalizable across studies and more specific to the expected compressive dynamics of the shoe’s region that is being perturbed. As such, it is a recommended best practice to report the compressive area of the loading apparatus and to design the peak loads and time courses of compression to simulate representative stresses and compressive cycle times experienced by that region of the shoe or to simply report stresses in addition to absolute loads. Furthermore, using representative stresses will result in displacements under the load that are more characteristic of the true strains experienced by the shoe in running. For reference, peak stresses on the shoe for a 70-kg runner at 3.5 m/s may be 300 to 370 kPa in the heel and forefoot and 100 to 130 kPa in the midfoot.31 Testing at stresses and strains outside of those typically experienced by the shoe may provide inaccurate descriptions of the midsole properties,26 as many elastomeric foams tend to behave nonlinearly outside of the ranges of stresses and strains to which they are typically used.20,26,32 This may lead to inaccurate characterizations of the midsole stiffness and/or resiliency with respect to how the shoe truly behaves beneath the foot of a runner. Furthermore, the region of the shoe should be considered as the heel region tends to yield higher resiliency and lower stiffness figures than the forefoot under the same stress, likely due to the greater respective strain.15

The Rigid Longitudinal Architecture

The second distinct feature of AFT is the use of rigid, embedded, and curved architecture. In the original AFTNVF, this was a carbon fiber plate that had a convex curvature under the metatarsophalangeal (MTP) joint. The ability of a rigid plate to enhance RE via increasing the LBS of the shoe was first reported by Roy and Stefanyshyn,33 who observed a 1% enhancement in RE with an intermediate plate stiffness. However, subsequent studies failed to demonstrate consistent benefits of increasing LBS in shoes.34 The AFTNVF was unique in that the plate was curved beneath the MTP joint and embedded within the shoe.1 This curvature was thought to reduce the energy lost at the MTP joint during dorsiflexion beyond that of a flat plate while reducing the work at the ankle imposed by the stiff plate.34–36 This curvature may also increase the distance from the MTP joint, resulting in a larger moment and greater effective stiffness.34 These ideas were challenged when runners failed to demonstrate any significant detriments to their RE while running in altered AFTNVF with lateral cuts through the midsole. These cuts effectively reduced the LBS and the hypothesized effect of the MTP joint alterations on RE.37 As such, the initial hypotheses around the plate’s function—reducing negative work at the MTP joint and conserving work in the ankle—seem to be challenged as the MTP joint did more negative work in the cut plate despite no observed differences in ankle mechanics or, ultimately, RE.

Two other unique functions of the plate have been proposed: first, that it behaves as a first-class lever—that is, a “teeter-totter”—wherein the downward force of plantar flexion in the anterior portion of the shoe (ie, the forefoot) late in stance creates an upward force in the posterior portion of the shoe (ie, the heel), enhancing forward propulsion.38 The magnitude of this effect, if it exists, was challenged by the aforementioned study from Healey and Hoogkamer37 wherein lateral cuts in AFTNVF—which would eliminate or reduce this first-class lever function—failed to substantially alter their benefits to RE. A second proposed function of the plate is that it may serve to convert the foam into an “area-elastic” structure rather than a “point-elastic” structure—a mechanical system where a point compression above the plate is distributed more evenly below the plate, reducing the stress and corresponding strain.9 The foams appear to be nonlinearly elastic at high stresses and strains, where substantial deformation nonlinearly increases the stiffness—that is, decreases the compliance.1,15 The effect of a “point-elastic” compression would be in applying higher stress for a given load, which would yield greater strain and possibly elicit these “stiffer” characteristics, which would compromise the amount of energy that could be stored (and returned) in the material. It may also decrease the resilience if it passes a critical strain—that is, the “bottoming out” phenomenon.15,20 The “area-elastic” phenomenon would serve to essentially decrease the stress on the foam for a given load, decreasing the strain, and thereby allow it to preserve its lower stiffness (ie, greater compliance) at those lower strains. We have previously explored this concept in benchtop materials testing wherein the plate was “surgically excised” from the heel of an AFTNVF shoe. Using a cylindrical stamp with a 50-mm diameter (simulating a human heel), we loaded the intact AFTNVF heel and excised-plate AFTNVF heel under 350 kPa (~700 N) of uniaxial load—a similar stress that would be expected during heel strike in that region.31 The load deformation curves were nearly identical, suggesting that the plate was not altering the foam’s behavior under compression. However, this was constrained uniaxial compression and a simulation of the blunt compression of a heel strike. This “area-elastic” function, if it exists, may be more pronounced in dynamic 3-dimensional compression of the foam, perhaps as it relates to the distribution or transfer of stored and returned energy in different regions of the shoe.

