Review



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Posted Date: 22 October 2025

doi: 10.20944/preprints202510.1724.v1

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# Advanced Footwear Technology in Endurance Running: Mechanisms, Economy, and Performance – A Review

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**Abstract**

Since the introduction of Advanced Footwear Technology (AFT) in 2017, numerous world records from 5 km to the marathon have been broken. Among these innovations, carbon-plated shoes have received particular attention. Studies report improvements of up to 4% in running economy (RE) and approximately 2% in performance. The rapid progression of performances has generated significant scientific interest; however, a clear understanding of the mechanisms driving the effectiveness of AFT remains limited. Despite widespread adoption and notable outcomes, neither researchers nor manufacturers can fully explain why design features such as increased stack height, embedded carbon fibre plates, and enhanced longitudinal bending stiffness are so effective, making optimisation of their benefits an ongoing challenge. This review summarises current knowledge on AFT and critically evaluates the biomechanical and physiological mechanisms underlying their effects on RE and performance. It also highlights the interaction between shoe design features and individual biomechanics, supporting evidence-based approaches to footwear selection and training strategies tailored to athletes' needs. A clearer understanding of these mechanisms may provide valuable insights for researchers, coaches, and athletes, and help maximise the potential benefits of AFT.

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## 1. Introduction

Running shoes can be categorised into several types based on their function and intended use, including minimalist, conventional, carbon-plated, motion control, support, and other types (Frederick, 2022; Ruiz-Alias et al., 2023b). All of these can influence running economy (RE) and performance in long-distance runners (Fuller et al., 2015, 2017; Beck, Golyski & Sawicki, 2020; Knopp et al., 2023) and may also alter running biomechanics (Bonacci et al., 2013; Beck, Golyski & Sawicki, 2020; Healey & Hoogkamer, 2021; Rodrigo-Carranza et al., 2022).

In recent years, increasing attention has been paid to carbon-plated shoes—running shoes with an embedded carbon fibre plate in the midsole combined with multiple layers and specialised foam structures (Hunter et al., 2019; Kiesewetter et al., 2022). There remains some ambiguity regarding how to categorise these shoes. In the literature, terms such as "plated shoes", "4% shoes", "super shoes", "super spikes", "neoteric shoes", "carbon shoes", and "ergogenic shoes" are used (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Frederick, 2022). In this review, we refer to this category collectively as Advanced Footwear Technology (AFT), with carbon-plated models representing the most widely recognised type.

Introduced by Nike in 2016 (Matties, 2024) and commercially available since 2017 (Stansbie & Almond, 2025), AFT has gained significant scientific and public interest due to its potential to enhance RE (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Hunter et al., 2019; Edgar, 2022; Joubert et al.,

 doi:10.20944/preprints202510.1724.v1



2024; Matties & Rowley, 2024; Yang et al., 2025) and endurance race performance (Bermon et al., 2021; Castellanos-Salamanca et al., 2023; Hébert-Losier & Pamment, 2023; Langley et al., 2023; Langley & Langley, 2024; Mason et al., 2024; Senefeld et al., 2021; Yang et al., 2025). The growth in performance, especially in female athletes (Bermon et al., 2021; Senefeld et al., 2021; Langley et al., 2023; Mason et al., 2024; Willwacher et al., 2024), has led some to compare AFT to the barefoot and minimalist running era of the 2000s (Frederick, 2022).

Although a growing number of studies have analysed different brands and models of AFT, there is still no clear consensus on the mechanisms that explain their effectiveness. Moreover, questions remain about how these shoes can be optimally applied to individual athletes, considering biomechanical and physiological variability (Nigg, Subramanium & Matijevich, 2022; Schwalm et al., 2024b). This raises broader questions: How far will technological advances go? How will they influence the evolution of performance outcomes and the nature of sport? Could they even be considered a form of "technological doping"? (Milford, 2024).

The purpose of this review is to summarise and critically evaluate the dominant factors determining the working mechanisms of AFT, highlighting their role in shaping RE and performance. It further identifies key considerations for future research design and interpretation and provides practical insights for coaches and athletes on effective AFT use tailored to individual needs. The ultimate goal is to support the development of evidence-based and practically applicable guidelines for the assessment and use of AFT in sport.

## 2. The Evolution of Advanced Footwear Technology

Although AFT is commonly associated with recent years of the 21st century, carbon fibre plates were used in running shoe construction as early as the 1980s (Hutchinson, 2020). At that time, the term "carbon-plated shoes" was not used; instead, they were often described as "energy return shoes" (Franz, Wierzbinski & Kram, 2012; Sinclair et al., 2016). In 1989, Brooks introduced the models The Fusion and The Fission, both featuring a carbon plate embedded in the midsole. Soon after, Fila also released racing shoes with this technology. A major step forward occurred when Adidas introduced a curved, geometrically designed carbon fibre plate called ProPlate. Running in shoes equipped with this design, Ethiopian long-distance runner Haile Gebrselassie set a new marathon record of 2:04:26 in 2007 (Hutchinson, 2020).

The modern era of carbon-plated footwear began in 2016 (commercially available from 2017) when Nike released the ZoomX Vaporfly 4% (Matties, 2024). The name reflected the manufacturer's claim of up to 4% improvement in RE, which was subsequently supported by independent studies (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Hunter et al., 2019). The Vaporfly 4% incorporated a carbon fibre plate embedded in the midsole together with other design elements intended to increase bending stiffness (Kiesewetter et al., 2022). This reduced movement at the metatarsophalangeal joint (MTPJ), facilitating more efficient energy transfer (Ortega et al., 2021) and contributing to forward propulsion, often described as a "springboard effect" (McMillan, 2024).

In 2018, Eliud Kipchoge set a marathon world record of 2:01:39 at the Berlin Marathon wearing the Nike Zoom Vaporfly 4%. The following year, Nike launched the Air Zoom Alphafly Next, which built upon Vaporfly technology with new features such as forefoot "Air Pods"—pressurised air units designed to smooth transition and enhance energy return (McMillan, 2024). Later that year, Kipchoge wore the Alphafly to complete the INEOS 1:59 Challenge in 1:59:40, breaking the two-hour barrier, though the performance was not officially recognised due to race conditions (Hébert-Losier et al., 2022; McMillan, 2024). Nike has since continued to refine its designs, most recently with the Alphafly Next% 3, worn by Kelvin Kiptum to set the current marathon world record of 2:00:35 at the 2023 Chicago Marathon (McMillan, 2024). This model was released commercially in January 2024.

The success of Nike's designs and the associated record-breaking performances prompted other companies to accelerate development of their own AFT models (Joubert & Jones, 2022). Today, nearly all major running shoe brands—including Adidas, Asics, New Balance, Saucony, and Hoka—offer carbon-plated models, and the industry continues to grow at a rapid pace.

## 3. Regulatory Responses to Advanced Footwear Technology in Elite Athletics

Opinions on the rapid development of AFT and its impact on performance are divided. On one hand, AFT can be viewed as a technological advancement that enables elite athletes, whose physiological limits are already near their peak, to further enhance performance. On the other, concerns have been raised about fairness and whether such external interventions align with the fundamental nature of sport, which traditionally centres on human physiological and technical abilities.

In the early stages of AFT development, not all athletes had equal opportunities to access these models. Initially, prototypes were provided only to select elite runners in high-profile competitions, creating potential inequalities. Even after their public release, some athletes continued to have access to the latest prototype models before they became commercially available, leading to situations where runners switched sponsors to obtain perceived performance advantages (McMillan, 2024).

To address these concerns, World Athletics introduced regulations in 2020 governing the use and design of AFT in elite competitions (Dyer, 2020). According to the updated competition technical rules (World Athletics, 2020a), the sole thickness of AFT shoes must not exceed 40 mm. Previous studies have suggested that even relatively small changes in stack height within a 20 mm range can meaningfully affect performance (Ruiz-Alias et al., 2023a). In addition, the shoe must not contain more than one carbon fibre plate, or any other material with similar properties, regardless of whether it spans the full length of the sole or only part of it (World Athletics, 2020b). These restrictions do not apply, however, to the National Collegiate Athletic Association or high school athletics, where all types of running shoe construction remain permitted (Burns & Joubert, 2024).

For athletics spikes, regulations allow an additional carbon plate only for attaching the spikes, and the sole thickness must not exceed 30 mm (World Athletics, 2020b). To uphold fairness, World Athletics also mandated that all innovative shoes released after 30 April 2020 must be commercially available to all athletes for at least four months before a relevant competition. Shoes not meeting this requirement are considered prototypes and are prohibited in competition (World Athletics, 2020b).

These regulations were designed to safeguard equality and fair play while establishing reasonable boundaries for technological innovation in sport-related performance enhancement.

## 4. Design Elements of AFT

The construction of carbon-plated shoes can be conceptualised as a layered structure, often described as a "sandwich", consisting of multiple layers of varying types and thicknesses compressed together (Hébert-Losier & Pamment, 2023). At the core is the carbon fibre plate (Frederick, 2022; Hébert-Losier & Pamment, 2023), which may be embedded within the shoe midsole or inserted directly into the shoe (Bräuer et al., 2021). These two placements differ significantly. Insertable carbon soles, which are not surrounded by cushioning foam, are stiffer and alter both the running feel and perceived comfort (Day & Hahn, 2020; Flores et al., 2021). However, they tend to last longer and may be a more economical option than purchasing new pairs of carbon-plated running shoes (Perrin et al., 2025).

Increased midsole stiffness is generally associated with improvements in RE and performance (Roy & Stefanyshyn, 2006; Day & Hahn, 2020; Rodrigo-Carranza et al., 2022, 2023; Perrin et al., 2025). This effect is thought to result from a reduction in bending motion of the foot during push-off and a decrease in energy absorption and dissipation at the metatarsophalangeal joint (MTPJ) (Stefanyshyn & Nigg, 2000; Willwacher et al., 2013; Ortega et al., 2021). These changes facilitate more efficient energy transfer and forward propulsion (Hoogkamer et al., 2018; Hoogkamer, Kipp & Kram, 2019; Hunter et al., 2019; Ortega et al., 2021; Song et al., 2024). However, recent research indicates that the benefits may be runner-specific (Chollet et al., 2023; Ghanbari et al., 2025b), and an "optimal shoe bending stiffness" may exist for different individuals (McLeod et al., 2020). In addition, some evidence suggests potential

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injury-prevention benefits due to increased stability and support for the foot and ankle joints (Song et al., 2024).

