PREPRINT DOI: 10.31236/osf.io/37uzr

Longitudinal bending stiffness does not affect running economy in Nike Vaporfly shoes

Laura A. Healey[1] & Wouter Hoogkamer[1]
[1]Integrative Locomotion Laboratory, Department of Kinesiology, University of Massachusetts, Amherst, MA

Please cite as: Healey, L., & Hoogkamer, W. (2021). Longitudinal bending stiffness does not affect running economy in the Nike Vaporfly. *SportRχiv*.

KEY WORDS

Footwear, biomechanics, energetics, performance, mechanical doping

ABSTRACT

Objectives: To determine the independent effect of the curved carbon-fiber plate in the Nike Vaporfly 4% shoe on running economy and running biomechanics.

Methods: Fifteen healthy male runners completed a metabolic protocol and a biomechanics protocol. In both protocols participants wore two different shoe conditions, an intact Nike Vaporfly 4% (VF_{intact}), and a cut Nike Vaporfly 4% (VF_{cut}). The VF_{cut} had 6 medio-lateral cuts through the carbon-fiber plate in the forefoot to reduce the effectiveness of the plate. In the metabolic protocol participants ran at 14 km/h for 5-minutes, twice with each shoe, on a force-measuring treadmill while breathing into an expired gas system. In the biomechanics protocol participants ran across a runway with embedded force plates at 14 km/h. We calculated running economy, kinetics, and joint mechanics of the lower limb.

Results: Running economy did not significantly differ between shoe conditions (0.5% higher in the VF_{cut} compared to the VF_{intact}). Biomechanical differences were only found in the metatarsophalangeal joint (MTP) with increased MTP dorsiflexion angle, angular velocity, and negative power in the VF_{cut}. Contact time was 1% longer in the VF_{cut}.

Conclusion: Cutting the carbon-fiber plate and reducing the longitudinal bending stiffness did not have a significant effect on the energy savings in the Nike Vaporfly 4%. This suggests that the plate alone plays a limited role in the 4% energy savings, and instead those likely result from a combination and interaction of the foam, geometry, and plate.

All authors have read and approved
this version the manuscript. This article
last modified on January 30th, 2021

For correspondence: laurahealey@umass.edu
Twitter: @laurahealey15
@woutersinas

1. INTRODUCTION

Performance running shoe technology has recently become a polarizing topic, most notably due to advances in footwear technology, such as midsole energy return and longitudinal bending stiffness (LBS) [1–6]. The Nike Vaporfly 4% (VF) shoe utilizes both these technologies to give athletes up to 4% savings in running economy compared to two popular high-end marathon racing shoes [1,7–9], which translates to improved running performance [10,11]. While scientists and bloggers debate whether the foam [1,12], geometry [3], or curved carbon-fiber plate [2,13] contribute more to these ‘super shoes’, the exact mechanisms resulting in 4% metabolic savings are not yet understood.

The use of carbon-fiber plates to improve running economy, while increasingly popular, is not new. In 2006, Roy and Stefanyshyn [12] showed small (1%) improvements in running economy with increased LBS. However, since then, reported effects of LBS on running economy have been mixed, with studies finding deteriorations [14], no effect [15–17], or small (~1%) [12,18], to large improvements (3-4%) [1,7,8,19] (for review see [20]). Importantly, the largest improvements in running economy have been reported in studies assessing VF shoes [1,7,8], suggesting that the geometry and stiffness of the curved VF plate may provide additional savings compared to flat plates previously tested. It is also important to note that the contributions of the foam to these savings are unknown as no studies have addressed the effects of the curved plate and foam independently. Earlier studies have shown that soft and resilient midsole foam using air pockets or TPU (thermoplastic polyurethane) foam, can improve running economy by 1% as compared to conventional EVA (ethyl-vinyl acetate) foam [21,22]. While the VF studies used state of the art baseline shoes with either EVA foam with air pockets or TPU foam (boost), the VF midsole foam (polyether block amide) is softer and more resilient than those [1]. Whether this foam provides additional metabolic savings has not been tested without the confounding influence of the carbon-fiber plate in the VF shoes.