We have also observed runners to exhibit markedly different plantar pressure patterns when running in AFT (Figure 3). The peak pressures seem to be blunted, which may be an effect of the greater foam volume and/or the “area-elastic” effect under the dynamic compression, especially as it is more pronounced in the forefoot where point compressions would be higher. The plate also seems to mediate their natural center-of-pressure (CoP) progression by it “pulling” the CoP toward the longitudinal axis of the plate so that the runner moves over the shoe in a more homogeneous manner. Further investigation of center-of-pressure progressions and dynamic pressure distributions while running may provide further insight into the nature of the plate’s influence on the runner.

Enhancement

Enhancement Assessment Considerations

Before reviewing and discussing the scientific literature that informs our understanding of the effects of AFT, it is important to clarify “best practices” and considerations in studying them. The laboratory outcome measure of consummate concern is submaximal RE—the energetic demand to run at a given speed below a subject’s anaerobic threshold, conventionally quantified as the oxygen consumption per unit distance (ie, VO₂ rate for a given speed as mL/kg/km) or as the total energetic cost per unit distance to account for substrate utilization differences (ie, Watts expended at a given speed as J/kg/km). Indirect calorimetry via gas exchange measurement (ie, oxygen consumption and carbon dioxide
production) is inherently noisy, both biologically and technologically. As such, very tight control around measurement execution and testing conditions is critical to study interventions. When controlling for time of testing, prior training load, nutritional status, and footwear, a test–retest coefficient of variation within individuals has been found to range from 1.3%–1.6% to 2.4%–2.5% when compared between days. To detect small changes (1%–2%) due to an intervention such as footwear, it is critical to employ a same-day, repeated-measures design. Furthermore, it is recommended to test footwear conditions in duplicate, as this has been shown to reduce the coefficient of variation by approximately one-half in our laboratory testing. With careful control, a reliable metabolic cart, appropriate sample sizes, and repeated-measures within individuals, it is possible to detect changes as small as 1%. Williams et al recommended 18 subjects to detect an effect size of 1.0 in RE at 3.5 m/s. In addition to adequate sample sizes and repeated measures on subjects, trials should last at least 4 minutes with data averaged over the final 1 to 2 minutes, and running should be conducted on as stiff a surface as possible.

### RE Enhancement

The primary outcome of interest with the introduction of AFT has been the enhancement of a runner’s submaximal RE. That is, the footwear reduces the energetic cost of running at a given speed, which may, in turn, allow an individual to run faster for a given energetic cost. The first study that presented AFT was conducted on a prototype of the original AFTNVF model that was compared to mass-matched, conventional racing shoes across 3 speeds (14, 16, and 18 kph). They observed an average improvement of 4.2% in a runner’s RE relative to the SFTAHS (again, a conventional “modern” SFT racing shoe with an EVA foam midsole and no rigid architecture) and 4.0% relative to the SFTAAB (an atypical “modern” SFT racing shoe with a slightly more resilient yet stiffer and heavier thermoplastic polyurethane foam and no rigid architecture). Although the exact magnitude of benefit has varied slightly, 2 subsequent studies replicated these findings in investigating the first commercially available AFTNVF with similar experimental protocols (eg, repeated and mirrored measurements, speeds of 16 kph for males and 14 kph for females). They observed RE enhancements of 4.2% (2.9% when mass matched) and 2.8% relative to the SFTAAB and 1.9% enhancement relative to the SFTNZE. A subsequent study observed a nonsignificant drop in oxygen cost of 1.0% to 1.9% compared with the Saucony Endorphin Racer (SFTSER; similar in construction to the SFTNZE albeit lighter) across several speeds relative to the individual’s velocity at VO2peak (vVO2) with large variability in the observed response to the AFTNVF (ie, −9.6% reduction to +9.7% increase in oxygen cost across speeds). However, footwear conditions were measured on separate days and in single repetitions of 3-minute duration with a 30-second window averaged, highlighting the need for repeated measures with longer measurement periods.