### 4.1. Carbon Plate Type and Curvature

Curved carbon plates are generally associated with greater improvements in RE and performance compared to flat plates (Roy & Stefanyshyn, 2006; Farina, Haight & Luo, 2019; Miyazaki et al., 2024; Ruiz-Alias et al., 2024; Song et al., 2024; Xu et al., 2025; Ghanbari et al., 2025a). However, the design must be optimised to ensure that the "teeter-totter effect" occurs at the correct location (heel of the foot), time (push-off), and frequency (determined by running velocity and ground contact time) (Stefanyshyn & Nigg, 2000; Nigg, Cigoja & Nigg, 2021).

According to Nigg, Cigoja & Nigg (2021), three key characteristics of curved carbon plates are required to achieve maximal performance benefits:

1. The shoe should have enough stiffness to shift the ground reaction force forward during stance.
2. The pivot point should be placed so it is not too far forward, allowing the sole to act as a fulcrum.
3. The toe spring should not be too high or too low, enabling an effective rocking motion.

As noted by Willwacher et al. (2013), translating these theoretical mechanisms into real-world running conditions is complex. Nonetheless, they provide valuable insights into critical design features that influence the effectiveness of AFT.

An S-shaped curvature, in which the heel sits slightly higher than the forefoot, has been associated with faster heel-to-toe transitions and a sensation often described by runners as "spring-like". This design helps maintain a straighter alignment of the hallux, reduces energy expenditure during push-off, and shortens ground contact time (Hoogkamer et al., 2018; Lam et al., 2018; Farina et al., 2019; Rodrigo-Carranza et al., 2022; Song et al., 2024). Furthermore, it may help reduce overuse injury risk by decreasing peak pressure on the forefoot without increasing loads in the metatarsal region, and by lowering demands on the ankle plantar flexors compared with flat-plate or non-plated shoes (Miyazaki et al., 2024; Song et al., 2024; Xu et al., 2025).

Plate location is also an important factor, particularly in models with increased stiffness (Flores et al., 2021). The design of the forefoot plate—whether full-length or segmented—can substantially alter running biomechanics and, consequently, performance outcomes (Flores et al., 2021; Fu et al., 2021). However, inappropriate plate curvature or stiffness may increase the risk of foot injuries (Flores et al., 2021; Tenforde et al., 2023; Song et al., 2024).

### 4.2. Foam Construction and Midsole Properties

Recent research has highlighted the significant role of midsole materials in improving RE and energy efficiency. Foam construction has been shown to play a particularly important role when interacting with carbon fibre plates (Joubert & Jones, 2022; Rodrigo-Carranza et al., 2024; Baumann et al., 2025) and may also influence shoe durability depending on the foam's microstructure (Aimar et al., 2024).

Aimar et al. (2024) compared five commercial midsole foams derived from three of the most commonly used polymers in carbon-plated shoes—ethylene-vinyl acetate (EVA), polyether block amide (PEBA), and thermoplastic polyurethane (TPU) (Rodrigo-Carranza et al., 2024)—plus one modified sample obtained from an additional insert of the same midsole to capture structural variability. Under mechanical fatigue testing, EVA foams reinforced with microfillers demonstrated improved mechanical strength but reduced rebound properties and accelerated wear, likely due to weak cohesion between fillers and the polymer matrix. In contrast, denser foams with hierarchical microstructures exhibited slower damage progression and enhanced durability; however, they were associated with poorer initial mechanical properties.

Lloria-Varella et al. (2022) examined whether shoe wear and degradation after a fatiguing trail run influenced biomechanics, and whether switching to a fresh pair of shoes could restore mechanics altered by worn footwear. After the race, participants' own shoes showed reduced midsole thickness

 doi:10.20944/preprints202510.1724.v1



and increased stiffness, confirming degradation. Running mechanics also changed: contact time and step frequency increased, while flight time and tibial peak-to-peak acceleration amplitude decreased. Contrary to their hypothesis, replacing the worn shoes with new ones did not significantly alter the main biomechanical variables, although it did affect shoe × time interaction.

*4.3. Stack Height*

Foam construction in modern AFT serves not only to provide additional cushioning but also to increase the stack height of the shoe (Rodrigo-Carranza et al., 2024; Baumann et al., 2025). Stack height is a critical design parameter, as it determines the thickness of the midsole and, consequently, the shoe's capacity to store and return mechanical energy. Functionally, stack height acts like a compliant spring: a thicker midsole allows greater elastic deformation during foot strike (via sole compression) and subsequent energy release during push-off, assisting propulsion (Hoogkamer et al., 2018). This mechanism not only influences RE and biomechanics but also affects comfort and impact attenuation (Ruiz-Alias et al., 2023a, c; Ferris et al., 2025; Baumann et al., 2025; Kettner, Stetter & Stein, 2025). It may also contribute to fatigue resistance and reduced muscle damage or soreness over longer distances (Kirby et al., 2019; Castellanos-Salamanca et al., 2023).

When comparing the Nike Zoom Vaporfly prototype (heel height: 31 mm; forefoot height: 21 mm) with two similar-technology shoes—the Adidas Adios Boost and the Nike Zoom Streak 6—Hoogkamer et al. (2018) reported that the prototype deformed nearly twice as much (11.9 mm; energy return: 87%) compared with 6.1 mm (75.9%) for the Adios Boost and 5.9 mm (65.5%) for the Zoom Streak 6.

A recent study by Baumann et al. (2025) confirmed that adding an additional 10 mm of stack height to the current 40 mm limitation improved running economy (RE) by 0.6% during treadmill running and 0.7% during overground running. Interestingly, this modification did not significantly affect perceived exertion ratings or running kinematic variables (step frequency, flight time, ground contact time, duty factor, etc.). Moreover, the shoes with the highest stack height (50 mm) were rated lowest in terms of subjective comfort. One possible explanation for this could be the reduced running stability, primarily resulting from lateral instability associated with greater ankle eversion — a factor previously linked to an increased risk of injury (Hoogkamer, 2020; Ruiz-Alias et al., 2023a; Barrons, Wannop & Stefanyshyn, 2023; Ferris et al., 2025; Kettner, Stetter & Stein, 2025), particularly among runners with pre-existing foot conditions or excessive pronation (Clark & Williams, 2023; Ferris et al., 2025). However, evidence supporting this remains limited, and further research is needed.

*4.4. Toe Spring*

A distinctive feature of many AFT models is rocker geometry, characterised by a slight forefoot elevation ("toe spring") that creates an S-shaped sole design. This configuration has been consistently associated with improvements in RE (Tenforde et al., 2023).

The toe spring facilitates a faster and more efficient heel-to-toe transition, often described as a "rollover" sensation, which reduces ground contact time and enhances forward propulsion. Mechanically, this effect is explained by the teeter–totter mechanism, in which the stiff carbon plate and curved sole act as a lever to reduce muscular effort during ankle dorsiflexion and push-off (Nigg, Cigoja & Nigg, 2021; Nigg, Subramanium & Matijevich, 2022; Ruiz-Alias et al., 2023a). In contrast, flatter shoe soles require greater muscular force and energy to complete this transition, leading to less efficient rollover mechanics. The combined interaction of toe spring, carbon plate, and foam midsole therefore functions like a spring mechanism, enabling elastic energy storage and release. As a result, these design features are expected to improve RE by supporting a more efficient stride with reduced energy expenditure (Nigg, Cigoja & Nigg, 2021).

## 5. Working Mechanisms of AFT

Understanding the underlying working mechanisms of AFT is essential for explaining the improvements in RE, biomechanics, and performance observed in recent years. The interaction between shoe geometry, material properties, and runner-specific biomechanics determines how effectively mechanical energy is stored, transferred, and returned during the gait cycle. Collectively, it illustrates that the effectiveness of AFT arises from various multiple element interaction. A deeper understanding of it may contribute to more effective performance outcomes.

### *5.1. Energy Return Mechanisms of Running Footwear: Implications for AFT Performance*

The primary function of the energy return mechanism in footwear is to recover energy stored in the midsole during stance and return it to assist subsequent movement, such as the swing phase. This process is associated with reduced oxygen consumption and improved RE (Bosco & Rusko, 1983; Frederick, Howley & Powers, 1986).

The storage and release of elastic energy is recognised as one of the main factors contributing to RE in both humans and animals (Willwacher et al., 2013). When analysing the role of mechanical energy in performance, three strategies are commonly identified (Roy & Stefanyshyn, 2006; Willwacher et al., 2013):

1. Optimization of musculoskeletal function.
2. Enhancement of energy return.
3. Reduction of energy expenditure.

Although the first factor has received less attention, the latter two strategies are highly relevant to AFT development, where material composition and mechanical properties are manipulated to maximise performance benefits (Willwacher et al., 2013; Oh & Park, 2017).

### *5.2. The Role of the Metatarsophalangeal Joint (MTPJ) in Energy Return Mechanisms*

The metatarsophalangeal joint (MTPJ) plays a central role in running efficiency, as its motion strongly influences mechanical energy transfer and potential energy loss during the push-off phase (Stefanyshyn et al., 1997; Stefanyshyn & Nigg, 2000). Carbon fibre plates are designed to limit excessive MTPJ dorsiflexion, thereby reducing energy dissipation and enhancing effective energy transfer (Ortega et al., 2021). Joint mechanics can also be modulated by changes in stiffness and elasticity of surrounding structures, further highlighting the importance of the MTPJ in footwear design (Stefanyshyn & Nigg, 2000).

Excessive bending motion at the forefoot or MTPJ can increase mechanical energy loss during running, sprinting, and jumping (Stefanyshyn & Nigg, 1997; Stefanyshyn & Nigg, 2000). Increasing the longitudinal bending stiffness of the midsole reduces MTPJ motion and thereby decreases energy absorption and dissipation, which is generally associated with improvements in RE (Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 2000; Willwacher et al., 2013; Day & Hahn, 2020; Ortega et al., 2021; Rodrigo-Carranza et al., 2022, 2023; Perrin et al., 2025).

Increasing MTPJ stiffness modifies joint mechanics by altering contraction velocity, propulsion duration, and the lever arm effect of the ground reaction force (GRF), shifting the centre of pressure forward during stance (Willwacher et al., 2013; Beck, Golyski & Sawicki, 2020). In a study of shoes with varying sole stiffness, Willwacher et al. (2013) observed that in the stiffest models, the centre of pressure shifted significantly toward the forefoot during the final 40% of stance.

