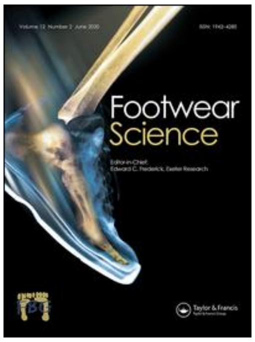

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COMMENTARY

Effects of running shoe construction on performance in long distance running

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In recent editorials of the *British Journal of Sports Medicine* (Burns & Tam, 2020) and *Footwear Science* (Frederick, 2020; Hoogkamer, 2020), the effect of midsole construction on running performance was discussed, probably in an attempt to provide context concerning the discussion of the new Nike Vaporfly 4%. Burns and Tam (2020) primarily debated the midsole characteristics (e.g. resilient midsole material, high stack height) of the Nike Vaporfly 4% and called for limiting the maximum midsole thickness. Frederick (2020) and Hoogkamer (2020), however, highlighted that there is currently not sufficient evidence justifying the regulation of competition marathon shoes. The fact that only midsole characteristics have been discussed initially by Burns and Tam (2020) suggest that the authors think that midsole thickness is the most important aspect contributing to changes in performance and/or that there are no other major aspects important for changing performance of a running shoe. In our view, such a conclusion is not correct. With this letter, we would like (1) to discuss possible characteristics of a running shoe that can influence performance and (2) to suggest some possible orders of magnitude of possible performance changes.

The construction features suggested to be performance influencers are:

1. Shoe weight
2. Midsole material
3. Heel thickness
4. Longitudinal bending stiffness (flat sole shape)
5. Longitudinal bending stiffness (curved sole shape)
6. Longitudinal bending stiffness and muscle mechanics

Some of the ideas have already been published, some findings have been tested internally and/or in industry projects, and some claims are speculated. Our objective is to document a comprehensive state of knowledge and to propose some new ideas.

1. Shoe weight

The effect of shoe weight on performance (oxygen consumption) has been described by Frederick and co-workers (1982) and comprehensively by Franz and co-workers (2012). In summary, both sources showed that a change in shoe mass of 100 g corresponds to a change in oxygen consumption of about 1%. Since oxygen consumption is linearly associated with changes in performance, 'laboratory-based running economy measurements can accurately predict changes in distance running race performance due to shoe modifications' (Hoogkamer et al., 2016).

Reasonable shoe mass differences of competition marathon shoes are around 50 g. Thus, shoe mass differences occurring in actual competition running shoes affect running performance by less than 1% (order of magnitude).

2. Midsole material

Sole material is often considered as an important part of a shoe with respect to performance. One often presented idea is that the material of the heel is deformed during impact and that this deformation energy is stored and returned during ground contact. In fact, the highest deformation energy is stored during the impact phase of ground contact. However, the corresponding energy is returned at

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the wrong time (about 10% into ground contact, i.e. too early) with the wrong frequency (about 12 Hz instead of 2–4 Hz) (Nigg et al., 2000). Thus, energy return due to the deformation of a specific material during landing should not play a role in the energy reduction during running. (Note: A few years ago, we compared oxygen consumption between shoes with different heel material properties. In all comparisons, oxygen consumption was (sometimes but not always significantly) lower for the viscoelastic heel – a counterintuitive result with respect to energy return. Other studies, however, showed that oxygen consumption can be decreased when running in shoes with softer (i.e. reduced hysteresis or energy loss as determined by a mechanical test) heel material (Worobets et al., 2014)).

Thus, using a specific high energy return material (where high energy return is determined with a drop test) should not have a substantial effect on running economy. We estimate the effect of high energy returning sole material on running performance to be less than 1%.

3. Heel thickness

A second possibility of an advantageous heel construction would include the increased thickness of the heel, as done in the Nike Vaporfly 4% (and its newer iterations). One could argue that this thicker sole would increase the ground contact time during a step, resulting in a stretching of the ground reaction force-time curve. Such a stretch would be advantageous for the timing of the energy return. However, it is unknown how much an increase in ground contact time of 6–13 ms (Barnes & Kilding, 2019; Cigoja et al., 2019; Flores et al., 2019) would affect the returned energy. Note: the increased ground contact times when running in stiff shoes could have a different function, as will be discussed later.

