# Advancements in running shoe technology and their effects on running economy and performance – A Current Concepts overview

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Tweet: Technology-advanced shoes are a controversial topic. This Current Concepts paper provides a brief overview on the topic of "super shoes" and "super spikes"

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# Advancements in running shoe technology and their effects on running economy and performance – A Current Concepts overview

Advancements in running shoe technology over the last five years have sparked controversy in athletics as linked with clear running economy and performance enhancements. Early debates mainly surrounded "super shoes" in long-distance running; but in the past year, the controversy has filtered through to sprint and middle-distance running with the emergence of "super spikes". This Current Concepts paper provides a brief overview on the controversial topic of super shoes and super spikes.

The defining features of technologically-advanced shoes are a stiff plate embedded within the midsole, curved plate and midsole geometry, and lightweight, resilient, high-energy returning foam that – in combination – enhance running performance. Since the launch of the first commercially-available super shoe, all world records from the 5 km to the marathon have been broken by athletes wearing super shoes or super spikes, with a similar trend observed in middle-distance running. The improvements in super shoes are around 4% for running economy and 2% for performance, and speculatively around 1 to 1.5% for super spikes. These enhancements are believed multifactorial in nature and difficult to parse, although involve longitudinal bending stiffness, the "teeter-totter effect", the high-energy return properties of the midsole material, enhanced stack height, and lightweight characteristic of shoes.

Keywords: athletics; footwear; review; endurance; sprint.

## Introduction

Advancements in running shoe technology over the last five years have sparked controversy amongst athletes (Gijy, 2021; Ingle, 2021; Kelly, 2021) and sport scientists (Burns & Tam, 2020; Frederick, 2020; Hoogkamer, 2020; Muniz-Pardos et al., 2021). Although there is no academic or consensus definition for the “super shoe”, the defining features include a stiff plate, curved plate and midsole geometry, and lightweight resilient high-energy returning foam that, together, enhance running performance. The early super shoe controversy surrounded long-distance running; but in the last year, the emergence of “super spikes” has seen the controversy filter through to sprint and middle-distance running (Bachman, 2021; Healey et al., 2022; Kelly, 2021). Although running economy and performance enhancements in technology-advanced shoes are believed multifactorial (Burns & Tam, 2020; Nigg et al., 2020) and likely result from the interaction between the shoe features themselves (Healey et al., 2022) and the shoe features and individual athlete (Hébert-Losier et al., 2020), there is scientific debate regarding the relative contribution of the various super shoe features on performance. Nigg et al. (2020; 2021) propose the primary shoe feature underlying performance enhancements in long-distance running is the “teeter-totter effect” resulting from the plate stiffness and curvature of the plate and forefoot region, although there is no experimental data to directly support the teeter-totter effect. On the other hand, Hoogkamer et al. (2018) advance the foam’s high-energy returning properties as the key contributor to running performance enhancement in super shoes.

In 2016, the three medallists of the men’s Rio Olympic marathon road race were reportedly wearing a curved carbon fibre plate prototype shoe with novel high-energy return Pebax® (polyester block amide) foam designed by Nike Inc. (Burfoot, 2020), as was the gold medallist of the women's marathon (Hill, 2021). This prototype was the precursor to the commercially available Nike Vaporfly 4%. The emergence of super shoes is perhaps more widely associated with Eliud Kipchoge's attempts to break 2 hours on the marathon distance. In 2017, Eliud Kipchoge wore a prototype of the Nike Vaporfly Elite during the Breaking2 event, which he completed in 2:00:25 (h:min:sec). In 2019 during the INEOS 1:59 Challenge, Eliud Kipchoge wore a prototype of the Nike Alphafly Next% and achieved his goal of running the marathon distance under 2 hours, completing the event in 1:59:40 (h:min:sec), a feat that some researchers predicted unlikely before the year 2100 (Weiss et al., 2016). In addition to the Vaporfly features, the prototype Alphafly contained cushioning Zoom Air pods in the forefoot region to increase energy return. The controversy surrounding the prototype used to break the 2-hour barrier led to World Athletics (2020b) modifying its footwear regulations to limit shoes used in competition to containing a single rigid plate or blade and a maximum thickness of 40 mm for non-spiked shoes. Nike has since released commercially available competition-legal versions of the Alphafly, including the Air Zoom Alphafly Next% (Nike Inc., 2022) that features on the World Athletics Shoe Compliance List (as of 14 January 2022).

