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LEADING ARTICLE

Can We Quantify the Benefits of "Super Spikes" in Track Running?

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Abstract

The recent and rapid developments in track spike innovation have been followed by a wave of record-breaking times and top performances. This has led many to question what role "super spikes" play in improving running performance. To date, the specific contributions of new innovations in footwear, including lightweight, resilient, and compliant midsole foam, altered geometry, and increased longitudinal bending stiffness, to track running performance are unknown. Based on current literature, we speculate about what advantages these features provide. Importantly, the effects of super spikes will vary based on several factors including the event (e.g., 100 m vs. 10,000 m) and the characteristics of the athlete wearing them. Further confounding our understanding of super spikes is the difficulty of testing them. Unlike marathon shoes, testing track spikes comes with a unique challenge of quantifying the metabolic energy demands of middle-distance running events, which are partly anaerobic. Quantifying the exact benefits from super spikes is difficult and we may need to rely on comparison of track performances pre- and post- the introduction of super spikes.

Key Points

New "super spikes" which use lightweight, compliant, and resilient foam, and often a carbon fiber plate, are thought to provide advantages over traditional track spikes.

In theory, these new technologies will result in mechanical advantages, such as improved energy return or increased ankle push off moments; however, these advantages are likely subject and event specific.

Testing track spikes comes with a unique set of challenges, including quantifying the metabolic energy demands of middle-distance running and limiting fatigue during testing, and therefore it is unlikely we will be able to put an exact number on the benefits from super spikes.

1 Introduction

Between the summers of 2020 and 2021, new world records have been set in various middle-distance and long-distance events, including the 1500 m indoor track event, and 5000 and 10,000 m outdoor track events for both men and women [1]. Similarly, outstanding performances have been set in middle-distance events by US high school and college athletes [2]. Notably, there are several potential explanations for these improved race times, such as pace-light technology, new track surface technology, and long durations of uninterrupted training during the COVID-19 pandemic. However, perhaps the most glaring change on the track is the evolution of spikes that athletes are wearing on their feet. This new generation of track spikes have become known as "super spikes."

In the past, spikes (i.e., track shoes with spikes on the bottom) served the primary purpose of providing grip while being as light as possible. They used a relatively simple design: a lightweight, snug upper and a plastic spike plate with little to no midsole sandwiched in between. Interestingly, this is not the first time that spike technology has been a topic of debate. In 1968, PUMA's brush shoe (Fig. 1), which employed 68 micro spikes, as opposed to the conventional four or six pins, were banned [3]. In recent years, ultra-lightweight, compliant, and resilient foams have emerged, providing cushion without sacrificing weight or dissipating a lot of energy. Adding this

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new, more substantial layer of foam allows for an embedded stiff plate, and in some cases, an increased rocker geometry. For the purpose of this perspective, we adopt the popular terminology “super spikes” to refer to modern spikes that combine lightweight, compliant, resilient foams (and air pods) with a stiff (nylon/PEBA/carbon-fiber), often curved, plate (see Fig. 1 for examples). This combination has been speculated to be the reason for the recent increases in track running performance [2, 4]. In turn, this raises the question to what extent these improvements are related to the athletes’ footwear, and by how much these super spikes improve performance [2, 5]. The short answer to these questions is that we do not know, and it might be difficult to ever find out; however, in this article we discuss what we currently know about the super spikes, and current limitations to testing them.

The current super spike discussions closely mirror the recent discussions around marathon racing shoes. In 2017, the Nike Vaporfly 4% sparked debate introducing the now familiar combination of lightweight, compliant, and resilient midsole foam and a stiff plate. The shoe was found to improve running economy compared to top marathon racing shoes by 4% on average in 18 men running 5-min trials at 14, 16, and 18 km/h [6]. This was later confirmed for 12 men and 12 women at 14, 16, and 18 km/h and 14, 15, and 16 km/h, respectively [7]. Wearing successor models of the Vaporfly, Eliud Kipchoge and Bridget Kosgei broke the marathon world records and Kipchoge ran the first sub-2-h marathon. In the years after their introduction, annual top 20, top 50, and top 100 men’s and women’s marathon times have been up to 2.0% and 2.6% faster than before, respectively [6, 7].