Willwacher et al. (2013) proposed four strategies to optimize the runner–shoe interaction at the MTPJ:

1. Prolong the propulsion phase to increase plantar flexion work, as positive work is mainly generated at the end of propulsion.
2. Increase longitudinal bending stiffness so dorsiflexion occurs earlier, allowing more time for plantar flexion and greater positive work.
3. Modify shoe construction (e.g., toe spring) to initiate dorsiflexion earlier; reducing excessive forefoot curvature may improve rollover mechanics and efficiency.
4. Optimize extrinsic muscle conditions by improving force–velocity characteristics.

Beyond these strategies, effective energy return depends on precise timing and location of sole flexion, ideally aligning plantar flexion with toe-off. The optimal scenario occurs when both midsole and toes perform plantar flexion at the end of propulsion, transmitting energy at the right time and place. Maximum benefit would occur if the flexion–extension cycle is fully realised within ground contact (Stefanyshyn & Nigg, 2000; Willwacher et al., 2013).

However, achieving such ideal conditions is unlikely. Footwear stores and returns far less elastic energy than tendons, with up to 30% lost in the process (Stefanyshyn & Nigg, 2000; Willwacher et al., 2013). Thus, the primary advantage of AFT may be reduction of energy dissipation rather than true energy return. Accordingly, footwear development should prioritise strategies to minimise energy loss rather than attempting to maximise energy return (Nigg & Segesser, 1992; Roy & Stefanyshyn, 2006).

### *5.3. Materials and Mechanical Properties of Carbon-Plated Shoes*

Recent studies indicate that the type of sole material and its mechanical properties may have a greater impact on RE than longitudinal bending stiffness (LBS) (Barnes & Kilding, 2019; Geisler, 2023; Rodrigo-Carranza et al., 2023; Aimar et al., 2024). Resilience (the ability to return part of the stored mechanical energy) and compliance (the deformation that occurs under a given force during compression) are identified as key properties in the design of AFT (Frederick, Howley & Powers, 1986; Kerdok et al., 2002; Worobets et al., 2014; Hoogkamer et al., 2018; Muzeau et al., 2025). Running shoes with more resilient and compliant midsoles can reduce adenosine triphosphate (ATP) consumption during muscle contraction, producing the same force with lower oxygen cost at any running intensity (Barnes & Kilding, 2019).

The most common midsole materials used in AFT are ethylene-vinyl acetate (EVA), thermoplastic polyurethane (TPU), and polyether block amide (PEBA) (Rodrigo-Carranza et al., 2024). Among them, PEBA is considered one of the most efficient materials for energy return (Hoogkamer et al., 2018; Barnes & Kilding, 2019). Its low density allows greater cushioning volume without significantly increasing shoe mass (Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2024).

Despite these favourable mechanical properties, PEBA's low density results in faster wear compared with conventional materials. This compromises both durability and long-term impact on RE. Rodrigo-Carranza et al. (2024) found that while new PEBA shoes improved RE more than EVA shoes, after 450 km of use the two materials had similar effects. Moreover, PEBA showed a larger increase in energy consumption ($0.32 \pm 0.38$ W/kg) than EVA ($0.06 \pm 0.58$ W/kg) when comparing new and worn shoes. These findings suggest that although highly effective in active use, PEBA midsoles have low durability, leading many runners to reserve carbon-plated shoes for races and high-velocity training sessions.

In summary, the performance gains of carbon-plated shoes arise from the interaction of midsole materials, shoe geometry, and runner-specific adaptation rather than any single factor (Barnes & Kilding, 2019). Midsole composition and mechanical properties critically influence efficiency and fatigue resistance (Castellanos-Salamanca et al., 2023; Rodrigo-Carranza et al., 2024; Aimar et al., 2024), explaining why results vary across shoes in the same category (Hoogkamer, Kipp & Kram, 2019; Joubert & Jones, 2022; Ruiz-Alias et al., 2023b). Optimal designs combine lightweight construction, effective traction, and compliant, resilient foams (Frederick, 1984; Hoogkamer et al., 2018; Aimar et al., 2024).

### *5.4. Interaction of the Rollover Feeling and the Teeter–Totter Effect*

The "ride" or "rollover" sensation is considered a key factor influencing both shoe comfort and purchasing decisions among runners, while also reflecting underlying biomechanical mechanisms (Lam et al., 2018; Bräuer et al., 2021). Since Nigg, Cigoja & Nigg (2021) proposed the "teeter–totter" effect as one of the primary mechanisms driving performance improvements in AFT, its role has been widely debated in the research community.

The ride sensation depends on a combination of shoe midsole construction, running velocity, and individual responses. Lam et al. (2018) reported that softer and more compliant midsoles were associated with smoother ride characteristics (lower anterior–posterior velocity of the centre of pressure) and higher comfort. However, notable inter-individual variability was observed: a subset of runners demonstrated smoother transitions in stiffer midsoles. This suggests that ride sensation is not determined solely by shoe properties but by the interaction between shoe stiffness, biomechanics, and anthropometric factors (Roy & Stefanyshyn, 2006).

Studies have suggested improvements in RE of up to 6% when the teeter–totter effect is effectively engaged in habitual runners (Nigg, Cigoja & Nigg, 2021). According to these authors, three conditions must be met to achieve the effect:

1. Sufficient sole stiffness to shift the ground reaction force forward during stance.
2. Proper pivot point placement, ensuring it is not positioned too far forward so the heel can act as a support point.
3. Appropriate forefoot curvature, enabling effective lever action and smooth rollover mechanics.

In practice, achieving these exact conditions is challenging, raising doubts about whether a single shoe feature can independently drive substantial changes in running biomechanics (Stefanyshyn & Nigg, 2000; Willwacher et al., 2013). Mao, Li & Ruan (2025) reported that carbon-plated shoes significantly improved RE even at relatively low speeds (10 km/h) in recreational runners, but they found no differences in toe pressure-time integrals, questioning whether the teeter–totter effect is the primary mechanism. Instead, RE improvements should be viewed as the result of the combined interaction of multiple shoe design elements (Hoogkamer, Kipp & Kram, 2019; Mao, Li & Ruan, 2025). For example, manipulating stack height may influence teeter–totter mechanics, but most modern manufacturers instead achieve rollover effects by incorporating increased toe spring and proximally placed rocker axes (Ruiz-Alias et al., 2023a).

At present, it is not possible to provide a definitive statement regarding the contribution of the teeter–totter effect to AFT performance. Future research should aim to clarify its specific role in shaping running biomechanics and RE.

## 6. Athletic Spikes and "Super Spikes"

The development of athletic spikes has mirrored that of AFT, with the term "super spikes" now commonly used alongside "super shoes" as a product of AFT innovation.

AFT-based athletic spikes first appeared in competition in 2019, with Nike introducing the first widely recognised model, the Nike ZoomX Dragonfly (Geisler, 2023; Burns & Joubert, 2024; Joubert et al., 2024). Today, super spikes are used by the majority of elite athletes in major competitions (Hébert-Losier & Pamment, 2023; Burns & Joubert, 2024). The Nike ZoomX Dragonfly and Nike Air Zoom Victory remain among the most prominent models, though manufacturers such as Puma are rapidly advancing their own designs (Bertschy et al., 2024).

In terms of construction, super spikes share many features with super shoes, including stiff curved carbon plates and lightweight, resilient foams with high energy return. Some models also incorporate additional technologies such as Air Units (Geisler, 2023; Hébert-Losier & Pamment, 2023). However, performance improvements reported for super spikes (typically 1–2%) remain slightly lower than those observed for carbon-plated road shoes, despite the spikes' lower mass (Barnes & Kilding, 2019; Hébert-Losier & Pamment, 2023; Oehlert et al., 2023; Ruiz-Alias et al., 2023b,c; Bertschy et al., 2024; Joubert et al., 2024). One possible explanation is the reduced midsole thickness of super spikes (20–25 mm compared with up to 40 mm in AFT road shoes), which may limit energy storage and return (Hoogkamer et al., 2018; Joubert & Jones, 2022). However, as stack height alone may not determine performance outcomes, further research is needed.

Testing spikes under controlled laboratory conditions is also difficult. In treadmill experiments, spikes are often removed, altering shoe mass and mechanical function, which can influence measured effectiveness (Healy et al., 2022; Bertschy et al., 2024; Burns & Joubert, 2024). To address these challenges, Bertschy et al. (2024) compared three middle-distance super spike models with traditional spikes in 12 competitive middle-distance runners, at their 800 m or 1500 m race paces. They also included a Puma prototype with 19 mm Nitro foam and a carbon sole. Running with super spikes increased velocity by 1.6–2.1% compared with traditional spikes, with the Puma prototype showing the greatest improvement (up to 3.1%), outperforming the Nike Dragonfly even under varied conditions. These improvements were attributed primarily to biomechanical changes, particularly ~2% longer stride length in super spikes versus traditional spikes.

Collectively, these findings suggest that super spikes are more economical than traditional athletic spikes, although the mechanisms remain unclear. Despite their lighter mass, super spikes still fall short of the improvements seen in AFT road shoes. Future research should focus on identifying design modifications that could narrow this gap while preserving the mass advantage, paving the way for the development of next-generation spike technology.

## 7. Effects of AFT on Running Biomechanics

Evidence suggests that AFT primarily influences running kinematics rather than physiology (Kiesewetter et al., 2022; Matties, 2024; Perrin et al., 2025; Ferris et al., 2025; Farina et al., 2025). These effects are reflected in changes to spatio-temporal gait parameters, including step length, step frequency, contact time, and flight time. Runners adapt their movement patterns depending on footwear (TenBroek et al., 2014; Matties, 2024; Eken et al., 2025) and running surface (Kerdok et al., 2002; Tung, Franz & Kram, 2014; Schütte et al., 2016; Van Hooren et al., 2020; Benson et al., 2022). Such adaptations can substantially affect metabolic measurements (Smith, McKerrow & Kohn, 2017), given the close relationship between running biomechanics and RE. Importantly, changes in kinematics may improve, impair, or have no significant effect on RE (Kyröläinen, Belli & Komi, 2001).

### *7.1. Working Mechanisms of Carbon-Plated Shoes*

Carbon-plated shoes influence running biomechanics by modifying force transmission through the foot–shoe–ground interface. The embedded carbon fibre plate acts as a stiff lever, resisting midsole bending and altering ankle and metatarsophalangeal (MTP) joint mechanics (Hoogkamer, Kipp & Kram, 2019; Matties, Kerr & Rowley, 2024; Milner et al., 2025). By limiting excessive dorsiflexion at the MTP joint during toe-off, the plate reduces energy loss in this region (Oh & Park, 2017; Ortega et al., 2021) and promotes a more efficient forward roll of the foot — often referred to as the "teeter–totter effect" (Nigg, Cigoja & Nigg, 2020; Nigg, Subramanium & Matijevich, 2022).