Since the introduction of super shoes, athletes wearing super shoes or super spikes have broken all world records from 5 km to the marathon (Muniz-Pardos et al., 2021), with a similar trend observed in middle-distance running (Healey et al., 2022). There have been calls from athletes, coaches, and scientists (Muniz-Pardos et al., 2021; Nigg et al., 2021) for more evidence-based regulations surrounding footwear used in competitions, increased accessibility of footwear to *all* athletes, and more research into their performance effects and individualised shoe responses to maintain fairness and integrity within the sport. This Current Concepts paper provides a brief overview to readers on the controversial topic of super shoes and super spikes.

## Super shoes

Much of the research on super shoes published to date focuses on the Nike Vaporfly models (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hoogkamer, Kipp, et al., 2019; Hunter et al., 2019; Senefeld et al., 2021), which is perhaps due to these models being the pioneering super shoes and their popularity on the elite stage (**Figure 1**). When these shoes were commercially available in 2017, full-length carbon fibre plates were common in track spikes, but a rare occurrence in road running shoes (Burns & Tam, 2020). The key defining features of the Nike Vaporfly models were the generous midsole thickness and stack height that contained a lightweight resilient foam and a full-length curved carbon fibre plate.

*****FIGURE 1*****

The Pebax® foam present in the Nike Vaporfly models is resilient, compliant, less dense, and lighter compared to previous foams (Burns & Tam, 2020; Healey et al., 2022; Hoogkamer et al., 2018). The high level of cushioning of the Nike Vaporfly 4% makes it a comfortable running shoe, more so than minimal lightweight running shoes (Hébert-Losier et al., 2020). The Nike Vaporfly returns 87% of the mechanical energy stored when examined under conditions mimicking running at 18 km/h (Hoogkamer et al., 2018), demonstrating superior mechanical energy return properties than competing models at the time of release. More specifically, the mechanical energy return was 75.9% and 65.5% in the Adidas Adios Boost 2 and Nike Zoom Streak 6 running shoes, respectively. Recent research suggests that competing footwear companies (Asics, Brooks, Hoka, New Balance, and Saucony) have not yet managed to launch super shoes that match the running economy advantages of Nike models (Joubert & Jones, 2022).

Not only is the foam used in super shoes superior at returning mechanical energy, shoe companies have also adopted a thicker heel (stack height) and midsole thickness. The newly released Nike Vaporfly and Alphafly models have 31 mm and 40 mm stack heights, respectively. This enhanced stack height lengthens the effective leg length of athletes (Burns & Tam, 2020), which is associated with a longer stride (Steudel-Numbers et al., 2007). Longer lower leg (shank) length is one anthropometric characteristics that has been linked with more economical running in elite runners (Lucia et al., 2006).

The full-length curved carbon fibre plate in the Nike Vaporfly models increases the longitudinal bending stiffness of the shoe (Hoogkamer, Kipp, et al., 2019), which reduces the mechanical energy lost at the metatarsophalangeal (MTP) joints (Farina et al., 2019), creates a larger external moment arm around the ankle (Stefanyshyn & Fusco, 2004; Willwacher et al., 2014; Willwacher et al., 2013), and reduces the positive and negative work at the ankle (Hoogkamer, Kipp, et al., 2019). The stiffness and curved geometry of the plate are suggested to contribute to maximising the teeter-totter effect (Nigg et al., 2020; Nigg et al., 2021). All of these footwear features are proposed to contribute to running economy and performance improvements to some degree, and are addressed in greater detail below (i.e., **What features are contributing to the gains?)**.

Despite the enhanced thickness of super shoes, additional cushioning, and integration of a curved stiff plate, these shoes remain relatively lightweight. The energetic cost of running has been shown to increase by ~0.9 to 1.2% per 100 g of added mass (Franz et al., 2012; Hoogkamer et al., 2016). That said, there appears to be a threshold at around 220 g per shoe where the benefits of lighter shoes are less clear for distance runners (Fuller et al., 2015). The Nike Vaporfly 4% and Alphafly Next% models weigh approximately 195 g and 210 g, respectively, despite their apparent bulkiness due to their thickness and rigidity conferred by their full-length carbon fibre plate.