The first study to investigate AFT other than the Nike Vaporfly examined 7 shoes that incorporated at least one AFT element (a rigid carbon-fiber plate)—AFTNVF, AFTNAF, AFTAMS, AFTSEP, Hoka Carbon Rocket X (AFTHCX), Brooks Hyperion Elite (AFTBHE), and New Balance Fuel Cell Elite (AFTNFC)—relative to the Asics Hyper Speed (SFTAHS; “modern” EVA racing shoe without rigid architecture). Importantly, only 5 of the shoes studied (ie, AFTNVF, AFTNAF, AFTAMS, AFTSEP, AFTNFC) would meet the criteria we now define for AFT, which includes highly resilient, compliant, and lightweight foams (eg, PEBA or a similar chemical composition) in addition to an embedded plate or rigid structure. The AFTHCX and the AFTBHE used an EVA midsole and the resiliency values we measured were similar to the SFTAHS. Using repeated measures across 2 days, they found that the AFTNVF along with the AFTNAF and AFTAMS had statistically similar RE improvements of 2.7%, 3.0%, and 2.5%, respectively, expressed as oxygen cost relative to the SFTAHS. Another “tier” of AFT, including the AFTSEP and AFTNFC, had significant improvements in RE of 1.5% and 1.4%, respectively, over the SFTAHS but were less than the top “tier” (AFTNVF, AFTNAF, and AFTAMS). The 2 shoes that included a carbon-fiber plate but were still composed of traditional EVA foam, AFTBHE and AFTHCX, did not confer significant differences in RE relative to the SFTAHS. A subsequent study compared 3 unspecified, commercially available AFT models with an unnamed control SFT racing shoe in recreational and elite runners at speeds set relative to their vVO2peak (averages of 13.1 and 17.0 kph, respectively). They observed 3.5% to 5.0% improvements in RE in the 3 AFTAAP
models relative to the SFT in recreational runners but failed to find significant differences in the elite runners. They similarly observed large variation in response, especially in the elite cohort, with RE changes in the AFT ranging from an 11.4% benefit to 11.3% decrement. Distinct from the previous studies,1–4 this investigation used single observations of RE with small sample sizes (7 in each cohort) and large periods of rest between trials (12 min). This may explain the large variation in RE observations, similar to those observed by Hébert-Losier et al.,12 who also used single repetitions per footwear condition and smaller average time windows. Paradisis et al44 compared the Saucony Endorphin Speed 2 (AFTSSES) with the Saucony Cohesion 13 (SFTSCH), an inexpensive nonracing SFT shoe. They observed benefits of 3.8% and 5.0% when subjects ran at 65% and 80% of their vVO2peak.

**Speed**

Speed appears to have an effect on the response of runners to AFT, with slower speeds (≤12.0 kph) eliciting smaller effects. The initial studies on AFT that used repeated measures across speeds did not observe a differential response in AFT-related RE improvements across speeds ranging from 14.0 to 18.0 kph.1,2 We examined the RE response of runners at 10.0 and 12.0 kph in the NVF compared with the AHS; the RE improvements were just 0.9% and 1.4%45 compared with the 2.7% benefit observed at 16.0 kph in the same laboratory in a different population of runners.4 Paradisis et al44 similarly observed a blunted RE benefit at slower speeds in runners using the AFTSSES relative to the SFTSCH. Their population ran at 65% and 80% of their individual vVO2peaks, which corresponded to 9.4 and 11.5 kph. The RE benefit in the AFTSSES was 5.0% at the faster speed but only 3.8% at the slower speed.

Although the mechanism for this apparent decline in RE enhancement at lower speeds is unknown, we hypothesized 2 potential mechanisms. The first may be related to the interaction of the runner with the plate, with the plate possibly facilitating less of a benefit at slower speeds.46 This may be related to the propensity of runners to natively stiffen their MTP joints at faster speeds47 and possibly mediated by the stiff plate lowering the shortening velocity of the gastrocnemius muscle and enhancing muscular efficiency.48 The second hypothesis relates to the greater forces that runners exchange with the ground at faster speeds. It may be that at slower speeds, where runners run with lower ground reaction forces, the beneficial foam is not being compressed to its full elastic capacity. Thereby, the absolute energy loss differential between SFT and AFT would be lower. At higher speeds, the forces and corresponding stresses on the foam may be high enough to “saturate” its elastic capacity, and the benefits of the shoes stabilize—that is, more similar absolute amounts of energy lost within the shoe—with correspondingly more homogenous responses observed above this “elastic threshold”—possibly 13.0 to 14.0 kph for many runners.1,2,49

**Gradient**

Gradient seems to moderate the beneficial effects of AFT on RE, but it does not eliminate it. Whiting et al49 found that an uphill 5% gradient reduced the beneficial effect of the AFTNVF to 2.8% over the SFTNZS from a 3.8% benefit observed during level running. Similarly, they found that a downhill 5% gradient elicited a 2.7% RE benefit over the SFTNZS. This was not significantly different from the level condition as the downhill running elicited much greater variation in response to the AFT. It is, as of yet, unclear as to which elements of AFT are more or less beneficial in uphill and downhill running conditions. For example, the more compliant midsole may be beneficial in downhill running, but the resiliency of it may be less important. Conversely, that resiliency may be beneficial in uphill running but the compliance less so. Furthermore, how the embedded rigid architecture affects the runner may have its own distinct interactions with these elements given differences in a runner’s kinetics and kinematics on gradients.50