Another possible argument for this construction change could be that the stored energy is increased. This is correct. However, the comments made above (Section 2) still apply. The energy is returned at the wrong time (about 15% into ground contact, i.e. too early) with the wrong frequency (about 12 Hz instead of 2–4 Hz).

Thus, in our view, the effects of the thickness of the heel of a running shoe on energy return discussed above are also speculated to be below 1%.

Note: the heel sole thickness in the Nike Vaporfly 4% has a different function, as will be discussed later.

4. Longitudinal bending stiffness (flat sole)

The effect of different longitudinal bending stiffnesses of a shoe sole on running performance has been studied in the early 2000s (Roy & Stefanyshyn, 2006; Stefanyshyn & Fusco, 2004; Stefanyshyn & Nigg, 2000) and summarised later (Nigg, 2010). In these studies, flat carbon-fibre plates were used in spike shoes. With these plates two primary effects were produced: First, the bending of the metatarsal-phalangeal joint was reduced (i.e. less mechanical energy was lost at the joint). Second, the lever between the resultant ground reaction force and the ankle joint was increased, thus, higher ankle joint moments could be produced if the triceps surae was strong enough. It is not known which effect was dominant, but we speculate that the increase in the ankle joint moment was the dominant effect. The speed experiments were done with four shoe conditions: their own shoes and their own shoes with carbon-fibre plates of three different stiffnesses. The results of this study (Stefanyshyn & Fusco, 2004) showed an average increase in running speed of 1.3% when comparing their own shoes with the test shoes. Although sprint and marathon performance likely depend on different factors, this study showed that, in principle, running speed can be improved when using a stiffened longitudinal midsole. The individual improvements ranged between 0% and 3%. The major shortcoming was that the sprinters' race start was compromised because they couldn't bend their metatarsal-phalangeal joint.

Changing the longitudinal bending stiffness of the running shoe can improve the running performance of athletes up to 3%. The optimal stiffness varies between athletes.

5. Longitudinal bending stiffness with curved sole

A curved stiff plate addresses the shortcomings of a stiff flat plate during take-off. However, we think

