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, 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 mechanical advantages these features may provide. Importantly, the effects of super spikes will vary based on several factors including the event-specific speed (i.e. 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 mid-distance running events, which are partly anaerobic. For this reason, putting an exact number on the benefits from super spikes is difficult.

1. INTRODUCTION

Between the summers of 2020 and 2021, new world records have been set in various middle distance and distance events, including the women's 1500 m indoor track event, and the men's and women's 5,000 and 10,000 m outdoor track events. Similarly, outstanding performances have been set in middle-distance events by US high school and college athletes [1]. Most of these performances have something in common: the athletes were wearing shoes that have come to be 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 utilized 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 (Figure 1), which employed 68 micro spikes, as opposed to the conventional 4 or 6 pins, were banned [2]. In recent years, ultra-lightweight, compliant, and resilient foams have emerged, providing cushion without sacrificing weight or dissipating a lot of energy. Adding this 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) plate (see Figure 1 for examples). This combination has been speculated to be the reason for the recent increases in track running performance [1,3]. In turn, many wonder to what extent these improvements are related to the athletes' footwear, and by how much these super spikes improve performance. The short answer to these questions is that we do not know, and that we might never know exactly.

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 by 4% on average, compared to top marathon racing shoes [4,5]. Wearing successor models of the Vaporfly, Eliud Kipchoge and Bridget Kosgei broke the marathon world records and Kipchoge ran the first sub-2-hour 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 3km time trial, where an anaerobic component can be expected. Further, 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].

Figure 1. 1968 historical spikes (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.

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 40mm 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 shifted from the road to the track [12]. In contrast to super shoes, no published scientific data on the benefits of super spikes over traditional spikes are available. While previous studies have compared running economy of aerobic efforts in traditional spikes vs. marathon racers [5,13], and others have looked at the effect of increased longitudinal bending stiffness on sprint performance [14–16], 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 m 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, both 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].

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 or running economy. Various footwear properties such as mass, cushioning and longitudinal bending stiffness have repeatedly been shown to affect running economy [4,21–25].

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 push-off, returning little of that energy. On average, energy loss at the MTP joint has been reported to be ~48 J during sprinting and ~21 J during running [26]. 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 a potential to improve the effectiveness of horizontal force application, thereby improving sprint performance as suggested by Willwacher et al. [16]. However, increasing the bending stiffness will increase force demands from the plantar flexor muscles, which can be detrimental for performance.

Stefanyshyn and Fusco [14] 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. Similarly, Smith et al. [15] 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 performance, however, on an individual level, some athletes improved with increased stiffness. When assessing the acceleration phase of sprinting, Ding et al. [27] and Nagahara et al. [28] found no performance improvements with increased bending stiffness and Willwacher et al. [16] observed reduced acceleration performance 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. [28] found that toe flexor strength, 'ankle continuous rebound jump' performance, and body mass were related to benefits from stiffer spikes. Further, Willwacher et al. [16] 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, while 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.

Irrespective of an athlete's calf strength, higher plantar flexor force production demands can be expected to come at a higher metabolic energy cost. Metabolic energy demands (i.e. running economy) determine distance running performance, and while sprint performance is mainly determined by acceleration and top speed, 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 which has been shown to decrease performance [8].

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% [29], and compliant EVA (Ethylene-Vinyl Acetate) has been shown to significantly improve running economy over a stiff EVA [30]. Tung et al. [31] 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 [30,31] 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% [21], whereas new PEBA (polyether block amide) foam can return beyond 85% [4]. 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 [4,32,33], it has not yet been quantified for spikes. However, already in 1978, McMahon and Greene [34] showed that a compliant, resilient track surface, that 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. Comfort might be a factor in the longer track events (5,000 and 10,000m) to reduce the metabolic cost of running [35,36], but until recently has typically been sacrificed to minimize metabolic penalties of added mass.

The classic track compliance studies from McMahon and Greene [34,37] 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 (Morin et al. 2012). 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 [37]. For very compliant surfaces, this resulted in reduced maximal running speeds, but “a range of track stiffness was discovered which actually enhances speed” [37]. This suggests that a similar range of stiffness exists for midsole foam.

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 [38]). 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 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. [39] 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 and combined with the right bending stiffness, reduce ankle plantar flexion moments (and associated plantar flexion muscle force demands) [40].

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. [16] found that an optimal shoe bending stiffness may be based on an athlete’s plantar flexor strength,

while Nagahara et al. [28] 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. In fact, many brands do provide their top-level athletes with customized spikes that differ from the generic, commercially available spikes.

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 [4,5,41,42] 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 [43]. Running economy experiments involve longer duration trials (usually 5-minute) 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 [44]. 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. [5]). Alternatively, track running can be paced using spaced cones and a metronome [13] or with modern pace light technology [45].

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 [46–48], 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 [49,50], which makes these distances inherently harder to study. While some have tried to

quantify the total metabolic energy demand (aerobic and anaerobic metabolic energy) by taking into account blood lactate concentrations [51,52], but that approach is outdated and ignores the fact that blood lactate concentrations result from the difference in lactate production and lactate utilization [50,53]. This is true irrespective of whether researchers attempt to convert blood lactate concentration to metabolic energy or use it as an intensity outcome itself. Furthermore, a rise in blood lactate concentration indicates non-steady-state metabolic energetics which makes comparisons between successively performed trials confounding.

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 [54]). 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 (~3hr - ~2:20hr 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 [55].

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, on the same time of day [8,56] and 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 2 conditions [57]. Further, while significant effects might be observed at a group level, day to day variability in performance readiness will make it challenging to relate 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

In the end, we might just need to rely on an unbiased 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 anecdotal evidence. It is tempting to attribute any new world record (at least partly) to footwear innovation, but the long-term performance trajectories of, for example, Sydney McLaughlin and Karsten Warholm, cannot be ignored. Further, confounding effects of COVID-19 measures on training focus, of 2021 being an Olympic year, and of pace light technology [45] should be accounted for in these historical analyses.

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