**Sex**

Despite population-level differences in anthropometrics and some aspects of running biomechanics,51,52 there does not appear to be a sex effect with respect to the RE enhancement of AFT. Barnes and Kilding5 examined RE in 12 men and 12 women in the AFTNVF and SFTAAB at 14 and 16 kph, and there was no difference in the advantage conferred each sex by the shoes to their REs—that is, 2.9% at both speeds. Martinez et al53 observed a 3% enhancement in RE in a cohort of 12 women at 12.9 kph, similar to the benefits observed in male populations.1,3,4 In addition, we also showed that the benefits of AFTNVF were similar between men and women at slower speeds.45

**Muscle Damage Mitigation**

One of the most common subjective pieces of feedback from runners regarding the purported benefits of AFT is the ability to “protect” their legs, leaving them feeling “less beat-up” and able to “recover quicker.” Whereas the RE enhancements of AFT have received the most attention, this aspect has received comparatively little attention despite the qualitative sensations commonly reported. One of the few pieces of evidence to support this phenomenon was a conference presentation from the Nike Sports Research Lab that observed lower levels of serum markers of muscle damage and inflammation (lactate dehydrogenase, interleukin-6, and white blood cell count) as well as lower levels of reported quadriceps muscle soreness after a marathon in athletes running in the AFTNVF versus athletes running in an SFT (Nike Pegasus 36).54

In a study examining the RE of runners immediately before and 2 days after the imposition of muscle damage via downhill running, runners did not show a differential response to shoes with AFT-like foam properties (ie, highly compliant and resilient) versus a control shoe with SFT-like foam properties.35 This suggested that the foam properties themselves did not afford an additional benefit when muscle tissue was damaged compared with its undamaged state. However, it is unclear whether the footwear intervention in the study was AFT and, if so, whether the results would extrapolate to conditions with fatigue (ie, immediately after the “damaging” run) or to the muscle trauma experienced by runners during a long race or training session.55

**Race Performance Enhancement**

How the aforementioned laboratory-based economy improvements translate to actual performance improvements in runners is still being disentangled. Hoogkamer et al56 demonstrated that altering a runner’s submaximal RE in the lab measured at 12.6 kph translated to a predictable alteration in 3-km time-trial performance (average speed: 17.3 kph), with the relation being a 0.7% decrease in performance for every 1.0% decrease in RE. Kipp et al15 demonstrated that the inherent curvilinear relation between speed and VO2 uptake combined with the nonlinear cost of overcoming air resistance at faster speeds resulted in a nonlinear relation between speed and how RE improvements translate to performance improvements. Their modeling supported the laboratory versus time-trial
findings of Hoogkamer et al\textsuperscript{56} and further predicted that a 4.0% improvement in RW would yield a 2.6% improvement in speed at elite-level marathon pace, taking a 2:04:00 marathon to 2:00:48 for a small professional male racer.\textsuperscript{5}

Observations for this performance translation in ecological race settings have been challenging. Recreational runners improved their 3-km time-trial performance by 1.8% (13 s) in AFT versus a lightweight SFT against a 1.0% to 1.7% RE benefit in the laboratory at slower speeds.\textsuperscript{42}

Barnes and Kilding\textsuperscript{2} reported that a subset of athletes who switched to racing in the AFT\textsubscript{NVF} from their track spikes improved race performances by 1.9% over 3 and 5 km, where the RE improvement in the AFT\textsubscript{NVF} compared with the spikes as measured in the laboratory was 2.6%.\textsuperscript{2} Although these results may have been confounded by improvements in fitness between periods of switching footwear, they do align with the modeled\textsuperscript{5} and observed\textsuperscript{56} estimates of performance improvements described earlier.

Several studies have examined race results retrospectively for periods pre-AFT (before 2017) and post-AFT (after 2017). Senefeld et al\textsuperscript{6} examined elite marathon performance in 4 major marathons—London, Tokyo, Boston, and New York—between 2010 and 2019, and they found that among the elite runners running in AFT, times were 2.0% faster for men and 2.6% faster for women. Berton et al\textsuperscript{7} also observed a significant drop in global road racing times from 2012 to 2019. The top 100 marathon times dropped by 1.2% for men and 2.0% for women between 2016 and 2019, which included athletes not wearing AFT. Of the top 20 marathon performers in the world, males who wore AFT were 0.8% (1:03) faster, and females were 1.7% (2:10) faster. In a subset of athletes who switched to AFT in the 2016–2019 period, average performances were 1.4% (1:43) and 2.1% (3:01) faster for males and females, respectively.\textsuperscript{7} Rodrigo-Carranza et al\textsuperscript{57} performed a similar study, examining the footwear worn by the top 100 male marathoners each year from 2016 to 2019. They found that athletes wearing AFT were 74 seconds faster than those wearing SFT during that time (1.0%)\textsuperscript{57} and that marathon times improved by 1.5% from 2015 (pre-AFT) to 2019 (post-AFT widespread adoption). They also observed a cohort of athletes with repeat performances; they demonstrated a 0.7% improvement in marathons after they adopted AFT.

