May 6th 2017, Monza, Italy. Eliud Kipchoge almost breaks the seemingly impossible barrier of two hours for a full marathon, finishing after just two hours and 25 seconds. On his feet were prototypes of the now infamous Nike Vaporfly shoes. What was then thought to be a small piece of the puzzle to breaking the two hour marathon, ended up in a worldwide shoe debate when Kipchoge managed to run a time of 1.59.40 in Vienna on October 12th 2019. Now in 2020, almost every major running brand has a shoe on the market which shares a couple of characteristics. Most of them have a high stacked, resilient, lightweight midsole foam combined with a carbon fibre plate. Combined, these have been thought to improve running economy, a major contributor to distance running performance. But how much of this claim is marketing? And how much is backed up by scientific evidence?

The concept of adding carbon fibre plates to midsoles is not new and goes back to the early 2000's, when Stefanyshyn and Nigg showed that an increase in longitudinal bending stiffness (a material property which describes a shoe's resistance to bending) lead to a higher vertical jumping height. A few years later it was found that stiffer shoes could also improve running economy by approximately 1%. However if the shoes were too stiff, this effect disappeared (Roy & Stefanyshyn, 2006).

There are a couple of biomechanical mechanisms which explain how increased bending stiffness can improve running economy. The most pronounced effects are seen at the metatarsophalangeal (MTPJ) and ankle joints. Stiffening the shoe limits the bending of the MTPJ, which causes a reduction in negative work. This means that less energy is wasted at the joint, and more can be used for propulsion (Willwacher et al., 2013).

Furthermore, running in stiffer shoes causes the point of application of the ground reaction force to shift more anteriorly, creating a longer lever arm around the ankle and MTPJ (Willwacher et al., 2014). A longer lever arm permits the muscle tendon units surrounding the joint to generate higher joint moments (see figure 1). As the ankle is responsible for propulsion during the end of the push-off phase of the gait cycle, you should be able to run faster in stiffer shoes as long as your calf muscles are strong enough.

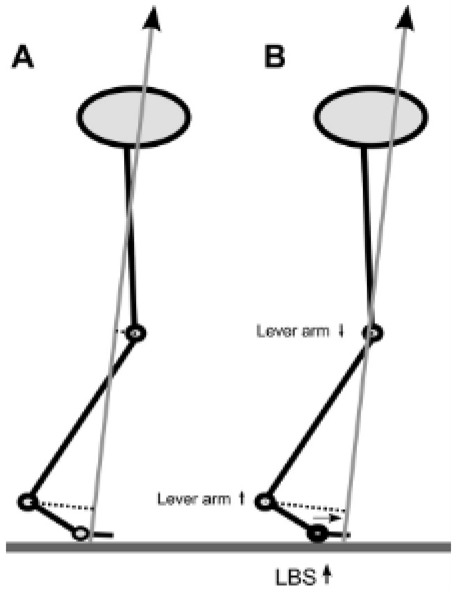

Figure 1: An increase in LBS (B) causes an anterior shift of the ground reaction force, increasing the lever arms at the ankle and MTPJ (Figure from Willwacher et al., 2014).

Up until this point, studies have been inserting flat carbon fibre plates in midsoles which could improve running economy by around 1%. Traditionally, long distance racing shoes had been made to be as light as possible, with very minimalist designs. The shoe which completely changed this paradigm was the Nike Vaporfly. Due to the use of an extremely light weight PEBAX foam for the midsole, this allowed Nike to significantly increase the stack height of the shoe without compromising for weight. This also gave more space to use a curved plate instead of a flat one. In a study done by Hoogkamer et al., which was published after the first breaking 2 attempt in 2017, it was found that this combination of a lightweight, resilient and compliant foam together with a curved carbon fibre plate improved running economy by 4% compared to the two fastest marathon shoes at that time (Hoogkamer et al., 2017). Nike named their commercial model of the Vaporfly after the results of this study: the Vaporfly 4%.

In a follow up study, Hoogkamer et al. tried to explain this difference in metabolic cost. It was shown that the Nike Vaporfly shoe reduced negative MTPJ work, in line with earlier studies with flat plates. The myth that the carbon fibre plate itself acted as a spring was debunked as the midsole foam returned almost 50 times more energy after compression than the plate did from bending. It was thus concluded that the midsole foam played a larger role in lowering the metabolic cost, compared to just the plate (Hoogkamer et al., 2018).