**Super spikes**

The technological advancements in road running shoes have now reached track spikes, with Nike releasing their Maxfly, Dragonfly, and Victory models (**Figure 2**). Alongside the release of these models and those from other companies, there have been several record-breaking performances, again fuelling debate around the technological advantages conferred by such shoes (Healey et al., 2022). Before the emergence of super shoes, the use of carbon fibre plates in track spikes was relatively common (Burns & Tam, 2020). Track athletes typically wear shoes that are much lighter than road running shoes, contain an embedded spike plate (Barnes & Kilding, 2019), and have a thin heel with little to no cushioning to minimise shoe mass (Healey et al., 2022; Logan et al., 2010). The comfort of a cushioning layer in track spikes compared to traditional shoes has, more often than not, been sacrificed for a lighter shoe (Greensword et al., 2012) given that shoe mass negatively affects running economy (Franz et al., 2012; Frederick et al., 1984; Hoogkamer et al., 2016). However, new modern foams are very light, adding negligible mass to shoes. Nike Inc.'s novel super spikes contain a small cushioning layer of the same highly resilient, compliant, and energy returning Pebax® foam used in the Vaporfly and Alphafly models, with some of the Nike super spike models also featuring forefoot cushioned Zoom Air pods.

*****FIGURE 2*****

**What are the gains?**

There has been a growing number of studies investigating the effects of super shoes on running economy and performance (Barnes & Kilding, 2019; Bermon et al., 2021; Hébert-Losier et al., 2020; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2022; Muniz-Pardos et al., 2021; Senefeld et al., 2021). Running economy is a measure of metabolic energy demand for a given velocity during submaximal running (Barnes & Kilding, 2015; Daniels, 1985; Saunders et al., 2004) and arguably one of the strongest determinants of long-distance running performance. Improved running economy has been linked to improved performances (Conley & Krahenbuhl, 1980; Daniels, 1985; Kipp et al., 2019). Prototypes and the commercial version of the Nike Vaporfly have been shown to improve running economy on average by approximately 4% (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019), and as much as 13.3% in some recreational runners when compared to their own habitual shoes (Hébert-Losier et al., 2020). At an elite level, advances in shoe technology has translated to around a 2% improvement in race times (Bermon et al., 2021; Senefeld et al., 2021), with a similar average 2% improvement reported for 3-km time-trial performances in recreational runners (Hébert-Losier et al., 2020).

In 2017, Hoogkamer et al. (2017) proposed that shoe design could contribute to a sub 2-hour marathon performance, which Eliud Kipchoge achieved as part of the INEOS 1:59 Challenge. It remains difficult to dissect, nonetheless, how much this feat is a direct result of shoe technological advancements given the contrived circumstances. Eliud Kipchoge ran the marathon distance in 1:59:40 (h:min:sec) wearing an unreleased Nike Alphafly prototype, but scientists provided support to determine optimal drafting, pacing, and fuelling strategies, as well as course design (Hoogkamer, Snyder, et al., 2019; Snyder et al., 2021). It is thought these strategies could improve an elite marathon time by around 2 minutes (Joyner et al., 2020), leaving it difficult to quantify the relative contribution of the shoe technology alone to the sub-2 hour marathon feat.

Similarly, the performance advantages resulting from technological advancements in spike footwear are challenging to quantify due to difficulties in measuring metabolic energy demands of anaerobic events and sparse data comparing super spikes and traditional spikes (Healey et al., 2022). Some researchers estimate the novel super spikes likely result in a 1 to 1.5% improvement in performance, which would equate to about a 15 m advantage in a 1500 m race at the elite level (Ingle, 2021). These speculated gains are yet to be empirically substantiated.

An important consideration is that running economy and performance gains due to footwear can vary between individuals, with some individuals being “high-responders” and some experiencing little to no gains (i.e., “non-responders”) (Hébert-Losier et al., 2020; Hoogkamer et al., 2016; Hunter et al., 2019; McLeod et al., 2020; Stefanyshyn & Fusco, 2004). This individualised shoe response highlights how shoe technology can considerably disadvantage non-responders, making it critical for governing bodies to provide regulations to maintain fairness and integrity based on empirical evidence, particularly at the elite level where small differences can transform a race. Some people, including Usain Bolt (Gijy, 2021), disagree with the use of super shoes and super spikes because of the “unfair advantage” they confer to athletes.