Although these retrospective analyses of performances are important pieces in understanding the trends, they may not fully characterize the true performance benefit of the shoes. The shifts in marathon times alone may be diluted with athletes not wearing AFT,\textsuperscript{7} especially in the 2017–2019 years, as several prominent shoe companies had not released their own AFT until 2020 or later. The shifts in marathon times may also be inversely affected by increased and more robust global antidoping efforts, especially in East Africa, from where the majority of the top performers analyzed come. Furthermore, in athletes who switched to AFT, there is a likely bias in the performance trajectories as it does not preclude the athletes who may have switched after being in lesser physiological shape than when they were observed in SFT. Repeated time trials, such as those used by Hébert-Losier et al.\textsuperscript{58} remain the most accurate indicators of the benefit of AFT with regard to absolute performance.

Biomechanical Alterations

AFT does impose distinct alterations in the biomechanics of runners. One of the primary areas of interest initially was in the MTP joint and the ankle as rigid plates in footwear—a necessary condition for AFT—alter the behavior of these joints for runners.\textsuperscript{34} The curved plate (or other rigid element) in AFT reduces the ankle’s range of motion through stance and reduces the overall work, both positive and negative, of the joint.\textsuperscript{36} AFT also reduces the range of motion at the MTP joint and further reduces its negative work (ie, work that does not directly contribute to forward propulsion) while leaving its positive work unaffected.\textsuperscript{36} The hip and knee joint do not have consistent differential responses to AFT in runners.\textsuperscript{3,36}

With respect to the gross kinetics and spatiotemporal characteristics of runners in AFT, compared with SFT, runners run with similar contact times, but their flight times are longer.\textsuperscript{36} This results in consistently lower step frequencies (and correspondingly longer stride lengths)\textsuperscript{3,4,36} with higher vertical ground reaction forces and impulses during ground contact.\textsuperscript{36} These are indicative of “stiffer” global spring mechanics, which have been linked to superior RE and performance.\textsuperscript{58} Hunter et al\textsuperscript{3} did not observe these increased vertical forces in AFT versus SFT but similarly observed longer strides (and lower step frequencies) with similar ground contact times. This similarly implies longer flight times, exhibited by the significant increase in vertical oscillation of the runners throughout the step cycle. Paradisis et al\textsuperscript{64} did not observe these changes in step frequency and step length but did observe shorter contact times and the aforementioned longer flight times within a step cycle in recreational runners running in AFT at slower speeds.

Biomechanical links to the differential benefits of AFT remain elusive. In the initial study on AFT, rearfoot strikers tended to gain more of an RE benefit from the AFT\textsubscript{NVF} than mid/forefoot strikers (−4.6% vs −3.6%).\textsuperscript{36} However, no subsequent studies have explored this potential differential benefit. Hunter et al\textsuperscript{3} found that ground contact time was inversely related with RE benefits in AFT wherein runners who exhibited shorter ground contact for a given speed tended to gain more of a benefit from the AFT. Aside from these limited observations, no further studies have linked the degree of RE improvement afforded to an individual by AFT to any specific mechanical metric.

Track Spikes

AFT has had 2 unique influences on track racing. Initially, it opened the question of whether AFT road shoes were superior to traditional track spikes for track racing. Many athletes were initially hesitant to use them for racing as commonly reported sensations were that they did not “feel” fast, with athletes being worried about the ability to achieve top sprint speeds at the end of races without spikes. However, Barnes and Kilding\textsuperscript{2} demonstrated that the NVF elicited a 2.6% superior RE to a top distance-racing spike despite being 86 g heavier.\textsuperscript{2} Some athletes also began racing on the track in the road-running AFT prior to the implementation of AFT in track spikes. In 2018, the men’s 10,000 m champions in all 3 National Collegiate Athletics Association Divisions won their races using the AFT\textsubscript{NVF}.

In 2019, the elements of AFT began to appear in competitive track spikes, first introduced by the Nike Dragonfly (AFT\textsubscript{NDF}). Although the beneficial effects of AFT on road racing were clear and their enhancement effects relatively easily demonstrable in a laboratory, the benefits of the spikes are more challenging to quantify.\textsuperscript{59} Because events contested in track spikes occur above the anaerobic threshold, submaximal RE may not be as direct an indicator of performance improvement as it would be for a race such as the marathon or half-marathon. However, changes in submaximal RE have been shown to translate directly to changes in maximal performance occurring above the anaerobic threshold.\textsuperscript{56} As such, we
can expect submaximal RE enhancement in spikes to translate to enhanced performance on the track.