This stiffening effect shifts the point of force application anteriorly, increasing the lever arm of the ground reaction force and thereby altering joint moments at the ankle and knee. In combination with compliant, resilient foams, the carbon plate enables elastic energy storage during loading and contributes to energy return during push-off (Willwacher et al., 2013; Hoogkamer et al., 2018; Joubert, Dominy & Burns, 2023; Hébert-Losier & Pamment, 2023; Burns & Joubert, 2024; Ferris et al., 2025). Ideally, these mechanisms promote a more even distribution of impact forces across the foot, reducing excessive load on the MTP region and lowering the energetic cost of running (Farina, Haight & Luo, 2019; Martinez et al., 2024; Song et al., 2024).

Recent studies indicate that these effects are further optimised with a curved carbon plate, which smooths transition through stance and reduces localised forefoot stress compared with a flat plate (Farina, Haight & Luo, 2019; Miyazaki et al., 2024; Song et al., 2024; Xu et al., 2025). This design may be particularly important in long-distance running, where sustained loading increases injury risk. By reducing forefoot stress and supporting smoother roll mechanics, curved carbon plates may contribute to both injury prevention and fatigue resistance (Kirby et al., 2019; Song et al., 2024; Castellanos-Salamanca et al., 2023).

### *7.2. AFT and Running Injuries: Altered Biomechanics Theory and Practical Examples*

Changes in running biomechanics caused by AFT can sometimes produce inadequate sensations for athletes. Increased midsole cushioning, common to nearly all AFT models, allows for reduced knee flexion (Tung, Franz & Kram, 2014). This encourages more rearfoot striking without the runner perceiving the same impact as in conventional shoes or, even more so, barefoot running (Frederick, 1984; Fuller et al., 2016).

Theoretically, this should enable runners to sustain higher speeds and longer distances with less fatigue, a notion supported by studies reporting reduced fatigue, muscle damage, and pain when using carbon-plated shoes during both interval training (5 × 1000 m with 90 s recovery) (Castellanos-Salamanca et al., 2023) and marathon running (Kirby et al., 2019). However, this explanation is overly simplistic. The absence of immediate discomfort does not mean bones, joints, and ligaments remain unaffected. A recent study by Baumann et al. (2025) indicated a potential increase in lower-limb loading when running in AFT. Over time, the passive musculoskeletal system may struggle to tolerate and recover from altered loading, increasing the risk of overuse injuries (Schwalm et al., 2024b; Baumann et al., 2025). Increased heel striking could also elevate the risk of rearfoot injuries, particularly when running on stiff surfaces (Frederick, 1984; Fuller et al., 2016; Smith, McKerrow & Kohn, 2017).

Although direct evidence is limited, case reports describe stress reactions and stress fractures of the midfoot (navicular bone region) in athletes using carbon-plated shoes at the time of injury (Tenforde et al., 2023). These cases involved individuals of varying age, sex, and sport, including triathlon. Some had a prior history of stress-related bone injury in the same region. Incomplete data on biomechanics during injury limit causal inference, but the observations suggest a potential risk associated with AFT use. Diagnosis of stress fractures typically requires weeks or months, complicating the interpretation of injuries appearing soon after AFT use (Milner et al., 2025).

Overall, while carbon-plated shoes clearly influence running biomechanics, the precise mechanisms and shoe features responsible for both performance gains and potential injury risks remain unclear — an issue highlighted in recent AFT research (Nigg, Subramanium & Matijevich, 2022). Individual factors such as training background, injury history, and biomechanical characteristics may determine whether a shoe model is beneficial or harmful (Schwalm et al., 2024b; Mao, Li & Ruan, 2025). Gradual integration of AFT into training is advisable to allow adaptation and reduce injury risk (Matties, Kerr & Rowley, 2024; Mao, Li & Ruan, 2025).

Thus, while AFT can provide performance benefits, its long-term effects on musculoskeletal health, natural running patterns, and stability require careful consideration.

## 8. Effects of AFT on Running Economy and Performance

Running economy (RE) reflects the oxygen cost at a given submaximal velocity and is widely regarded as one of the most important performance determinants in long-distance running (Sinclair et al., 2014; Kiesewetter et al., 2022; Joubert & Jones, 2022).

Despite extensive study, findings on AFT remain inconsistent. Reported outcomes range from significant improvements to no measurable effect (Healey & Hoogkamer, 2021), or even negative impacts on RE and performance (Tenforde et al., 2023). Placebo effects have also been proposed (Pfister, 2024) and were recently demonstrated in recreational runners (Hébert-Losier et al., 2025).

Many studies have reported ~4% improvements in RE with AFT (Hoogkamer et al., 2018; Hunter et al., 2019; Barnes & Kilding, 2019; Rodrigo-Carranza et al., 2022; Hébert-Losier & Pamment, 2023), consistent with the performance claims of Nike's first carbon-plated model — the ZoomX Vaporfly 4% (Mason et al., 2024; Matties, 2024). Translating these gains to race performance suggests improvements of ~1–2% (Barrons et al., 2024), equivalent to ~79 seconds in a world-class men's marathon, based on the estimate that each 1% increase in velocity shortens finishing time by ~79 s (Langley & Langley, 2024).

Several studies have highlighted the positive impact of carbon fibre soles on RE (Sinclair et al., 2016; Rodrigo-Carranza et al., 2020; Beck, Golyski & Sawicki, 2020; Hébert-Losier et al., 2022; Joubert & Jones, 2022). Investigations of the Vaporfly and Alphafly have demonstrated both increased $VO_2$max (Beck, Golyski & Sawicki, 2020) and faster times in controlled 3 km and 5 km trials (Rodrigo-Carranza et al., 2023).

Hoogkamer et al. (2018) reported an average 4% improvement in RE (reduced oxygen consumption) at 14–18 km/h when running with a Vaporfly prototype compared with Nike Zoom Streak 6 flats and Adidas Adios BOOST 2 shoes, despite equalised shoe mass (+51 g). This was widely linked to the sub-2-hour marathon barrier, which Kipchoge later broke wearing the Vaporfly Next% (Hébert-Losier et al., 2022; McMillan, 2024). Barnes & Kilding (2019) confirmed similar benefits at matched speeds. In contrast, Healey & Hoogkamer (2021) cut the Vaporfly's carbon plate and found no significant change in RE (–0.55% ± 1.77%), suggesting that the plate alone does not explain performance benefits.

AFT outcomes appear to depend on multiple interacting factors. Internal influences include individual responses to specific shoe models (Chollet et al., 2023; Schwalm et al., 2024b), training level and genetics (Knopp et al., 2023), and biomechanical, physiological, and anthropometric characteristics (Roy & Stefanyshyn, 2006; Nigg, Subramanium & Matijevich, 2022; Atherton, McCarthy-Ryan & Wilkau, 2024; Mao, Li & Ruan, 2025). External factors include surface stiffness (Van den Bogert & Hamill, 2004; Smith, McKerrow & Kohn, 2017), running velocity (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Day & Hahn, 2020; Rodrigo-Carranza et al., 2022; Castellanos-Salamanca et al., 2023; Joubert et al., 2024; Yang et al., 2025), race distance (Kiesewetter et al., 2022; Hoeft, 2023; Perrin et al., 2025), and shoe mass (Frederick, 1984; Hoogkamer et al., 2016; Hoogkamer, Kram & Arellano, 2017). Design features such as midsole bending stiffness (Burns & Tam, 2020; McLeod et al., 2020; Ortega et al., 2021), foam compliance and resilience (Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2024; Aimar et al., 2024; Ferris et al., 2025), plate type and curvature (Roy & Stefanyshyn, 2006; Farina, Haight & Luo, 2019; Nigg, Cigoja & Nigg, 2021; Engel et al., 2024; Song et al., 2024), and stack height (Ruiz-Alias et al., 2023a,c; Barrons, Wannop & Stefanyshyn, 2023; Baumann et al., 2025; Kettner, Stetter & Stein, 2025) could further modulate outcomes (Ruiz-Alias et al., 2023b; Burns & Joubert, 2024; Yang et al., 2025).

To reliably capture these effects, methodology must account for device variability. Measuring RE requires at least two same-day trials, as day-to-day variability of metabolic systems can reach 14%, producing coefficients of variation in RE from 0.3–8.5% (Williams, Krahenbuhl & Mohan, 1991; Barrons et al., 2024). Averaging same-day measurements therefore provides more stable values, at least in moderately trained male runners.

Collectively, these findings indicate that AFT-related improvements in RE and performance arise from multiple interacting factors rather than any single feature such as the carbon plate (Healey & Hoogkamer, 2021; Atherton, McCarthy-Ryan & Wilkau, 2024). The following section examines these internal and external factors in greater detail, highlighting their roles in enhancing RE and performance and offering strategies to maximise AFT effectiveness at the individual level.

## 9. The Main External and Internal Factors Influencing the Working Mechanisms of Advanced Footwear Technology

Understanding AFT requires examining not only its design, but also the internal and external factors determining its effectiveness. Careful analysis of these variables is equally important for coaches and athletes choosing footwear, and for researchers refining methodologies to produce more objective and applicable evidence.

### *9.1. Running Velocity*

Running velocity strongly influences the effective realisation of AFT benefits. Nearly all previous studies have observed differences in RE and performance across velocities (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Day & Hahn, 2020; Hébert-Losier et al., 2023).

The observed differences are largely explained by velocity-dependent changes in running kinematics (stride length, frequency, vertical oscillation, etc.), which are known to vary substantially between lower and higher running speeds (Fukuchi, Fukuchi & Duarte, 2017). At lower velocities, the biomechanical conditions necessary to fully exploit AFT benefits may not be achieved, limiting the "shoe potential," since AFT is primarily designed for racing applications.

Day & Hahn (2020) confirmed this by comparing conventional shoes with models of increased and very high stiffness at velocities of 14, 17, and 20 km/h. RE improved significantly at 17 km/h in the stiffest shoes, despite being 50 g heavier than the control model — a weight difference too small to meaningfully affect RE (Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2020). Participants

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also reported greater comfort at higher velocities in stiffer shoes, supporting the hypothesis that velocity-dependent biomechanical changes, particularly at the ankle and MTPJ, influence AFT function (Hoogkamer, Kipp & Kram, 2019; Day & Hahn, 2020; Ortega et al., 2021; Matties, Kerr & Rowley, 2024).