Importantly, the reported 4% metabolic energy savings should not be expected to result in 4% faster marathon times. Hoogkamer et al. [8] showed that changes in aerobic energy demand due to changes in shoe mass, result in faster times, even for a 3 km time trial, where an anaerobic component can be expected. However, because of the inherent curvilinearity of the metabolic rate—running velocity relation and the additional curvilinear cost of overcoming air resistance, observed metabolic savings can be expected to result in smaller time savings. This effect is velocity dependent and at elite marathon pace, time savings can be expected to be about two-thirds of the metabolic savings [9].

By now, almost all brands have their own marathon shoe that combines a modern, lightweight, resilient foam with a stiff plate, and the governing body, World Athletics, has updated their footwear regulations by limiting stack height (midsole + outsole thickness) to 40 mm and allowing only “one rigid plate or blade made from carbon fibre or another material with similar properties or producing similar effects” [10]. In the meantime, the “footwear arms race” [11] has

Fig. 1 Historical spikes from 1968 (**A**) and 2021 “super spikes” for a range of distances (**B–F**). **A** PUMA brush spikes (the Tahoe) have 68 needle-like spikes and were banned from competition in 1968. **B** Nike Air Zoom Victory, which combines a top loaded carbon fiber plate with ZoomX foam made with PEBA (polyether block amide) and an air unit under the forefoot. **C** Nike ZoomX Dragonfly which combines a PEBA plate with ZoomX foam; the plate is embedded at the heel and transitions to the spike plate under the forefoot. **D** New Balance FuelCell SD-X, which combines a bottom loaded carbon fiber plate with FuelCell foam made with nitrogen infused TPU (thermoplastic polyurethane) on top. **E** Adidas adizero Avanti 2021 track spike with ‘Lightstrike Pro’ foam, and glass fiber energy rods in the forefoot. **F** PUMA evoSPEED Distance Nitro Elite + with Nitro foam made with nitrogen infused EVA and an embedded full-length carbon fiber plate

shifted from the road to the track [5]. In contrast to super shoes, no published scientific data on the benefits of super spikes over traditional spikes are available. Whereas previous studies have compared running economy of aerobic efforts in traditional spikes versus marathon racers [12–16], and others have looked at the effect of increased longitudinal bending stiffness on sprint performance [12–14], research into the benefits of spikes on middle distance performance is lacking and the benefits of super spikes specifically at any distance have yet to be explored. Here we discuss potential reasons for this knowledge gap and provide context on what to expect in the future.

2 Potential Mechanisms for Spike Performance Improvements

Track running events range from 60 to 10,000 m, and traditionally spikes are worn for all track races. While some of the mechanisms that create successful marathon shoes can be translated into track spikes, several key differences must be considered, between road and track, as well as between distance and sprint events.

Sprint performance is determined by acceleration and top speed [17], which depend on how much propulsive horizontal ground reaction force can be produced at a specific running velocity [18], i.e. the individual athlete's force–velocity profile [19]. Interestingly, footwear longitudinal bending stiffness can shift muscle force–velocity behavior [20–22].

In contrast to sprinting, in events that are highly aerobic, such as the 10,000 m and marathon, performance mainly depends on the rate of metabolic energy consumption, i.e., running economy. Various footwear properties such as mass, cushioning, and longitudinal bending stiffness have repeatedly been shown to affect running economy [23–28]. Other factors determining distance running performance include maximum oxygen uptake ($\dot{V}O_2$max), the fraction of $\dot{V}O_2$max that can be sustained throughout the duration of the race [29], and the finite amount of energy that can be expended above critical speed (i.e., the anaerobic work capacity) [30], but these seem independent of footwear.

To improve performance, spikes should allow an athlete to run faster by increasing their acceleration, their top speed, and/or improving their running economy. The biomechanical and energetic demands of each track event vary based on the distance, thereby creating a need to modify spikes to optimize them for different distances.

2.1 Bending Stiffness

Longitudinal bending stiffness is a key consideration for both marathon shoes and track spikes. Although sprint spikes have been stiffened with carbon fiber plates for more than 20 years, the exact effect of increased longitudinal bending stiffness on sprinting performance is still not well understood.