**Regulatory changes**

In January 2020, World Athletics restricted the stack height of road running shoes worn in competition to 40 mm, and spiked shoes to 30 mm (World Athletics, 2020b). The latter was further restricted in July 2020 to 25 mm for distances over and including 800 m, and to 20 mm for distances up to 800 m (World Athletics, 2020a). Limiting stack height was selected as a means to encourage footwear innovation whilst preventing shoes becoming an “unrecognisable extension of the body” (Burns & Tam, 2020). Frederick (2020) questioned why World Athletics primarily regulated midsole thickness when other features have been found to contribute more substantially to performance. Nigg et al. (2020) proposed that the bent midsole stiffness resulting in the teeter-totter effect affected performance the most (i.e., around 4-6%). That said, Burns and Tam (2020) argued that introducing rules for every shoe feature was unfeasible, supporting regulating stack height. World Athletics also limited shoes to containing no more than one embedded plate and, if in more than one part, these parts must exist sequentially in one plane (World Athletics, 2020b).

The January 2020 regulatory changes were not the first instance during which the governing body for athletics faced regulatory issues relating to footwear. In the 1960s, the 200 m and 400 m world records were broken within two weeks of each other by athletes wearing the Puma brush shoe. The rapid fall of previous records led to the governing body at the time banning the shoe that contained 68 micro spikes and introducing a rule that restricted the number of spikes permitted on the sole (McKnight, 2019; Puma, 2014).

**What features are contributing to the gains?**

It is difficult to distinguish how much the individual components of technologically-advanced shoes aid performance (Nigg et al., 2020), and how these effects translate outside of the laboratory into record-breaking performances (Joyner et al., 2020). The fact many world records and overall performance enhancements in running have coincided with the introduction of novel shoe technologies is unlikely a coincidence or a result of physiological adaptations (Joyner et al., 2020; Muniz-Pardos et al., 2021; Senefeld et al., 2021).

As previously noted, the majority of research on the effects of running shoe technology have been on running economy and race performance datasets. Numerous physiological (Barnes & Kilding, 2015), biomechanical (Moore, 2016), and footwear characteristics affect running economy and performance (Fuller et al., 2015; Nigg et al., 2020; Rodrigo-Carranza et al., 2021; Sun et al., 2020). Here, we will briefly address concepts in reference to footwear characteristics only, which are visually represented in **Figure 3**.

*****FIGURE 3*****

*Bending stiffness*

Based on a recent meta-analysis, increased longitudinal bending stiffness of footwear improves running economy by 3.15% when footwear mass is controlled (Rodrigo-Carranza et al., 2021). It is important to note that this percentage improvement is probably inflated by including footwear interventions that were more than increased bending stiffness. This percentage improvement does not account for other moderating factors, such as running speed, degree of longitudinal bending stiffness, responder status, and plate curvature, length, or location.

From a biomechanical perspective, during the stance phase of running, the metatarsophalangeal (MTP) joint dorsiflexes from touchdown until toe off, absorbing mechanical energy (Stefanyshyn & Nigg, 1997). Imbedding a stiff plate in a shoe increases shoe stiffness. This increased longitudinal bending stiffness decreases the amount of mechanical energy lost, particularly at the MTP joint (Farina et al., 2019; Hoogkamer, Kipp, et al., 2019; Roy & Stefanyshyn, 2006; Willwacher et al., 2013). If less mechanical energy is lost, the amount of metabolic energy required to generate the muscular force needed to run at a given velocity is lower (Kipp et al., 2018), which is a factor proposed to enhance running economy.

Imbedding stiff plates in shoes to increase the longitudinal bending stiffness also creates a larger external moment arm around the ankle (Stefanyshyn & Fusco, 2004; Willwacher et al., 2014; Willwacher et al., 2013) and increases the gear ratio at the ankle joint. The higher gear ratio due to this anterior shift of the ground reaction force lever arm may lead to higher ankle joint moments with a similar push-off time in some runners, or smaller ankle joint moments with a longer push-off time in other runners (Willwacher et al., 2014). Hence, how the anterior shift directly affects ankle joint moments remains unclear, although the shift likely reduces plantarflexion velocities (Ortega et al., 2021). Indeed, in stiff shoes (Madden et al., 2016) or when running in prototype Nike Vaporfly shoes (Hoogkamer, Kipp, et al., 2019), ankle plantarflexion velocities in stance are typically lower, suggesting slower triceps surae muscle shortening velocities that are more economical (Hill, 1938).