The greatest RE improvements (~4%) have been reported at submaximal intensities of 14–18 km/h, corresponding to typical race-pace velocities in well-trained endurance runners (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Joubert & Jones, 2022). Barnes & Kilding (2019) found Nike Vaporfly shoes improved RE by 4.2 ± 1.2% and 2.6 ± 1.3% compared with Adidas Adios Boost 3 and Nike Matumbo 3 spikes at these velocities. Hoogkamer et al. (2018) reported nearly identical improvements when comparing Vaporfly to Adidas Adios Boost and Nike Zoom Streak 6, defining RE as energy consumption (W/kg). In this case, percentage improvements were consistent across all velocities tested, with the largest benefits at 18 km/h. It is important to note, however, that even 18 km/h is ~13% slower than the average marathon world record pace (21 km/h), limiting direct extrapolation of these findings to world-class performance. Future research should focus on elite marathoners, who already operate at exceptionally high RE.

### 9.2. Lower Intensities

Runner training level and baseline ("natural") RE, which differ between recreational and elite athletes, can strongly influence outcomes (Knopp et al., 2023). Nonetheless, improvements are also possible at lower intensities (Hébert-Losier et al., 2023; Joubert, Dominy & Burns, 2023; Burns & Joubert, 2024; Isherwood et al., 2024; Bolliger, Spengler & Beltrami, 2025).

Joubert, Dominy & Burns (2023) tested runners at 10 and 12 km/h in conventional and carbon-plated shoes, observing RE improvements of 0.9% and 1.4%, respectively, compared with conventional models. Similarly, Bolliger, Spengler & Beltrami (2025) reported significant reductions in oxygen consumption and heart rate ($p < 0.001$) in recreational runners wearing Cloudboom Echo 3 AFT shoes versus conventional and prototype models of the same brand, with no clear velocity-dependent effect.

Other studies have not found significant biomechanical changes at lower intensities. For example, Bolliger et al. (2025) observed no significant differences in step frequency, flight ratio, or leg stiffness (cf. Hoogkamer et al., 2018; Kiesewetter et al., 2022; Corbí-Santamaría et al., 2025). Interestingly, the most comfortable shoes were associated with higher oxygen cost, challenging the assumption that comfort directly improves efficiency (Luo et al., 2009; Van Alsenoy et al., 2023). Shoe material properties (Rodrigo-Carranza et al., 2024), mechanical behaviour (Hébert-Losier & Pamment, 2023; Rodrigo-Carranza et al., 2023, 2024), and design features (Aimar et al., 2024) may also be important determinants.

Hébert-Losier et al. (2023) compared habitual (OWN), minimal (FLAT), and Nike Vaporfly 4% (VP4) shoes in 18 male recreational runners. Each runner completed three 1.5 km trials (1.1 km at a self-selected comfortable pace and 400 m at perceived 5-km race pace). Minimal biomechanical differences were found between shoes, although FLAT produced higher step frequency and stiffness at slower velocities. VP4 reduced propulsion time and was perceived as more comfortable than FLAT, while OWN was rated most comfortable overall and least likely to cause injury. Comfort ratings appeared to depend more on individual perception than biomechanics, with running velocity strongly influencing perceptions.

Isherwood et al. (2024) investigated sex differences across three AFT models. Both innovation and commercial models lowered oxygen consumption and improved subjective perception compared with another commercial model. Although female runners exhibited higher vertical loading rates and reduced joint motion, these differences did not affect subjective ratings. Both sexes benefited from AFT at moderate velocities, supporting its relevance for recreational populations.

Although the magnitude of improvement at lower velocities is smaller than that observed at higher intensities, these findings suggest that AFT benefits extend beyond professionals to amateur and recreational runners. However, a "critical velocity" may be required to fully activate AFT mechanisms. Runners unable to reach this threshold may experience limited benefits and potentially increased injury risk due to altered biomechanics.

 doi:10.20944/preprints202510.1724.v1



*9.3. Distance Length*

Physiological and biomechanical differences across running distances are well established (Fukuchi, Fukuchi & Duarte, 2017; Bräuer et al., 2021; Kiesewetter et al., 2022). Although carbon-plated shoes are primarily designed for long-distance events (5 km to the marathon), relatively few studies have examined their impact in runs longer than 10 minutes (Kiesewetter et al., 2022; Hoeft, 2023; Milner et al., 2025; Perrin et al., 2025). This is noteworthy, as evaluating effects over extended durations would more closely reflect the physiological, biomechanical, and perceptual conditions of actual race distances.

Kiesewetter et al. (2022) analysed biomechanical and physiological responses during a 10 km run in three carbon-plated shoes (Puma Fast–FWD, Puma Fast-R, Nike Vaporfly Next %), which differed in plate configuration and midsole properties but not mass. Significant biomechanical adaptations were observed, particularly in footstrike pattern and joint kinematics, suggesting style adjustments to reduce lower-limb loading. Despite these biomechanical changes (e.g., maximum angular velocity, eversion velocity, heel strike angle), physiological measures such as heart rate and $VO_2$ did not differ significantly. A likely limitation was the relatively low exercise intensity (70% $VO_2max$), which may not have fully activated AFT benefits. In addition, runs were performed on separate visits, introducing day-to-day variability that may have reduced measurement reliability (Saunders et al., 2004; Perrin et al., 2025).

Hoeft (2023) conducted a similar study in which eight runners completed two 30-minute treadmill runs in carbon-plated versus non-plated racing flats. Participants were blinded to running velocity, and performance was expressed as changes in pace and speed. Carbon-plated shoes increased velocity by 0.237 km/h, equivalent to ~3.5 s/km (≈ 1.5% performance gain). However, physiological parameters (e.g., heart rate, RER, RE, RPE) showed no significant differences, although a non-significant 3.2% improvement in RE ($p = 0.184$) was observed during a submaximal warm-up.

Perrin et al. (2025) tested 13 well-trained male runners in a half-marathon treadmill trial at 95% of the second ventilatory threshold, comparing high longitudinal bending stiffness (HLBS; carbon-plated) versus standard stiffness (SLBS; conventional) shoes. Six-minute constant-velocity runs (12 km/h) were performed before and after the half-marathon to assess energy cost and ankle plantar flexor muscle force. No difference in energy cost was observed during the half-marathon itself, though HLBS shoes were marginally more economical (~1%) in the shorter pre- and post-trials. HLBS shoes also induced a greater reduction in plantar flexor force (–20.0 ± 9.8% vs. –13.3 ± 11.0%, $p = 0.048$) and were rated less comfortable (–1.2 ± 1.5 Borg points during the run and –0.8 ± 1.3 after). Biomechanically, HLBS shoes increased contact time and push-off duration while reducing step frequency, leg stiffness, and vertical stiffness.

These findings contrast with earlier reports suggesting that carbon-plated shoes reduce energy cost and mitigate fatigue (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Kirby et al., 2019; Hébert-Losier & Pamment, 2023; Castellanos-Salamanca et al., 2023). A potential limitation was the specific shoe model tested (Kiprun KS 900), in which the carbon plate was inserted as an insole rather than embedded in the midsole, differing from current AFT designs. Furthermore, trials were conducted over two sessions separated by 2–4 weeks, introducing individual variability and metabolic measurement instability that can affect outcomes (Williams, Krahenbuhl & Mohan, 1991; Barrons et al., 2024).

Recent findings by Madsen et al., 2025 indicated that carbon-plated shoes consistently demonstrated improved RE, lower heart rate, blood lactate, and oxygen consumption values over an 80-minute running session at 95% of lactate threshold, compared to non-plated shoe models. However, the progression of these physiological markers over time remained similar between shoe types. These results suggest that AFT improves RE without altering fatigue-related physiological responses, and that individual variability and spatiotemporal variables, such as contact and flight time, may play a key factor in performance outcomes.

Overall, these findings suggest that while AFT can alter running style, this does not always translate into improved RE. The duration of the distance is therefore an important factor, and further studies are needed to clarify the effects of AFT during prolonged running, particularly under fatigue conditions.

*9.4. Running Surface*

Different running surfaces exhibit varying stiffness levels, which influence shock absorption and thereby alter biomechanical patterns and potentially affect RE (Kerdok et al., 2002; Hardin, Van den Bogert & Hamill, 2004; Tung, Franz & Kram, 2014; Schütte et al., 2016; Smith, McKerrow & Kohn, 2017; Van Hooren et al., 2020; Nigg, Subramanium & Matijevich, 2022; Benson et al., 2022).

When conducting laboratory research, the mechanical properties of treadmill surfaces require careful consideration, as they can significantly influence metabolic and performance outcomes (Smith, McKerrow & Kohn, 2017; Benson et al., 2022). Motorised treadmill surfaces can either increase, decrease, or have no effect on energy consumption, depending largely on their stiffness (Tung, Franz & Kram, 2014; Smith, McKerrow & Kohn, 2017). Some treadmill surfaces equipped with additional shock absorbers can store and return up to 12% of mechanical energy (Kerdok et al., 2002; Smith, McKerrow & Kohn, 2017).

Smith, McKerrow & Kohn (2017) compared running on two treadmills (HP Cosmos vs. Quinton), which differed in surface stiffness by a factor of 4.5. The stiffer treadmill was associated with higher oxygen consumption, carbohydrate oxidation, heart rate, and perceived exertion, alongside lower fat oxidation. Similarly, Kerdok et al. (2002) demonstrated that reducing surface stiffness by 12.5 times lowered metabolic rate by 12% and increased leg stiffness by 29%, without notable changes in support mechanics (e.g., ground reaction force, contact time, stride frequency, stride length, vertical displacement of the centre of mass).

These results suggest that surface stiffness affects RE primarily through adjustments in leg stiffness, which help maintain centre of mass dynamics. Softer surfaces promote straighter leg mechanics, reducing muscle activity and energy demand (Kerdok et al., 2002; McMahon, Valiant & Frederick, 1987), likely due to enhanced shock absorption (Hoogkamer et al., 2018). A similar principle applies to track surfaces with added amortisation ("fast tracks"), where athletes often show notable performance improvements (McMahon & Greene, 1978).