One benefit of increased bending stiffness is decreasing the amount of energy lost at the metatarsal-phalangeal (MTP) joint. While running and sprinting, the MTP joint dorsiflexes during stance phase, absorbing mechanical energy, and remains dorsiflexed throughout the majority of the push-off, returning little of that energy. On average, energy loss at the MTP joint has been reported to be ~ 48 J during sprinting at 7.1–8.4 m/s and 13–21 J during running at 4.0–4.4 m/s [31, 32]. Stiffening the sole will limit MTP dorsiflexion, and, in turn, limit the amount of energy lost. Along with altering MTP mechanics, increasing longitudinal bending stiffness shifts the point of force application more anteriorly, creating a larger moment arm at the ankle. Moreover, the change in moment arm might offer the potential to improve the effectiveness of horizontal force application, thereby improving sprint performance, as suggested by Willwacher et al. [14]. However, increasing the bending stiffness will increase force demands from the plantar flexor muscles, which can be detrimental for performance [33].

Stefanyshyn and Fusco [12] found that, on average, when a plate with a stiffness of 42 N/mm was added to a participant's spikes, participants improved their 20 m sprint time (after a 20 m acceleration). Interestingly, further increasing plate stiffness to 90 N/mm and 120 N/mm did not improve average performance compared to the control spikes, although not all individuals responded the same. It should be noted that significance in this study was set at $p < 0.1$, compared to the traditional $p < 0.05$. Smith et al. [13] timed 40 m sprints from a standing start in shoes with different stiffnesses. They reported that on a group level, increasing bending stiffness did not improve sprint times; however, on an individual level, some athletes improved with increased stiffness. It should be noted that a number of studies report results from responders, even when no changes were observed at the group level. Readers should be cautious when interpreting such responder results since even with a sham intervention, random measurement errors will suggest improvements in some individuals (and deteriorations in others). Just assessing the responder group may lead to false conclusions about the intervention. When assessing the acceleration phase of sprinting, Ding et al. [15] found no improvements in laser-measured sprint speeds at 5, 10, 15, and 20 m or in ground reaction force impulses during a sprint start out of starting blocks with increased bending stiffness. Similarly, Nagahara et al. [16] did not observe any differences in 0–30 m, 30–60 m, and 0–60 m times out of starting blocks with increased bending stiffness. Willwacher et al. [14] observed reduced acceleration performance (defined as the average horizontal center of mass power, i.e., the amount of change of horizontal kinetic energy divided by the time needed for that change) with increased longitudinal bending stiffness. Similar to the studies observing performance improvement at the group level, these studies assessing acceleration performance found individuals responded differently to different stiffness conditions. In fact, Nagahara et al. [16] found that toe flexor strength, "ankle continuous rebound jump" performance, and body mass were related to benefits from stiffer spikes. Further, Willwacher et al. [14] found that depending on plantar flexor strength, participants used a different strategy to overcome the increased ankle joint moment demands. Stronger participants were able to increase their ankle joint moment and keep ground contact time similar, whereas weaker participants kept their ankle joint moment the same but increased their ground contact time. This suggests that optimal bending stiffness, and how much an athlete can benefit from increased bending stiffness (if at all), is subject/strength specific.

Higher plantar flexor force production demands without longer contact times or slower shortening velocities, can be expected to come at a higher metabolic energy cost [34, 35]. Metabolic energy demands (i.e., running economy) are generally only considered for distance running performance, since sprint performance is mainly determined by acceleration and top speed; however, increased metabolic energy demands will affect how long one can run at top speed. So, both the athlete's plantar flexor strength and duration that they can maintain that strength must be taken into consideration in relation to their specific race distance.

2.2 Midsole Foam

Traditionally, track spikes have had a very minimal midsole thickness. While thicker midsoles provide more cushioning, conventional midsole foams are relatively heavy and a substantial part of the mechanical energy that is absorbed is not returned. For a long time, this trade-off resulted in sacrificing cushioning to minimize mass and mechanical energy dissipation during each landing. Modern foams are so lightweight that they allow for optimization of cushioning, energy return, and comfort, without adding much mass, a factor that has been shown to decrease performance [8]. Currently, World Athletics rules limit midsole thickness to 20 mm for track events shorter than 800 m, and 25 mm for events 800 m and longer [10].