Increasing the longitudinal bending stiffness of footwear is proposed to shift the centre of pressure anteriorly during the second part of ground contact (Hunter et al., 2019; Nigg et al., 2020; Willwacher et al., 2013). In experimental laboratory settings, however, Hoogkamer, Kipp, et al. (2019) did not observe a more rapid anterior movement of the centre of pressure under the foot in prototype Vaporfly shoes compared to Adidas Adios Boost 2 marathon shoes. This lack of difference in centre of pressure movement between shoes was attributed to both shoes being substantially stiffer than those involved in prior studies (Willwacher et al., 2013). The lower metabolic cost recorded in the prototype Vaporfly shoes was instead linked to the lower positive and negative work at the ankle indicative of lesser triceps surae muscle involvement (Hoogkamer, Kipp, et al., 2019).

Although the benefit of increased longitudinal bending stiffness on running economy is, on average, clear (Rodrigo-Carranza et al., 2021); there are numerous moderating factors to consider and optimal shoe stiffness varies between individuals (McLeod et al., 2020; Nagahara et al., 2018; Smith et al., 2016; Stefanyshyn & Fusco, 2004; Willwacher et al., 2016), leading to some authors recommending personalised shoe stiffness (McLeod et al., 2020; Stefanyshyn & Fusco, 2004). Like shoe mass (Fuller et al., 2015), there may be a threshold beyond which additional longitudinal bending stiffness does not provide further running economy or performance gains. For example, compared to an intact carbon fibre plate, adding six medio-lateral cuts to the Nike Vaporfly 4% shoe reduced its longitudinal bending stiffness by two-thirds without significantly influencing running economy measures (Healey & Hoogkamer, 2021). There are also various carbon fibre or stiff plate configurations to consider, including plate location (Flores et al., 2021), amount of curvature (Farina et al., 2019), and degree of longitudinal bending stiffness (Roy & Stefanyshyn, 2006), which have been shown to affect running biomechanics and economy to various extents (Ortega et al., 2021; Rodrigo-Carranza et al., 2021). The implications of these various plate configurations on running performance, running injury, and footwear comfort have not yet been fully explored, with their individual and combined contributions remaining difficult to quantify.

Whilst running economy is a measure for submaximal running and therefore not directly applicable to sprinting (and some middle-distance) performance, the performance improvements observed with a stiff plate does not only apply to long-distance running. Track spikes have contained carbon fibre or stiff plates for some time now, also to reduce mechanical energy loss at the MTP joint. Running more efficiently, and having a better running economy, enables an athlete to run at their top speed for longer, thus potentially improving sprint performance (Daniels, 1985). Stefanyshyn and Fusco (2004) found sprint performance to improve by 0.69% on average with a stiff plate (42 N/mm) placed inside sprint shoes compared to standard shoes. This improvement is considered a worthwhile enhancement at an elite level with the potential to change the outcome of a high-level sprint race (Hopkins et al., 1999). Worth noting, though, is that individual responses to footwear stiffness have been reported for sprinting also, with not all athletes sprinting faster in stiffer shoes (Nagahara et al., 2018; Stefanyshyn & Fusco, 2004). These findings again suggest individual-specific stiffness is needed to maximise performance.

Alongside individualised shoe stiffness considerations, the benefits of shoe stiffness may be limited to certain event distances and race speeds as the metabolic savings associated with increased longitudinal bending stiffness are speed dependant (Day & Hahn, 2020; McLeod et al., 2020). Whilst bending stiffness has been shown to improve sprint times (Stefanyshyn & Fusco, 2004), studies indicate no improvements in acceleration performance (Ding et al., 2011; Nagahara et al., 2018) and even a reduced acceleration performance (Willwacher et al., 2016). Hence, super spikes with carbon fibre or other stiff plates may be unfavourable for short sprints (e.g., 100 m) where the acceleration phase represents a larger proportion of the race.