9.4.1. Treadmill and Overground Running in the Analysis of AFT: Comparable or Not?

Despite these surface-related effects, most AFT studies are conducted indoors on motorised treadmills, raising questions about external validity. Van Hooren et al. (2020) compared treadmill and overground running, concluding that the two are broadly comparable but biomechanical differences - especially sagittal-plane kinematics at footstrike - must be considered. Benson et al. (2022) further noted that while some metrics, such as running power (Aubry, Power & Burr, 2018), may be similar across conditions, treadmill data cannot fully capture outdoor running dynamics.

Such differences complicate comparisons between treadmill-based RE studies and real-world overground performance (Kerdok et al., 2002; Smith, McKerrow & Kohn, 2017; Kipp et al., 2019; Van Hooren et al., 2020; Nigg, Subramanium & Matijevich, 2022; Benson et al., 2022). Future research should therefore prioritise overground testing using wearable sensors (e.g., IMUs), which have been validated for accuracy in field conditions (Bertschy et al., 2024; MacDonald et al., 2025).

9.4.2. Uphill, Downhill, and Level Running Conditions

While most AFT research focuses on flat-surface running, fewer studies have addressed incline and decline conditions.

Whiting, Hoogkamer & Kram (2022) tested Vaporfly shoes at treadmill inclines of +3° and –3° (~5%) at 13 km/h (3.61 m/s), reflecting gradients typical of the Boston Marathon. Vaporfly reduced energy consumption across all conditions compared with controls, though savings were ~1% smaller uphill (2.82%) and downhill (2.70%) than on flat terrain. Footstrike patterns shifted forefoot-uphill and rearfoot-downhill, suggesting that shoe design (e.g., stack height ratios, midsole properties) may require adaptation for gradients. Muzeau et al., 2025 observed similar results when testing trail

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running shoes with AFT foam compared to traditional running footwear. Although, the effect of the AFT on oxygen consumption was more pronounced (+2.1%) in the flat condition, uphill running also indicated ~1.0% RE improvement, whereas downhill running resulted in only a minor (+0.2%) improvement. By contrast, Hunter et al. (2022) observed no metabolic benefits when comparing Saucony Pro (carbon-plated) to conventional shoes across 0%, +4%, and –4% inclines (~2.3°). They concluded that incline-specific adaptations may not be necessary, opposing the earlier findings of Whiting et al. (2022).

Corbí-Santamaría et al. (2025) further reported no RE improvement when using AFT on varied outdoor terrain. However, biomechanical adaptations were evident, including reduced step frequency and increased vertical oscillation, especially on inclines. Runners also perceived reduced forefoot flexibility in AFT models, suggesting that shoes optimised for flat roads may not translate to unstable surfaces like trails.

Overall, evidence regarding AFT effectiveness on gradients is inconsistent and strongly dependent on shoe model, running velocity, incline level, and individual response. This underscores the need for shoe designs adapted to varied surfaces to maximise AFT benefits.

### *9.5. The Role of Shoe Mass in Running Economy: Reevaluating Its Impact on AFT*

Earlier studies consistently showed an inverse relationship between shoe mass and RE, with oxygen cost increasing by approximately 1% per additional 100 g (Frederick, 1984; Franz, Wierzbinski & Kram, 2012; Hoogkamer et al., 2016). Frederick (1984) first reported this trend, and Franz et al. (2012) confirmed nearly identical effects, observing $VO_2$ increases of 0.92% (barefoot) and 1.19% (shod) per 100 g. Hoogkamer et al. (2016) likewise reported a 1.11% increase in metabolic rate at 12.6 km/h and a 0.78% slower 3000 m time trial for each 100 g added to racing flats.

In AFT, however, mass interacts with advanced design features, making the classic 1% rule less predictive (Joubert & Jones, 2022). Cushioning and midsole material properties exert a major influence on locomotion economy (Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2023, 2024; Aimar et al., 2024). Thicker cushioning layers can improve RE more than lighter weight alone, as added mass near the body's centre of mass reduces moment of inertia and energetic cost (Frederick, 1984; Scholz et al., 2008; Barnes & Kilding, 2019). Combined with longitudinal bending stiffness (LBS) and carbon plates, such cushioning enhances the conditions for reducing energy consumption (Hoogkamer et al., 2018; Barnes & Kilding, 2019; Rodrigo-Carranza et al., 2023).

Empirical evidence supports this. Joubert et al. (2024) reported a 2% improvement in RE with AFT road shoes and spikes versus conventional models, with the heavier road shoes showing the greatest benefit. Barnes & Kilding (2019) found that Nike Vaporfly (205 g) improved RE by 4.2 ± 1.2% compared with Adidas Adios Boost 3 (236 g) and by 2.6 ± 1.3% compared with Nike Matumbo spikes (118 g) at velocities of 14–18 km/h. Despite being 87 g heavier than the spikes, Vaporfly retained a 2.9 ± 1.3% RE advantage even after additional mass was added to match the Adidas shoe. Similarly, Hoogkamer et al. (2018) reported ~4% lower metabolic cost for Vaporfly versus Adidas Adios Boost and Nike Zoom Streak 6 when shoe masses were equalised.

These results suggest that while shoe mass clearly influences conventional footwear (Frederick, 1984; Franz et al., 2012; Hoogkamer et al., 2016), the effect cannot be directly applied to AFT, particularly road models introduced since 2017 (Joubert & Jones, 2022).

The impact of shoe mass likely depends on both distance and velocity. At higher velocities, differences of up to 50 g appear negligible (Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2020). In contrast, over shorter distances shoe mass may play a greater role, whereas in longer races midsole properties are more decisive, facilitating energy return and sustaining economical technique over time (Ruiz-Alias et al., 2023b; Hoogkamer et al., 2018).

### *9.6. Training Level, Racing Performance, and Individual Variability in Response to AFT*

Individual response and training level are major factors influencing adaptation to AFT and the benefits gained. Identical shoe models can elicit highly individualised biomechanical responses

(Mao, Li & Ruan, 2025), resulting in markedly different effects on RE (Knopp et al., 2023; Burns & Joubert, 2024). This complexity makes it difficult to define the overall effect of AFT, particularly from a biomechanical standpoint (Nigg, Subramanium & Matijevich, 2022; Schwalm et al., 2024b).

Based on response, runners can be classified as non-responders, positive responders, or negative responders (Joubert & Jones, 2022; Knopp et al., 2023). These differences are associated with natural RE, training level (Joubert & Jones, 2022; Knopp et al., 2023; Rodrigo-Carranza et al., 2023), individual biomechanics (Mao, Li & Ruan, 2025), and potentially shoe-specific biomechanical "skills" required to exploit a model's full potential (Schwalm et al., 2024b). Gradual integration of AFT into training may further maximise benefits (Matties & Rowley, 2023).

AFT often alters spatio-temporal variables, which can improve, reduce, or have no effect on RE depending on the runner (TenBroek et al., 2014; Joubert & Jones, 2022; Matties, 2024). For high-level athletes with already stable running biomechanics and efficient RE, improvements could be smaller, as their efficiency is close to physiological limits (Joubert & Jones, 2022; Knopp et al., 2023). In contrast, recreational runners, whose gait patterns may be less stable, are more responsive to shoe-induced changes (Chapman et al., 2008; Joubert & Jones, 2022; Rodrigo-Carranza et al., 2023), but it does not always lead to a positive outcome (e.g., improved RE). Among recreational runners, RE improvements often correlate with subjective comfort, with greater RE gains observed in shoes rated more comfortable (Van Alsenoy et al., 2023).

Transitioning to new footwear, however, can present risks. Eken et al. (2025) found that runners reported higher discomfort and injury incidence when switching to cushioned shoes (On CloudSurfer) compared with their habitual footwear during an eight-week transition. Biomechanical changes induced by AFT may therefore enhance or impair performance depending on how well an individual's biomechanics align with the shoe's design. Joubert & Jones (2022), for example, compared seven carbon-plated models and reported that fewer than 10% of runners shifted fully to a forefoot strike pattern. The lowest responder in Nike Alphafly already exhibited high natural RE, with cadence averaging 186 steps/min and vertical oscillation ~8.5 cm, compared with higher-responding runners who had lower cadence and greater oscillation.

Rodrigo-Carranza et al. (2023) compared carbon-plated shoes with increased LBS to control models in trained and national-level runners. At both submaximal intensities (9–13 km/h) and in 3000 m time trials, trained runners showed greater improvements than national-level athletes. Among national-level runners, improvements were observed only at high velocities, again attributed to already elevated baseline RE.

Knopp et al. (2023) compared three carbon-plated shoes and racing flats in world-class Kenyan and amateur European runners at ~70–75% "$VO_2$"max (marathon pace). Amateur runners demonstrated RE changes ranging from +9.7% to –1.1%, while Kenyan runners ranged from +11.4% to –11.3%. Barnes & Kilding (2019) likewise found substantial inter-individual variability, with RE differences of 1.72–7.15% between Nike and Adidas models and 0.50–5.34% between Nike road shoes and spikes.

These findings indicate that despite training level or genetic advantages, large inter-individual variations exist in response to AFT (Barnes & Kilding, 2019; Knopp et al., 2023; Mao, Li & Ruan, 2025). It cannot be unequivocally stated that AFT guarantees improvements in RE or biomechanics, nor are benefits evenly distributed across runners (Joubert & Jones, 2022; Schwalm et al., 2024b). Runners whose biomechanics align more closely with a shoe's design "sweet spot" have greater potential to benefit, which also explains why elite athletes often use prototypes customised to their biomechanical, anthropometric, and physiological characteristics.

*9.7. AFT and Fatigue Resistance*

A growing body of research has linked AFT to improved neuromuscular fatigue resistance in long-distance running. These effects suggest that AFT may not only help maintain performance but also delay fatigue-related declines in RE, offering potential benefits for endurance athletes beyond immediate performance.

Ruiz-Alias et al. (2023d) tested thirteen highly trained athletes in 9-minute and 3-minute time trials using Nike ZoomX Dragonfly track spikes and Nike ZoomX Vaporfly Next% 2 road shoes. Although pace differences were not statistically significant ($p \geq 0.072$), runners in AFT shoes increased pace in the final lap, unlike those in spikes. Ground contact time decreased across the session, and stride length tended to increase with AFT. Most notably, neuromuscular fatigue was lower: countermovement jump height decreased by –5.6% in spike users compared with only –0.61% in AFT users. These findings suggest that AFT may help sustain propulsion efficiency and cushioning during prolonged running, enhancing fatigue tolerance.