The beneficial effect of cushioning on running economy is well documented. In steady-state running, shoe midsoles with embedded air units have been shown to improve running economy by 2.8% [36], and compliant EVA (ethylene–vinyl acetate) has been shown to significantly improve running economy over a stiff EVA [37]. Tung et al. [38] showed that running on a compliant EVA foam improves running economy by ~ 1.6% as compared to running on a rigid treadmill deck. While the metabolic cost of cushioning hypothesis [37, 38] suggests that these running economy benefits are related to midsole compliance properties, midsole resiliency cannot be ignored. For a long time, more compliant, soft midsoles were considered too soft and not "responsive" enough for track running, but recent technology has drastically changed the properties of foams to provide a much higher energy return. For example, conventional EVA foam returns less than 70% [24], whereas new PEBA (polyether block amide) foam can return beyond 85% [23]. Combining these new foams with even higher energy return technology, such as air pods, can be expected to improve running economy and performance even further. While the spring function of the foam has been argued to be the major factor for the observed running economy improvements in the Vaporfly shoes [23, 32, 39], it has not yet been quantified for spikes. However, already in 1978, McMahon and Greene [40] showed that a compliant, resilient track surface, which was specifically tuned to running, improved race times by an average of 2.9% over a college track season. Lastly, another added benefit of foam is increased comfort. Again, this is likely not fully independent from the metabolic cost of cushioning hypothesis. Reports have been mixed about the effect of comfort on metabolic cost [41, 42]. While some authors have suggested that improved comfort improves metabolic cost, a number of confounding factors such as shoe construction were not controlled. Nevertheless, until recently comfort has typically been sacrificed to minimize metabolic penalties of added mass.

The classic track compliance studies from McMahon and Greene [40, 43] also explain that while a more compliant foot–ground interaction results in a longer ground contact time, it does not necessarily reduce top speed. In sprinting, reduced ground contact time has been linked to increased performance [19]. However, the longer ground contact time from more compliant foot–ground interaction is accompanied by a longer "step length," i.e., the distance covered during ground contact [43]. For very compliant surfaces, this resulted in reduced maximal running speeds, but "a range of track stiffness was discovered which actually enhances speed" [43]. This suggests that a similar range of stiffness exists for midsole foam. Further, increased ground contact times allow the muscle more time to produce force [44]. Therefore, elongating contact time can decrease metabolic cost, or allow the runner to produce more force (through a favorable shift on the force–velocity curve [20]) and thereby increasing their speed.

2.3 Geometry

The addition of midsole foam has allowed for changes to spike geometry, namely, an increased stack height and increased forefoot rocker (the radius of the outsole at the forefoot [45]). Increased stack heights have mainly been seen in middle distance spikes, rather than sprint spikes, as faster speeds typically have less pronounced heel strikes, and therefore do not benefit from increased cushioning from foam in the heel area. It is possible that middle distance runners will adopt more of a heel strike now that spikes have added improved heel cushioning. It should be noted that while stack height in these super spikes is often higher, it is limited partially due to regulations of 20 mm for track events shorter than 800 m, and 25 mm for events 800 m and longer [10]. With regards to rockers, the exact effect they have on running performance has not been quantified. Nigg et al. [46] have suggested that the majority of metabolic savings in Vaporfly shoes come from a so-called teeter-totter effect, but this mechanism has not been fully defined or experimentally verified. Regardless, a rocker can be expected to improve the midfoot to toe off transition ("ride") and combined with the right bending stiffness, reduce ankle plantar flexion moments (and associated plantar flexion muscle force demands) [47, 48].

2.4 Variability (One Size Does Not Fit All)

It is worth considering that track spikes may not have a "one size fits all" optimal solution. Willwacher et al. [14] found that an optimal shoe bending stiffness may be based on an athlete's plantar flexor strength, while Nagahara et al. [16] related performance improvement with stiffer spikes to toe flexor strength, jump performance, and body mass. Other considerations such as foot size, leg length, running pattern, and event-specific speed may also influence the optimal bending stiffness, midsole foam properties, and geometry for a specific athlete.

This inter-individual variability, combined with distance-specificity and the limited market for track spikes (as compared to marathon shoes), partly explains why no studies on super spikes have been published. For a running shoe company, it is more important to optimize their spikes for their elite athletes than to investigate how well they perform on average in a group of high-caliber runners. So, larger scale controlled studies such as those on marathon super shoes [23, 49–51] might never be performed for super spikes (irrespective of the challenges of quantifying footwear benefits at middle-distance racing speeds, as discussed below).