*Teeter-totter effect*

The carbon fibre or stiff plates within super shoes and super spikes are curved, as is the forefoot region of shoes. Nigg et al. (2020; 2021) propose the appropriate use of a curved carbon plate and resulting teeter-totter effect can easily improve performance by 4-6% compared with regular shoes, although the teeter-totter effect and associated performance gains have yet to be experimentally quantified. During ground contact, the foot experiences a ground reaction force. More specifically in relation to the teeter-totter effect, when the ground reaction force occurs perpendicular to the stiff plate, the heel is propelled forwards and upwards (Nigg et al., 2020; Nigg et al., 2021). This phenomenon is proposed to be one of the key contributors to improved running economy in super shoes and presumed maximised when the stiffness of the plate is sufficient to cause an anterior shift of the resultant ground reaction during stance, the pivot point is not too far forward to enable the sole to act as the fulcrum, and the shoe and plate are sufficiently curved to cause a teeter-totter effect (Nigg et al., 2020; Nigg et al., 2021).

*Midsole foam*

Nike Inc.'s Pebax® foam and other modern foam layers emerging from other manufacturers return a large proportion of the mechanical energy stored. Nike Inc.'s Pebax® foam returns 87.0% of the mechanical energy following compression, whereas the Adidas Adios Boost 2 returns 75.6% of the mechanical energy stored (Hoogkamer et al., 2018). Running barefoot with no cushioning increases the metabolic cost of running compared to running with 10 mm of cushioning (Tung et al., 2014), as does running barefoot compared to with shoes when mass is equalised (Franz et al., 2012). Prior to the emergence of super shoes, running in shoes with softer and more resilient midsoles was shown to lower oxygen consumption by 1% on average during over ground and treadmill running (Worobets et al., 2014). This 1% improvement in running economy would enable an elite marathoner to run 0.65% faster based on modelling (Kipp et al., 2019). For perspective, in the 2016 Olympic marathon race, if any of the top five women ran 0.51% faster, they would have won (Beck et al., 2020). Frederick et al. (1983) advanced the "cost of cushioning" concept given findings of similar running economy between running barefoot and in cushioned shoes, with the detrimental effect of adding mass to footwear via cushioning negating the benefits of reduced muscular work. In other words, there is a trade-off between reducing muscular work through adequate cushioning and keeping the shoe light, which influences running economy. The foam material used in super shoes and super spikes is less dense and more lightweight than conventional midsole foam materials, therefore mitigating the trade-off. However, the extent to which the amount of mechanical energy return from the midsole material directly translates to improved running economy or performance is unclear, with contradictory findings in the literature. For example, the magnitude of mechanical energy return of midsoles (48.2% versus 62.2%) had no effect on running economy in some studies involving prototype shoes of equal mass (Flores et al., 2019).

The novel, lightweight, resilient, high-energy return foam technology combined with the stiff plate, curved shoe geometry, and teeter-totter effect likely interact in a manner where the whole is greater than the sum of the parts, resulting in the overall running economy and performance enhancements reported in super shoes. To optimise the mechanical energy return from midsole foam, it has been advanced that the energy must be returned at the correct time, in the appropriate direction, with the proper frequency, and at the appropriate location (Stefanyshyn & Nigg, 2000), all of which have not yet been comprehensively examined with regards to super shoes and super spikes. Some researchers have argued that another function of the rigid plate might be to keep the foam stable (Burns & Tam, 2020) and allow distribution of forces under the foot over a larger foam area (Healey & Hoogkamer, 2021), which might facilitate utilisation of the mechanical energy returned from the midsole. Again, though, these propositions have not yet been experimentally confirmed.

*Stack height*

Increasing stack height lengthens the effective leg length of athletes (Burns & Tam, 2020), which is linked to longer strides (Steudel-Numbers et al., 2007). Lucia et al. (2006) observed that lower leg (shank) length was longer in more economical elite runners. Effective limb length explains 98% of the variance in the energetic cost of locomotion across numerous species (Pontzer, 2007). Since stack height does not linearly scale to shoe size (Muniz-Pardos et al., 2021), although marginal, shorter athletes should experience a relatively larger increase in leg length when stack height is increased. An increased stack height also allows greater curvature of the carbon fibre or stiff plate embedded within the shoe, which contributes to the teeter-totter effect (Nigg et al., 2020). Given that increasing plate curvature reduces net MTP work and mechanical energy lost at the MTP joint (Farina et al., 2019), increasing curvature should be of greater benefit to running economy.