Similarly, Castellanos-Salamanca et al. (2023) compared Vaporfly Next/textpercent 2 shoes with conventional models during interval training (5 × 1000 m, 90 s recovery). AFT shoes improved training performance by 2.4% (p = 0.009) without significant changes in heart rate or running power and were associated with reduced neuromuscular fatigue and perceived muscle pain. Countermovement jump height decreased less following the AFT session, supporting its potential role in attenuating fatigue. In agreement, Kirby et al. (2019) reported that recreational runners wearing Vaporfly 4% shoes experienced less post-marathon muscle soreness and muscle damage compared with conventional footwear.

Beyond fatigue outcomes, Xu et al. (2025) examined how carbon plate geometry influences biomechanics under fatigue. Compared with flat plates, curved plates reduced hip and knee contact angles, decreased hip flexion moments, and modified tibialis anterior activation patterns both before and after fatigue exposure. These adaptations may contribute to maintaining efficiency and lowering musculoskeletal load under fatigue.

### *9.8. The Role of Footstrike Patterns*

Footstrike patterns can considerably alter running kinematics, thereby influencing RE and overall efficiency. AFT is often associated with biomechanical adaptations, as runners adjust their gait to the shoe's mechanical features. Footstrike-related kinematic changes may positively, negatively, or neutrally affect RE. No single running style has been proven superior with AFT, although emerging evidence points to potential trends warranting further investigation.

Hoogkamer et al. (2018) compared the Nike Zoom Vaporfly prototype with traditional marathon shoes (Nike Zoom Streak 6) and the then–world record model, adidas adizero Adios BOOST 2. Energy consumption did not differ significantly between heel, midfoot, or forefoot strikers. However, a borderline shoe–footstrike interaction (p = 0.0502) suggested slightly greater benefits for dominant rearfoot strikers.

A similar interaction is seen with sole stiffness (McLeod et al., 2020; Ortega et al., 2021). McLeod et al. (2020) tested six custom-made carbon fibre soles of varying stiffness at lower (2.98 m/s) and higher (4.47 m/s) velocities. Heel strikers benefited most from greater stiffness at higher intensities, likely due to kinematic differences that placed them in a more favourable position than midfoot strikers. Terrain may also modulate these effects. Fukuchi et al. (2024) tested AFT trail shoes with an inserted carbon sole and found that the curved plate design produced greater forefoot benefits during uphill running, where forefoot loading is naturally increased.

Martinez et al. (2024) further analysed super shoes (Nike Vaporfly Next% 2) in relation to footstrike pattern, reporting a 4.2% improvement in metabolic power compared with control shoes. Importantly, no significant interaction emerged between footstrike pattern and the metabolic benefit.

At present, relatively few studies treat footstrike as a primary determinant of AFT effectiveness. Instead, most mention footstrike as a possible secondary factor or hypothesis, inferred from kinematic and RE data. To establish more objective patterns, further dedicated research is required.

### *9.9. Sex Differences in Biomechanical and Performance Outcomes with AFT*

When evaluating the influence of AFT on RE and performance, it is essential to consider sex differences. Anatomical and physiological distinctions can influence biomechanical parameters during running and may shape the extent to which athletes benefit from AFT footwear.

Since the release of AFT in 2017, performance improvements have been particularly notable in women across distances from 1500 m to the marathon (Bermon et al., 2021; Senefeld et al., 2021; Langley et al., 2023; Mason et al., 2024; Willwacher et al., 2024). Analyses of elite performances show that women improved by ~1.7–2.3% compared with 0.6–1.5% in men, corresponding to ~2 minutes faster marathon times (Bermon et al., 2021). Similar findings have been reported by Langley et al. (2023), who observed ~1.7% gains across 10 km, half-marathon, and marathon in the fastest female runners during the AFT era, with greater improvements in AFT adopters compared with controls. Senefeld et al. (2021) further showed that among the top 50 male and female finishers in World Marathon Majors, women improved by 4.3 minutes compared with men's 2.8 minutes, with relative improvements of 1.6% versus 0.8%. Overall, these gains have contributed to narrowing the performance gap between men and women from ~12% to ~8–9% over long-distance events (Mason et al., 2024).

Several factors may underlie these observed differences. One explanation relates to physiological reserve and training history. Men's performances have historically clustered more closely to physiological ceilings, whereas women may retain greater room for improvement (Mason et al., 2024).

Intensity levels and velocity thresholds may also be important. Some evidence suggests that AFT benefits manifest most clearly above certain running velocities, while studies at lower velocities and in recreational runners report more modest or inconsistent effects (Isherwood et al., 2024; Hébert-Losier et al., 2023; Joubert, Dominy & Burns, 2023; Burns & Joubert, 2024). This may be linked to velocity-dependent alterations in running biomechanics (Fukuchi, Fukuchi & Duarte, 2017).

Finally, biomechanical and anthropometric factors may influence AFT benefits. Energy-saving effects depend on compressing the foam midsole and flexing the sole during stance. Carbon plates with greater stiffness require substantial muscle force to deform the midsole. Studies on midsole stiffness, even before carbon plates were introduced, show that heavier or stronger athletes gain greater metabolic savings due to enhanced foam compression (Roy & Stefanyshyn, 2006; Oh & Park, 2017). For example, Roy & Stefanyshyn (2006) reported ~1% RE improvements with stiffer midsoles, with heavier runners benefiting more. Oh & Park (2017) likewise observed an inverse correlation between body mass and "$VO_2$" change in shoes with medium stiffness. While direct evidence in AFT-specific footwear is limited, these principles may partly explain why individual response varies across sexes.

Given the limited and variable evidence, it remains premature to determine whether one sex consistently derives greater benefit from AFT. Future research should aim to clarify whether anatomical, physiological, or biomechanical differences underpin the observed patterns.

### *9.10. The Evolving Role of AFT in Trail and Mountain Running Biomechanics and Performance*

The popularity of trail running has grown significantly in recent years, and an increasing number of running shoe manufacturers now offer AFT specifically designed for trail conditions. However, evidence on their effectiveness remains limited, making it difficult to evaluate the role of AFT in trail performance.

Traditionally, carbon-plated shoes have been designed for smooth, flat surfaces, most often asphalt. Trail running, by contrast, takes place in natural environments with diverse terrains such as mountains, slopes, meadows, and forests (International Trail Running Association, [n.d.]; Fukuchi et al., 2024), with asphalt typically representing only ~20% of total distance (Corbí-Santamaría et al., 2023). Such surface differences substantially alter running biomechanics, meaning results from asphalt cannot be directly extrapolated to trails (Hamill et al., 2022; Corbí-Santamaría et al., 2023). Open questions remain as to whether the design of AFT shoes, often characterised by minimal ankle and foot joint stabilisation, can be reconciled with the stability and containment requirements of trail running, and whether including these support functions could allow AFT to deliver comparable improvements to those observed on asphalt.

Several models of carbon-plated trail shoes with modified outsole surfaces and added tread are now available, but most retain very light and thin upper constructions. Moreover, the increased stack height typical of carbon shoes is known to reduce stability and may even increase injury risk on uneven surfaces (see chapter Stack Height; Whiting, Hoogkamer & Kram, 2022). This likely contributes to

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the absence of consistent performance benefits in trail running, although biomechanical effects have been observed (Corbí-Santamaría et al., 2025), similar to those reported in road-running AFT studies (Perrin et al., 2025). Another limiting factor is the scarcity of empirical data, as trail-specific AFT is still relatively new. In addition, laboratory-based performance testing is almost impossible in trail conditions. While treadmill running may help predict potential trends, it cannot replicate natural trail environments.

9.10.1. Current Research Findings in Trail Running

To the authors' knowledge, only a few studies have examined the impact of carbon-plated shoes on RE under natural trail conditions.

Fukuchi et al. (2024) compared trail-specific shoes (Carbitex Speedland—considered the world's first hyper-performance trail running shoe, combining high-quality materials with comfort and sustainability (Speedland, 2024)) with and without carbon soles in eleven runners. Testing was performed over a 50-metre marked section including ~18.5% ascent and ~17.2% descent, run at self-selected comfortable velocity for 10 minutes each. Segment acceleration and plantar pressure were assessed using IMU sensors. No significant differences were found in velocity, contact time, foot acceleration, or maximum plantar pressure across the four-foot regions (toes, metatarsals, midfoot, heel). However, carbon-plated shoes produced lower maximum axial acceleration of the lower leg during uphill running and slightly higher forefoot pressure. This likely reflects biomechanical adaptations, as uphill running requires a forward lean and increased forefoot loading (Hunter et al., 2022).

The authors proposed that this forefoot shift may enhance the spring-like effect of the carbon sole. Specifically, the curved plate increases LBS, limits foot flexion, and promotes energy savings (Ortega et al., 2021). Consequently, AFT for trail running may be more effective uphill than downhill, since forefoot activation is more pronounced during uphill running (Hunter et al., 2022). A limitation of this study was the relatively low running velocity (2.5 m/s) and short uphill/downhill distances (11 m), which may not have allowed the shoes to demonstrate their full potential (Burns & Joubert, 2024).

A recent study by Corbí-Santamaría et al. (2025) supports these observations. Although AFT did not improve simulated mountain running performance or physiological responses, it significantly altered biomechanics, reducing step frequency and increasing vertical oscillation of the centre of mass, particularly on variable terrain.

Finally, one of the earliest studies assessing physiological variables reported ~1% improvement in RE and reduced perceived effort when running in carbon-plated shoes compared with traditional footwear across different gradient conditions, with the most pronounced effect observed on flat terrain (Muzeau et al., 2025). However, a key limitation of this study was that all trials were conducted on a treadmill, which cannot accurately be translated to real-life trail running conditions (Benson et al., 2022).

Despite the limited and mixed evidence, manufacturers continue to develop AFT models for trail running. More comprehensive studies are required to identify the optimal design features that balance stability and support while maximising potential RE benefits under the unique biomechanical demands of trail environments.

## 10. The 'Barefoot Running Era': Lessons for Modern Running Technology

In 2009, Christopher McDougall published Born to Run. By 2010, interest in barefoot running peaked, with online search volumes rising by more than 80% from their previous maximum (Tiller, 2023). Many runners altered their training habits, motivated by claims that barefoot running reduced injury risk, encouraged a more natural gait, and improved RE (Tam, Tucker & Astephen Wilson, 2016). Although the barefoot and minimalist running trend has since declined, overtaken by AFT, valuable insights from this period remain relevant for understanding the mechanisms underlying modern footwear.