We examined the AFT in track spikes relative to traditional track spikes and road racing AFT, comparing the AFTNDF spike and the Adidas Avanti TYO (AFTAAT spike) with the Nike Zoom Rival (SFTNZR spike) and a variety of AFT shoes. The AFT track spikes elicited RE improvements of 2.1% and 1.8%, respectively, over the SFT track spike. Furthermore, on average, the RE improvement they afforded relative to the SFT track spike was not different than the AFT road-racing shoe. This indicated that the detriment of heavier mass of the shoes was likely offset by the added benefit of its greater cushioning. There was heterogeneity in this response, though, with 7 of 11 subjects showing ≥0.5% RE difference between their best AFT shoe and spike and 3 of 11 ≥1% RE difference, further indicating that different individuals likely benefit more from cushioning, whereas some benefit more from a reduced shoe mass.

Ruiz-Alias et al compared performances in AFT spikes (AFTNDF) and AFT shoes (AFTNVF) over 9- and 3-minute time trials separated by 30 minutes of rest. They observed no difference in the initial 9-minute performance but a small ~1% difference in the subsequent 3-minute performance that favored the AFT shoe over the spike. It is unclear whether these latter differences observed were related to fatigue from the initial “fresh” 9-minute trial or the intensity at which the 3-minute trial was conducted. The lack of consistent differences in the initial 9-minute trial corroborates the population-level similarity in RE response to AFT spikes and shoes described earlier. Furthermore, the heterogeneity observed was similar wherein half the athletes favored the shoes and half favored the spikes, with 10/14 having a >0.5% difference between the 2.

Response Variability

One common element that appears in the discussion of AFT is the relative heterogeneity of individual response to the AFT. Hoogkamer et al observed that among 18 highly trained male subjects, across 3 speeds and with each observation repeated twice, the response of subjects to the weight-matched AFTNVE versus the AFTAAB was 2.0% to 6.1%. Barnes et al observed a similar range in 24 males and females across 4 speeds repeated twice, where the RE difference in the same shoes (non–weight matched) ranged from 1.7% to 7.2%.

The nature and cause of this variability has yet to be understood, but it likely has 2 components that should be considered in its interpretation. First is the inherent within-individual variation in RE measurement in any condition. This variability will always be due to 2 components: biological variability (ie, true within-subject RE variability) and technological variability (ie, variability in RE measurement due to a device’s inherent measurement variability). Hoogkamer et al reported a mean within-subject variation in RE across days for the SFT condition at 14 kph to be 2.7% (1.0%–4.3%), and visual inspection of the individual response plots would suggest that the AFT response elicited similar variability within individuals. Barnes and Kilding reported that their average daily RE variation in subjects was 1.9%. Although these numbers address the methodological variability of measuring RE between days, the literature is still lacking in research addressing the within-day variability of RE measures tested in duplicate, or single trials for that matter. Likewise, it is difficult to critically address the question of between-subject variability in responsiveness (high vs low responders) to AFT without a study that first establishes the variability in the between-day RE benefits of AFT within subjects. Thus, although it is suggested to always measure each footwear condition on the same day and in duplicate, we do not know whether a 3% benefit of AFT in one individual one day might be a 5% benefit on another day in the same individual. The magnitude of this within-subject variability in the responsiveness to AFT is essential to characterize true response variation and to draw conclusions around “high” and “low” responders.

Second, there should be consideration of inherent response variation to footwear, in general. Changing typical features of SFT, such as LBS, can be beneficial for some runners and detrimental for others. Tung et al observed a variation in RE response to barefoot running on a hard surface versus barefoot running on 10 mm of foam cushioning to range from a 1.3% decrement to 5.7% benefit, with an average of 2.1% benefit. This indicates that the cushioning in shoes alone elicits a heterogeneous response similar to that which is typically observed in AFT.

Regulations

When AFT first appeared in competition, the only rule regulating shoe selection was World Athletics’ Technical Rule 143.2: “Athletes may compete barefoot or with footwear on one or both feet. The purpose of shoes for competition is to give protection and stability to the feet and a firm grip on the ground. Such shoes, however, must not be constructed so as to give athletes any unfair assistance or advantage. Any type of shoe used must be reasonably available to all in the spirit of the universality of athletics.” The ambiguity of the rhetoric prevented any sort of action around the Nike Vaporfly or subsequent AFT between 2017 and 2019. In 2019, it was proposed that midsole thickness may be an appropriate and operationally efficient means to regulate the extent to which footwear could provide an advantage to a runner. This conceptually limited the extent to which synthetic material could be added to the biological limb, with a “black box” for innovation and customization within those limitations. This was later the subject of criticism as there had been no evidence demonstrating that midsole thickness itself was beneficial and that there was likely an “optimal” thickness for given materials and constructions. However, the concept of thickness as a regulatory metric was, in part, not that this feature of the shoe alone was necessarily beneficial but that substantially more beneficial shoes would likely be necessarily thick relative to SFT. This simple metric was aimed striking a compromise that allowed for further and continued innovation while limiting the scope of what footwear could potentially add to the athlete and, critically, “future-proofing” against substantial unforeseen developments in materials, architectures, and other potentially enhancing features.