3 Quantifying the Effects of Super Spikes on Performance

Conceptually, there seem to be two successful approaches to quantify the effects of footwear on performance on either end of the sprint-marathon spectrum: (1) quantify speed outcomes (acceleration and/or top speed) for all-out efforts, or (2) quantify effort related outcomes (running economy) at a controlled running speed. These outcomes can all be quantified fairly easily in controlled experimental conditions. Quantifying acceleration and top speed each require short-duration, high-intensity trials. Therefore, with enough recovery time in-between, they can be repeated at the same intensity without decreases in performance outcomes [52]. Running economy experiments involve longer duration trials (usually 5 min) at a sustainable, aerobic, steady-state intensity. Calculating the rate of metabolic energy expenditure from oxygen uptake and carbon dioxide production rates is only valid at aerobic intensities and several trials can be performed without introducing fatigue. This allows researchers to assess the effects of different footwear conditions within a single visit, which eliminates day-to-day variability related to the participants' physiology, measurement equipment, or other environmental factors [53]. For road shoes, running speed during economy tests can easily be controlled by using a treadmill; however, for spikes one needs a specific treadmill that allows for spike running (e.g. [49]). Alternatively, track running can be paced using spaced cones and a metronome [54] or with modern pace light technology [55]. Although a 5-min running economy trial is drastically shorter than the duration of a marathon, changes in running economy have been shown to translate into changes in 3 km time-trial performance [8].

Spikes that are intended to improve acceleration and/or top speed can most easily be studied. The major challenge comes with spikes that are intended to make running less metabolically costly at race speed. Anticipating that metabolic benefits are speed-specific, related to biomechanical differences between speeds, it is important to realize that traditional aerobic running economy measurements will not be valid at race speed (except for maybe the 10,000 m). Athletes run track events at an intensity above their aerobic, steady-state capacity [56–58], and therefore aerobic running economy values do not capture the full energetic demand. The anaerobic metabolic energy contribution is hard to quantify accurately and reliably [59, 60], which makes these distances inherently harder to study. While some have tried to quantify the total metabolic energy demand (aerobic and anerobic metabolic energy) by taking into account blood lactate concentrations [61, 62], that approach is outdated and ignores the fact that blood lactate concentrations result from the difference in lactate production and lactate utilization [60, 63]. This is true irrespective of whether researchers attempt to convert blood lactate concentration to metabolic energy or use it as an intensity outcome by itself. Furthermore, a rise in blood lactate concentration indicates non-steady-state metabolic energetics that makes comparisons between successively performed trials confounded.

Even if metabolic benefits can validly be quantified for track events, we still will not know how much of a specific performance improvement should be attributed to footwear. For the Vaporfly, the metabolic savings were 4%, but the time savings are smaller [6–9]. The exact time savings depend on running velocity, the runner's individual metabolic savings from the shoes at that velocity, and their individual metabolic rate—velocity relation (including their individual efficiency to overcome air resistance [64]). Therefore, in the case of marathon shoes, while we have a number for the average metabolic savings across 18 high-caliber male runners over a range of speeds (~3 h to ~2:20 h marathon pace) in one specific model (i.e. Vaporfly 4%), without additional personal metabolic data, one cannot know precisely how much of a performance improvement was due to footwear [65].

With all the current hurdles of metabolic benefits quantification and conversion at middle-distance race speed, an approach more similar to studies on top speed might be more relevant. Studies assessing the effects of an intervention on time-trial performance often schedule time-trials a week apart, at the same time of day [8, 66], and, theoretically, time trials have a substantial effect on the athletes training load. Together this makes it harder to recruit high-caliber athletes, specifically when comparing more than two conditions [67]. Further, day-to-day variability in performance readiness will make it challenging to correlate individual improvements in time-trial performance from super spikes to an athlete's individual characteristics, such as their race speed, body mass or plantar flexor strength.

4 Conclusion

Rather than relying on lab-measured predictors of track running performance, we might just need to rely on comparison of track performances pre and post the introduction of super spikes, or, at the individual level, changes in an athlete's training or race times. In several years, we can expect performance analyses into the historical development of annual top 20 and top 50 performances, similar to those currently being published for marathon super shoes [6, 7]. Until then, we need to be careful with attributing new world records (at least partly) to footwear innovation. For example, when considering the 400 m hurdle world records of Sydney McLaughlin and Karsten Warholm, the long-term performance trajectories of these athletes cannot be ignored. Further, confounding effects of COVID-19 measures on training focus, of 2021 being an Olympic year, and of pace light technology [55] should be accounted for in these historical analyses.

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