*10.1. Barefoot vs. Minimalist Shoes: Key Differences in Running Style*

Although barefoot and minimalist running are often treated as synonymous, biomechanical studies show clear differences (Bonacci et al., 2013; Fuller et al., 2016, 2017). Barefoot running produces distinct kinematic and kinetic adaptations compared to minimalist shoes, including reduced ankle dorsiflexion at initial contact, greater plantar flexion at push-off, and reduced knee flexion at midstance (Bonacci et al., 2013; Frederick, 1984; Moore, Jones & Dixon, 2014; Worobets et al., 2014).

Muscle activation also differs - intrinsic foot muscles (e.g., flexor digitorum brevis, abductor hallucis) are more active in shod conditions (Kelly et al., 2016; Bell, Hibbert & Domire, 2020), whereas barefoot running elicits greater pre-activation of the triceps surae (Divert et al., 2005).

Importantly, transitioning between styles is not always straightforward. Prior use of minimalist shoes does not guarantee an easy shift to barefoot running. In fact, Mills, Collins & Vicenzino (2022) reported that participants transitioning from minimalist to barefoot running had twice the dropout rate compared with those transitioning from conventional shoes to minimalist footwear. Although minimalist shoes can facilitate a gradual adaptation, success is not assured (Azevedo et al., 2016). These findings underscore the distinct biomechanical demands of each style and the variability in individual capacity to adapt.

*10.2. Shoe Mass*

Shoe mass is closely linked to RE. Oxygen consumption ( "$VO_2$") typically decreases by ~1% for every 100 g of shoe mass removed and increases by a similar amount when added (Frederick, 1984; Franz, Wierzbinski & Kram, 2012; Hoogkamer et al., 2016). However, the relationship is complex, as other factors interact with shoe mass (Frederick, 1984; Moore, Jones & Dixon, 2014; Tiller, 2023).

Franz, Wierzbinski & Kram (2012) found nearly identical oxygen and energy consumption between barefoot and minimalist shoes, yet 8 of 12 runners showed better RE in minimalist shoes despite greater mass. Even when mass was equalised, "$VO_2$" cost and metabolic power remained 3.4% lower in shod than in barefoot running. Adding +150 g increased oxygen and energy cost by ~4%, whereas tripled shoe mass produced inconsistent results; "$VO_2$" was not significantly different (2.6% lower in shoes, $p = 0.099$), although metabolic power remained 3.3% lower when shod. Divert et al. (2008) also showed that mass, rather than shoe type, was the critical factor affecting oxygen consumption. Testing barefoot, standard and weighted diving socks, and matched-mass shoes, they found significant effects of added mass but not shoe type. These results caution against attributing superior economy solely to barefoot running.

A 20-week transition study found that >70% of runners adapted to barefoot running through minimalist shoes, but 19 participants dropped out due to pain or discomfort (e.g., calf or foot pain), and two sustained injuries (Achilles tendinopathy, calf strain) (Mills, Collins & Vicenzino, 2022). Runners with a rearfoot strike in conventional shoes may face higher risks during transition, as barefoot running requires a midfoot or forefoot strike to compensate for reduced cushioning (Fuller et al., 2016). Frederick (1984) described this as the “cost of cushioning,” involving acute gait changes such as shorter stride length, higher step frequency, reduced vertical oscillation, and greater plantar flexion at push-off (Frederick, 1984; Moore, Jones & Dixon, 2014; Worobets et al., 2014; Fuller et al., 2016). While often associated with improved RE, these adaptations must be considered alongside other compensatory mechanisms to avoid oversimplified conclusions (Bonacci et al., 2013).

*10.3. Individual Factors and Responses*

Transitioning to barefoot or minimalist running induces acute biomechanical changes, yet long-term adaptations remain uncertain (Hollander et al., 2017). Reducing sole thickness typically results in shorter, faster strides and often a shift from rearfoot to mid-/forefoot striking, which helps attenuate impact forces (Sinclair et al., 2014; Tung, Franz & Kram, 2014; Fuller et al., 2016, 2017; Lindlein et al., 2018). However, these adaptations also increase energy demands at the ankle, placing greater load on the gastrocnemius, soleus, tibialis anterior, and tibialis posterior, which can accelerate fatigue over longer distances (Bonacci et al., 2013; Mills, Collins & Vicenzino, 2022).

Many less-trained runners cannot perform rapid gait adjustments due to insufficient muscular conditioning (Moore, Jones & Dixon, 2014), often resulting in foot, calf, or Achilles pain (Bonacci et al., 2013; Mills, Collins & Vicenzino, 2022). In such cases, a preparatory period of strength training for relevant muscle groups may be necessary before transitioning (Tam et al., 2017). Not all runners adapt similarly: after eight weeks of minimalist shoe running, half of participants showed no gait changes (Tam, Tucker & Astephen Wilson, 2016). Adaptation depends largely on training level, footstrike pattern, and individual variability, meaning some runners experience positive, neutral, or even negative responses (Tam et al., 2017; Abolins et al., 2018; Mills, Collins & Vicenzino, 2022). Shifting load from the knee to the ankle may be advantageous for runners with chronic knee pain and could reduce impact at an optimal stride frequency (Divert et al., 2005; Bonacci et al., 2013). However, evidence for such benefits remains limited.

### *10.4. Loading Rate of Vertical Ground Reaction Forces*

The loading rate (LR) describes the slope of vertical ground reaction forces during foot strike. Higher LR values (a steeper force increase at landing) are typically linked to greater injury risk. Barefoot running is often associated with reduced LR, primarily due to a shift from rearfoot to mid-/forefoot striking (Lieberman et al., 2010; Tam, Tucker & Astephen Wilson, 2016). However, no consistent relationship between barefoot running and injury risk has been established (Tam et al., 2017; Bell, Hibbert & Domire, 2020).

Tam et al. (2016) reported that habitual shod runners displayed a 54% higher average LR when running barefoot, with wide inter-individual variability (12.3–622.8 BW/s barefoot vs. 27.2–315.3 BW/s shod). This counterintuitive finding highlights that LR, and average ground reaction forces may be similar between conditions; higher LR values occur primarily when runners continue striking with the rearfoot (Shih, Lin & Shiang, 2013; Tam et al., 2016). Thus, benefits such as reduced LR may only emerge when runners successfully adapt their gait to a mid-/forefoot strike, whereas non-responders who fail to adjust maintain higher LR and derive little benefit (Abolins et al., 2018; Mills, Collins & Vicenzino, 2022).

### *10.5. Muscle Stiffness*

Barefoot running is frequently promoted as strengthening the foot and improving the natural impact response by enhancing stiffness in the muscle–tendon–ligament complex. However, current evidence does not fully support this assumption.

Bell, Hibbert & Domire (2020) reported no increases in internal foot structure stiffness when running in minimalist shoes compared with conventional footwear. The only difference observed was greater stiffness in the hallucis tendon of the flexor under shod conditions. Similarly, Tam et al. (2017) found greater ankle joint stiffness in shod compared with barefoot running.

These findings suggest that barefoot running does not necessarily enhance structural stiffness as commonly claimed and may even elevate injury risk if higher loading rates are not accompanied by sufficient adaptation in musculoskeletal structures (Bell, Hibbert & Domire, 2020).

## 11. Conclusions

Despite extensive study of AFT in recent years, important misconceptions and uncertainties remain regarding its working mechanisms and performance benefits. Much of this stems from methodological limitations, including: (1) difficulty explaining how individual shoe components contribute to overall improvements in RE and performance; (2) challenges in linking biomechanical changes to metabolic outcomes; (3) over-reliance on group means rather than individual differences; and (4) the predominance of treadmill-based testing rather than field studies. Nevertheless, several clear insights can be drawn from the evidence, along with directions for future research.

1. The carbon fiber plate is not the sole performance determinant; improvements result from the combined interaction of multiple design features and should be evaluated holistically.
2. Shoe mass has a limited influence. The traditional rule of a 1% increase in oxygen cost per 100 g does not fully apply to AFT; heavier shoes with advanced features can still outperform lighter, less advanced models.
3. Individual adaptation is crucial. The same AFT model can produce different running economy effects across runners, depending on biomechanical compatibility and the ability to utilize specific movement patterns.
4. Efficiency must be balanced with injury risk. While AFT can improve speed and economy, long-term effects on musculoskeletal health are unclear. High stack height with low weight may reduce stability and increase injury risk, especially in runners with weakness, poor control, or excessive pronation.
5. Performance gains may be reduced on trail surfaces. Technologies designed for asphalt do not consistently transfer to uneven terrain, highlighting the need for trail-specific AFT development.
6. AFT primarily influences biomechanics rather than physiological parameters, with the greatest effects observed on stride mechanics, contact time, and force application, particularly at higher speeds.
7. Velocity influences the magnitude of benefits. Submaximal speeds close to race pace tend to maximize AFT effects and comfort, whereas improvements are smaller at lower speeds due to mechanical constraints.
8. Recreational runners also benefit, though to a lesser extent than elite athletes, and only when their biomechanics align with the shoe's functional design.
9. Current "super spikes" provide smaller performance gains than AFT road shoes, likely due to lower cushioning and reduced shock absorption despite their lighter mass.

## 12. Future Directions

Further research is needed to clarify the long-term health effects of AFT, particularly its influence on musculoskeletal function and injury risk with sustained use. More field-based studies are required to complement treadmill investigations, using wearable sensors to capture natural biomechanics in training and competition. Moreover, further research should be done in prolonged running distances and in velocity close or equivalent to race pace, monitoring the effects of AFT in fatigue conditions, more objectively describing the working mechanisms of AFT in race conditions. Understanding individual variability remains essential, with future work focusing on personalised shoe–runner matching to optimise benefits and reduce risks. Finally, research should expand into trail-specific AFT designs and durability testing to guide both competitive and recreational applications of this rapidly evolving technology.

**Notes on contributor(s):** First author: Literature search and analysis, writing. Second author: Conceptualisation, literature analysis, writing, editing, supervision.

**Funding:** This research was funded by Riga Stradins University through the Student Research and Innovation Grants program.

**Generative AI statement:** During the preparation of this manuscript, generative AI tools (ChatGPT, OpenAI, San Francisco, CA, USA) were used to improve the clarity, flow, and grammar of the text. The authors carefully reviewed and edited the content and take full responsibility for the final version.

**Disclosure statement:** The authors declare that they have no conflicts of interest related to this research.

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