In January of 2020, World Athletics amended their technical rules to regulate racing shoes by their midsole thickness with a further stipulation that the shoe could only contain one rigid structure within. Road racing shoes are limited to 40 mm for an EU size 42 (US M8.5), and track distance racing shoes are limited to 25 mm. The thickness measurement is taken from the heel at 12% the length of the shoe and at the forefoot from 75% the length of the shoe. Shoes that have been reviewed for these requirements are included on a regularly updated list of approved footwear for different track, road, and cross-country events, and it is publicly available for download on the World Athletics website. Although this was an important step in transparency around regulations, there are several challenges with their current implementation. First, the thicknesses defined (eg, 40 mm) are for a single shoe size. The thickness of a shoe scales typically with its size.
size, but the nature of this scaling differs depending on manufacturing and design specifications. Different specifications may allow for relatively thicker or less thick shoes around that specified size. World Athletics notes that these differences may be “marginal,” but that marginality is not quantified, and as such, it would be impossible to enforce the thickness rule on shoes larger or smaller than an EU 42 without fair discretion. Furthermore, the new regulations allow for prototype shoes, which may not be made in uniform size runs. So if a noncommercially available shoe is “approved” as an EU 42, the manufacturer may be free to customize the thickness of the shoe outside of that without an operational definition of how thickness should scale with size. Second, the points of measurement may not reflect the true maximum sole thickness. As shoes evolve more extreme “rocker” shapes, the midfoot of the shoe may become the thickest point of the shoe. We have measured the thicknesses of many models of AFT, and the Nike Alphally is unique in that its thickest point (measured from the ground to the top of the inner sole) is at the midfoot of the shoe. A simple solution would be to take the measurement as the thickest point on the longitudinal axis of the shoe or within a specified range rather than a discrete point. Finally, the regulations around rigid structures are likely unnecessary and already contradictory with approved footwear. For example, the “rigid structure” within the Adidas Adizero Adios Pro (“energy rods”) exists in multiple planes—example, it is both curved (multiple horizontal planes) and converging toward the midfoot and heel (multiple mediolateral

Table 1 Suggested research questions

<table>
<thead>
<tr>
<th>Pertinent research questions</th>
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<tr>
<td>AFT characteristics</td>
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<tr>
<td>- Do SFT shoes with AFT foams but without plates confer a benefit?</td>
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<td>- What are the polymers and material properties of non-PEBA advanced foams?</td>
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<td>- Does the degree of plate curvature beneath the MTP joint affect RE enhancement?</td>
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<td>- Do AFT benefits change with shoe age?</td>
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<td>- Do AFT shoes age differently than SFT?</td>
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<td>- What are the energetically optimal thicknesses of current AFT?</td>
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<td>- Do different embedded architectural constructions or novel foams mediate an optimal thickness?</td>
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<td>AFT response</td>
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<td>- Does outdoor running confer a different efficiency advantage than treadmill running?</td>
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<td>- How does intraindividual AFT response variance compare with intraindividual variance in SFT?</td>
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<td>Biomechanics</td>
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<td>- Does body mass mediate response?</td>
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<td>- Does foot strike mediate response?</td>
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<td>- Does duty factor mediate response?</td>
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<tr>
<td>- Do local muscle and joint functional movement characteristics (ie, strength and/or mobility at the ankle or MTP joint) mediate response?</td>
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<td>Fatigue</td>
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<tr>
<td>- Does response to AFT change with fatigue?</td>
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<td>- Does AFT mitigate muscle damage?</td>
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<td>Adaptation</td>
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<tr>
<td>- Do the RE benefits change over time with habitual AFT use?</td>
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<tr>
<td>- Do an individual’s biomechanical characteristics change in AFT and/or SFT over time with AFT use?</td>
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<tr>
<td>- Do local muscle and joint functional movement characteristics change over time with AFT use?</td>
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<tr>
<td>Populations</td>
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<td>- Do older runners have a differential response?</td>
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<td>- Do youth runners have a differential response?</td>
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<tr>
<td>- Do youth runners have a differential response after prolonged periods of training in AFT?</td>
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Suggested research practices