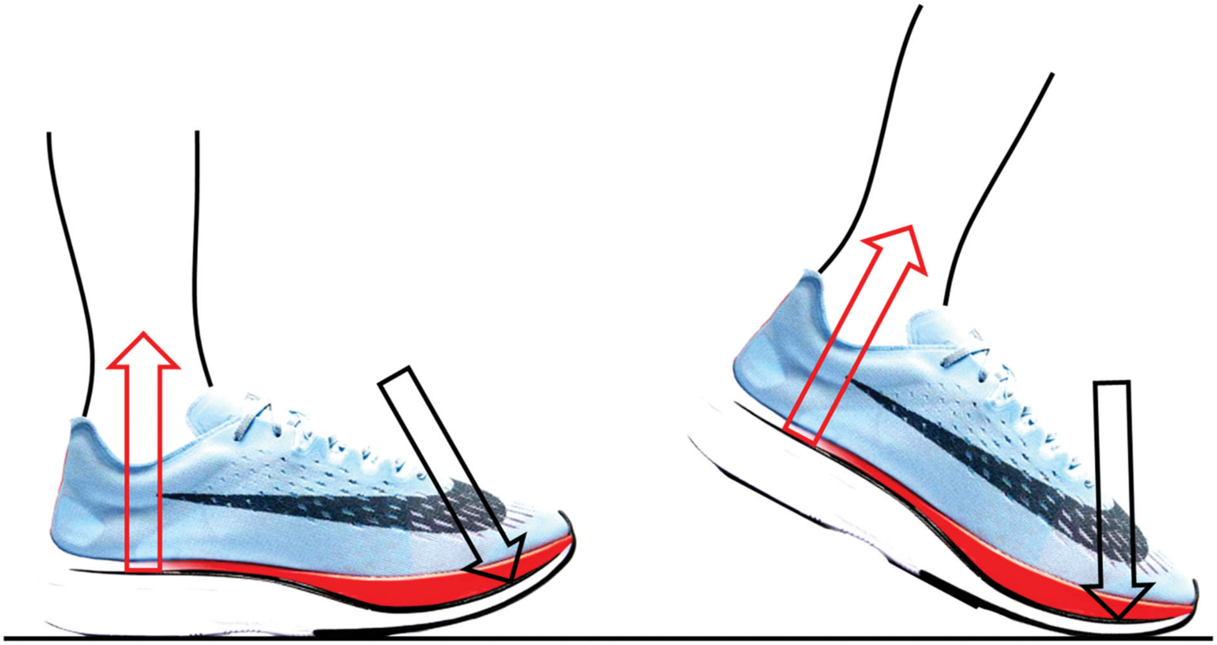

Figure 1. Schematic illustration of the teeter-totter effect when the force of the runner (black arrow) is applied at the front part of the shoe and the reaction force at the heel of the foot (red arrow) during early/mid stance (left orientation) and push off (right orientation). Modified from Burns and Tam (2020).

there is a much more important effect on running mechanics, the '***teeter-totter effect***'. The point of application of the resultant ground reaction force moves anteriorly during the second half of ground contact towards the front end of the curved carbon fibre plate. In this position, the ground reaction force produces a reaction force at the heel in upwards direction (perpendicular direction of the plate; Figure 1).

If the curvature of the plate is designed correctly, the teeter-totter mechanism will result in a force acting on the heel during push-off that acts at the right location (heel of the foot), at the right time (during take-off) and with the right frequency (depending on the running velocity and the ground contact time somewhere between 2 and 4 Hz). We assume that this teeter-totter force is a substantial contributing factor for improved running economy.

To ensure a maximal performance improvement with the curved carbon fibre plate, three main characteristics need to be considered when constructing it:

1. The stiffness of the curved plate must be so that the resultant ground reaction force moves far enough anteriorly during the stance phase of running.
2. The bending point (around which the teeter-totter effect takes place) should not be located too far anteriorly, allowing the shoe sole to act as a fulcrum.
3. The curvature of the shoe sole in the forefoot must be substantial (Farina et al., 2019) but we suggest that it should not be too extreme to allow for the desired teeter-totter effect. In this context, the thickness of the heel becomes important. A thicker heel allows the stiff plate to be more curved, which increases the teeter-totter effect.

Pressure measurements in the shoe are a simple way to quantify the teeter-totter effect during running. Compared to a 'normal' shoe, a correct execution of the teeter-totter effect should yield higher take-off pressure at the heel during the push off phase.

Unpublished model estimations of the magnitude of this teeter-totter effect have been made for a prototype shoe with different curved carbon fibre plates. A previously described dynamic finite element model of the leg (Sissler & Giandolini, 2019) was adjusted to test for the effect of different curvatures of carbon plates. The model estimations predicted a 6% increase in performance, and a forward shift of the ground reaction forces' point of application for the (curved) carbon fibre plate. Unpublished results of an experimental study confirmed these performance improvements of 6%. Independent studies, however, should investigate whether these performance benefits can be reproduced in the future. Further individual optimisation of these curved plates may yield even larger performance benefits.

The importance of the high heel in the Nike Vaporfly may be better understood in relation to the teeter-totter effect. The high heel probably shifts the point of application of the resultant ground reaction force forward during take-off. This corresponds to an increase of the teeter-totter effect and an increase of the propulsive force on the heel, which helps to increase performance. In addition, the high heel allows the use of a more curved plate, which increases the teeter-totter effect and improves performance.

Based on these model calculations one should conclude that the curved stiff plate and the resulting teeter-totter effect are the major contributors to the performance improvement of the Nike Vaporfly and any other shoes constructed similarly. They create an increased force on the heel of the foot during take-off. The improvement of performance compared to regular shoes could be 4–6%.