Noteworthy is the concern of instability with increased stack height. Since much of the running research is conducted on a treadmill, it is difficult to understand how stack height might affect frontal plane stability during a road race, where turns and corners are likely (Hoogkamer, 2020). Despite World Athletics focusing on stack height in their regulations (World Athletics, 2020a, 2020b), it is argued by some researchers that there is insufficient evidence to support the regulation of footwear for this feature alone (Frederick, 2020; Hoogkamer, 2020; Nigg et al., 2020).

*Shoe mass*

Despite the presence of carbon fibre or stiff plates and a greater midsole thickness, super shoes and super spikes remain relatively lightweight. As mentioned previously, 100 g of additional shoe mass has been shown to increase the energetic cost of running by ~0.9 to 1.2% (Franz et al., 2012; Hoogkamer et al., 2016). In distance running, there appears to be a threshold at around 220 g per shoe where the benefits of lighter shoes are less clear (Fuller et al., 2015). The Nike Vaporfly 4% and Alphafly Next% models weigh approximately 195 g and 210 g, respectively, and hence can be considered lightweight for road running shoes. Track shoes are typically lighter than road running shoes, with the cushioning foam layer often sacrificed to maintain the overall shoe lightness (Greensword et al., 2012) and minimise the dissipation of mechanical energy at each ground contact (Healey et al., 2022). The modern-day super spike typically also contains a foam layer and a full or partial-length stiff plate, whilst remaining lightweight. For example, the Nike ZoomX Dragonfly and Nike Air Zoom Maxfly models weigh approximately 133 and 162 g, respectively; which is within the shoe mass range of the Puma spikes worn by Usain Bolt (Cashmore, 2010) prior to the emergence of super spikes.

## Further research

With the emergence of more high-quality research, governing bodies will be able to make better evidence-informed regulatory decisions around this controversial topic of super shoes and super spikes. There is currently limited understanding of how features, such as bending stiffness, plate and shoe curvature, midsole foam, and stack height, affect running economy and performance in isolation (Day & Hahn, 2020; Frederick, 2020; Nigg et al., 2020) and in combination (Burns & Tam, 2020; Healey et al., 2022). A better understanding of how laboratory findings translate to race performances is required to inform decision-making processes (Joyner et al., 2020). Importantly, improved understanding of the variability in individuals' responses to shoes (Hébert-Losier et al., 2020; Hunter et al., 2019; McLeod et al., 2020; Stefanyshyn & Fusco, 2004) and how these individual responses vary with race distance and speed will also aid regulatory decisions. There should be a uniform measurement of stack height/midsole thickness (Frederick, 2020) and a standard test to measure bending stiffness (Ortega et al., 2021) used in science and practice to enhance scientific inferences and knowledge translation. Governing bodies have a duty to consider safety when introducing shoe regulations. Therefore, it is important for future research to address injury risk and incidence in relation to these new shoe technologies (Hébert-Losier et al., 2020; Hoogkamer, 2020; Muniz-Pardos et al., 2021; Ortega et al., 2021; Sun et al., 2020).

## Conclusion

New running shoe technologies have played a part in history-making moments and record-breaking performances over the last few years. The bending stiffness, teeter-totter effect, high-energy returning midsole foam, increased stack height, and relatively low mass of technologically-advanced shoes are proposed to underpin the performance gains linked with super shoes and super spikes at this point in time. Some of these aspects, such as the teeter-totter effect, have yet to be experimentally verified. It remains challenging to quantify the relative contribution of each one of these aspects to performance gains in isolation, especially given the variability in responses to footwear and footwear features reported to exist between individuals. It may be that the whole is greater than the sum of the parts, where it is the combination and interaction of shoe features and that ultimately lead to enhancing running performance.

Although super shoes and super spikes have been, and continue to be, a controversial topic; the advancements in shoe technology present an exciting prospect in athletics, to the footwear industry, and for sports biomechanics researchers. With the emergence of more high-quality research, governing bodies will be able to make better evidence-informed regulatory decisions around this controversial topic to maintain fairness and integrity within the sport.

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None to declare

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## Figures

**Figure 1**. Nike Vaporfly 4% Flyknit – The first commercially available super shoe.

**Figure 2.** Nike Air Zoom Maxfly – One of the commercially available super spikes.


**Figure 3.** Summary of footwear characteristics of super shoes and super spikes proposed to contribute to running economy and performance gains.