- Ensure subjects are fasted for minimally 2 h prior to trials (3 is better if feasible).
- Use repeated measures (minimally 2 trials) on shoe conditions.
- Randomize shoe conditions.
- Use a neutral, widely available control SFT (eg, Asics Hyper Speed).
- Use a tachometer to enforce precise belt speed for treadmill trials.
- Use a very stiff treadmill if possible.
- Use trials lasting a minimum of 4 min.
- Have a maximum of 8 trials in 1 session (ie, 4 conditions if repeating within the session; 8 conditions if repeating across multiple sessions).
- Minimize and standardize downtime between trials (eg, at most the duration of the trial).
- Have subjects drink ~100 mL of water between trials to maintain hydration status throughout.
- Average gas exchange data over the final 1.5–2.0 min of each trial.
- Verify that the individual remains below their second lactate threshold via blood lactate measurement or respiratory exchange ratio monitoring (<1.0).
- Report within-subject and between-subjects variation metrics.
- For determination of midsole stiffness/compliance and resilience, use uniaxial vertical compressive testing.
- For materials testing, use cycle times similar to the in vivo loading of the shoe’s region.
- For materials testing, use loads that correspond to stresses that simulate the in vivo loading of the midsole (ie, 200–400 kPa).
- For materials testing, report stresses and/or the contact area of loading fixtures.

Abbreviations: AFT, advanced footwear technology; PEBA, polyether block amide; MTP, metatarsophalangeal; RE, running economy; SFT, simple footwear technology.
planes). The Nike Alphafly contains more than one distinct rigid element, as it has its carbon fiber plate as well as rigid structural elements above and below the air units. With a midsole thickness regulation already in place limiting the geometric space for substantially advanced architecture, this element of the regulations may be an unnecessary addition to the rules and one that may be challenging to enforce.

Although World Athletics uses these rules for international competition under its jurisdiction, other member federations and nonmember federations are free to set their own rules. Many have simply adopted these regulations, with some notable exceptions. In the United States, the major junior-level sports federations—the National High School Athletics Association and the National Collegiate Athletics Association—have not adopted any footwear regulations. As such, athletes are free to compete in any footwear. The notable consequence of this is the prevalence of distance runners on the track using AFT road-racing shoes at the high school and collegiate levels.

**Practical Applications**

A list of salient research questions and a compilation of best practices around footwear investigation are provided for researchers in Table 1. For the price-insensitive runner looking to purchase AFT with access to a metabolic testing facility (ie, a lab with a treadmill and a metabolic cart), we would recommend acquiring several models of AFT (3–4 models for a single testing session, 6–8 if able to do 2 testing sessions) and following the suggested research practices (Table 1). For the runner without access to a metabolic testing facility, the algorithm is quite simple: Look for AFT from manufacturers that publicly state that the shoe uses PEBA foam and ensure that the shoe has a rigid plate (or similar longitudinal element) embedded within with some curvature beneath the MTP joint. Furthermore, if performance is a critical concern, make sure the shoe is light relative to other footwear (eg, 170–210 g for a US M9). Finally, in AFT, unlike SFT, comfort may not be a strong indicator of RE enhancement. The authors have observed this phenomenon in their own testing, as well as through personal communications with other laboratories conducting AFT research, wherein a subject’s perceived “best” shoe is not a strong predictor of the shoe that is actually the most economical. However, a shoe with all of these ingredients—PEBA foam or similar, embedded rigid longitudinal architecture, and a low mass—will likely be quite beneficial for most runners, and the difference between AFT models with all of these ingredients will likely be small compared with the difference relative to SFT.

**Conclusions**

Advanced footwear technology (AFT) has changed running as both a sport and a recreational activity. Although we do know a fair amount about its gross characteristics and the changes it confers in runners, we know enough to know that we do not know even more. We know the “first-order” benefit of AFT—that it facilitates more economical and faster running—but we do not yet understand the “second-order” implications of AFT—for training, adaptation, fatigue, injury, and so on. We know the nature of ingredients in isolation—more resilient and more compliant foams from new thermoplastics made with advanced manufacturing techniques coupled with stiff, embedded longitudinal pieces with some curvature beneath the metatarsophalangeal (MTP) joint—but we do not yet know the relative contributions of each and the mechanism behind their apparent interaction. We know that there is some variability in how runners respond to AFT, but we do not yet know what features of the footwear are best suited to different individuals. Understanding the features of AFT that mediate a runner’s response and the features of runners that mediate that response are the 2 critical areas to unravel to begin better tailoring and choosing AFT.

It is obvious that the “postmodern” era of running is different—it is more efficient and faster—and it is clear that the ingredients within the complex of AFT at least partially confer their benefit through enhancing energy storage and return through the runner’s step cycle. But beneath these initial observations and understandings—burning a few fewer calories per kilometer and going a bit faster using better materials—the mechanisms and implications underfoot of how we interact with this new equipment under our feet must still be untangled to know more fully where we are at and where we are going.

**References**