6. Longitudinal bending stiffness and muscle mechanics

One major finding of recently published studies were significantly longer stance times when running in shoes with increased midsole bending stiffness compared to a control shoe (Barnes & Kilding, 2019; Cigoja et al., 2020; Flores et al., 2019). If total mechanical work must remain the same between shoe conditions when running on a treadmill, the lower limb muscles would have more time (due to increased stance times) to contract in a stiff shoe, and therefore, would be able to shorten (i.e. contract) at slower velocities compared to a control shoe. Generating equal forces at slower shortening velocities would require less motor unit recruitment, allowing for more economical muscle force generation (Roberts et al., 1998). This could reduce the metabolic cost of running.

A recent study modelled the shank muscle-tendon unit mechanics (sMTU) when running in a stiff compared to a control shoe (Cigoja et al., 2020). This study found that sMTU forces (i.e. Achilles tendon forces) did not differ between stiffness conditions; however, the peak shortening velocity of the sMTU was significantly lower in the stiff compared to the control shoe. Because this study *modelled* sMTU behaviour, clear conclusions on whether the reduced shortening velocities should be attributed to the tendon or the muscle in series could not be drawn. Therefore, future studies should perform in-vivo assessments of the major ankle plantar-flexor muscles and the Achilles tendon while running in footwear with systematically altered midsole bending stiffness.

Changes in metabolic energy of running can almost entirely be explained by the inverse of stance time and the volume of active leg muscle (Kipp et al., 2018). It is known that stance times are significantly affected by increased midsole bending stiffness (Cigoja et al., 2019, 2020). It is unknown, however, if the mechanics of activated leg muscles are altered as well. If substantial changes in muscle mechanics are achieved by increasing the midsole bending stiffness of shoes, it is hypothesised that large performance benefits could be observed. It is speculated that these performance benefits could be in the order of 1–3%.

7. Conclusion

It has been claimed that wearing the Nike Vaporfly 4% (and its iterations) can result in increased running economy of (on average) about 4% (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Quealy & Katz, 2018). However, researchers still lack clear evidence as to which footwear features caused these performance improvements and how much the corresponding improvement are.

Based on the discussions of this letter to the editor, it seems to be inadequate to speculate that the recent world records in 100 km, marathon, half-marathon, and 15 km were primarily broken due to increased midsole thickness. As a matter of fact, we suggest that the effect of the midsole is less than 1%. We propose that an appropriated use of a bent midsole stiffening is the main contributor and that these contributions to improvement in running performance can easily be 6%. Therefore, it appears inappropriate to regulate one specific footwear feature (i.e. midsole characteristics) before

Table 1. Estimated (*) or documented (#) changes in performance due to different running shoe construction features.

Shoe characteristic	Influence average [%]		Influence range [%]		Reference
Shoe weight	0.5	#	0–1	#	Frederick et al. (1982)
Midsole material	0.5	*	0–1	*	
Heel thickness (energy return)	<0.5	*	0–0.5	*	
Heel thickness (teeter-totter)	1	*	0–2	*	
Longitudinal bending stiffness (flat sole shape)	1.3	#	0–3	#	Stefanyshyn and Fusco (2004)
Longitudinal bending stiffness (curved sole shape and teeter-totter)	4	#	2–6	#	Hoogkamer et al. (2018)
Longitudinal bending stiffness (muscle mechanics)	2	*	1–3	*	

understanding where these performance advantages originated from (Frederick, 2020). However, our current knowledge suggests that, compared to the teeter-totter effect, all other shoe characteristic contributions to running performance are relatively small or negligible.

Based on our understanding, we have summarised the different potential performance improvements due to specific shoe features (Table 1). Based on the results in this table, it seems obvious that the curved stiff sole, the corresponding teeter-totter effect and the additional force on the heel during take-off are the major contributors to the improved performance.

Disclosure statement

Benno Nigg is the founder and Chief Science Officer of Biomechanigg Sport & Health Research Inc. (BSHR) and Sandro Nigg is the owner and Chief Executive Officer of BSHR. BSHR is a biomechanics consulting company, where past and present research projects have been funded by many different sporting good companies, such as adidas AG, Salomon Group, On AG, Li-Ning Company Ltd., Mizuno Corporation, and Brooks Sports Inc.

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