Nowadays, lots of studies are being done to investigate how running shoe properties alter running economy and biomechanics. Some of these results include that the optimal stiffness in running shoes is speed dependant (Day & Hahn, 2020), (Mcleod et al., 2020) and that running in stiffer shoes redistributes the positive work from the knee to the MPTJ (Cigoja, 2019). In a recent review, Benno Nigg summarizes six main parameters which have shown to influence running economy, and at what magnitude. They are: Shoe weight, midsole material, heel thickness, longitudinal bending stiffness (flat sole shape), longitudinal bending stiffness (curved sole shape), longitudinal bending stiffness and muscle mechanics. Contrary to popular belief, Nigg claims that the midsole material does not matter all that much, as the energy which is put into midsole during landing is returned at the wrong time. The biggest contributor he thinks is the use of a curved, stiff plate. By using a curved plate instead of a flat one, this creates a so called 'teeter-totter' effect (see figure 2). Because the point of application of the resultant ground reaction force is at the front of the foot during the second half of ground contact, a reaction force at the heel is produced in an upward direction at toe-off. This reaction force at the heel will propel the runner forward more than in conventional running shoes. When designing a carbon fibre plated shoe it is important to take into account both the stiffness and the curvature of the plate.

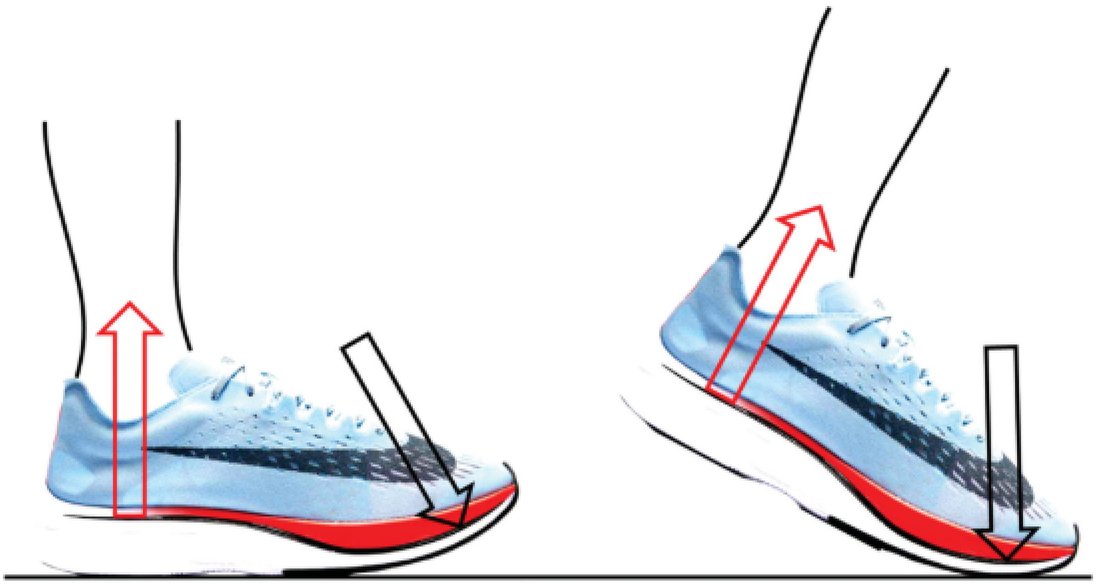

Figure 2: A schematic representation of the 'teeter-totter' effect. The force of the runner is applied at the front of the foot (black arrow) and creates a resultant force (red arrow) at the heel, propelling the runner forward (Nigg et al., 2020).

Even though shoe companies have been limited by World Athletics to have a maximum stack height of 40mm, there is still plenty of development to be done. Future projects will likely focus on the synthesis of lighter, more responsive midsole foams as well as experiment with different geometries for maximal efficiency.

To conclude, carbon fibre plates have shown to improve running economy but simply adding a carbon fibre plate does not directly relate to better performance. The optimal stiffness for a running shoe is both, dependant on running velocity and individual biomechanical differences. It is an exciting time to be a runner, as shoe companies are pushing their boundaries to produce the tools for the best possible running experience and results.

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