From a biomechanical perspective, increased LBS has been shown to reduce negative work done at the metatarsophalangeal (MTP) joint [23–25] and to alter joint mechanics in the ankle [12,15,23,24,26,27], and knee [24]. Specifically, in a biomechanical analysis of the VF, Hoogkamer et al. [23] found the curved carbon-fiber plate in the VF prototype resulted in lower work rates at the ankle and reduced dorsiflexion and negative work at the MTP joint compared to control shoes. They concluded the curved plate provided a clever lever and a stiffening effect that likely contributed to the 4% energy savings. However, an important limitation of that study is that the tested VF prototype shoes differed in both geometry (taller stack height), foam properties (more compliant and resilient) *and* LBS (stiffer; carbon-fiber plate) from the control shoes, once again making the contribution of the plate alone difficult to pinpoint. A recently introduced concept suggests that the curved plate may act like a teeter-totter and alone can result in up to 6% savings [2,13], however, this unconfirmed concept originated based on pilot work and simulation data and has not been experimentally tested.

In the current study, we attempt to determine the isolated effects of the carbon-fiber plate in the VF by cutting the plate to reduce its LBS. Our aim was to determine how LBS independently affects running economy and biomechanics in the VF. Based on previous literature, we hypothesized that reducing LBS by cutting through the carbon-fiber plate of the Nike Vaporfly 4% would increase metabolic rate during running by about 2%. To accommodate this increased metabolic rate, we hypothesized that decreasing LBS would (1) decrease ankle dorsiflexion angle and plantarflexion moment, and (2) increase MTP dorsiflexion angle, plantarflexion moment, and power.

2. METHODS

2.1 Participants

A power analysis was performed a-priori (G*Power 3.1, Universität Kiel, Germany) and it was determined a sample size of 14 was necessary to achieve an effect size of 0.95. We recruited 17 male participants (aged 24 ± 4 years, mass 67.8 ± 4.3kg, height 173.3 ± 3.6cm) who wore US size M9.5 shoes. Thirteen subjects took part in both the biomechanics and metabolic protocols, while four participated in only one protocol (two in each). For the biomechanics protocol, inclusion criteria consisted of running at least 10 miles per week. For the metabolic protocol, participants had to be capable of running a 5 km in 19 minutes, or an equivalent performance (10 km in 39 minutes, marathon in 3 hours). For both protocols, participants were excluded if they had a lower extremity injury or surgery in the past twelve months, or had any existing orthopaedic, cardiovascular, or neuromuscular conditions. All participants gave written consent per the University of Massachusetts Amherst Institutional Review Board.

2.2 Shoe Conditions

Participants wore two pairs of shoes: an intact Nike Vaporfly (VF_{intact}), and a cut Nike Vaporfly (VF_{cut}). In lieu of having two identical shoes with and without a carbon-fiber plates, we made six medio-lateral cuts through the carbon-fiber plate of new VFs to reduce the plate's effectiveness in bending, while keeping all geometry and foam properties the same (Figure 1). We measured the shoe's LBS in flexion using a standard flex tester (Shoe Flexer, Exeter Research, Brentwood NH), calculating flexion stiffness for the final five of fifty 30-degree flexion cycles. We also measured the LBS in extension with a 3-point bending test using a standard material testing machine (Instron ElectroPuls 10000, Norwood, MA, USA). To perform this test, the shoe was placed on two support frames 80mm apart. The Instron tip, aligned with the MTP joint, displaced 5mm while recording force.

To test the midsole foam properties, we used a custom cylindrical head attached to a material testing machine (Instron ElectroPuls 10000, Norwood, MA, USA). The head was aligned in the rearfoot and loaded the shoe at ~ 2000 N with a contact time of ~ 185 ms for 100 cycles [1]. We used the last 20 cycles to calculate energy return.

[Fig. 1]

2.3 Experimental Set-up and Protocol

The study comprised of two testing protocols: a metabolic protocol and a biomechanics protocol. If subjects completed both protocols on the same day, biomechanics testing was done first.

2.3.1 Metabolic protocol

Participants wore their own shoes for a warm-up; at least 5-minutes at the test pace of 14 km/hr (6:54 min/mile). During the warmup participants wore a mouthpiece attached to an expired-gas analysis system to get accustomed to running with it. After the warm-up, participants completed four, 5-minute trials at 14 km/hr on a level, force-measuring treadmill with a rigid deck (Treadmetrix, Park City, UT, USA). Shoe order was randomly assigned, and participants wore each shoe twice in a mirrored order (e.g. VF_{intact}, VF_{cut}, VF_{cut}, VF_{intact} or VF_{cut}, VF_{intact}, VF_{intact}, VF_{cut}). We used lightweight shoe covers to blind participants to the shoes they were wearing. During each trial we measured horizontal and vertical ground reaction forces at 1200

Hz, as well as submaximal rates of oxygen uptake and carbon-dioxide production using an expired-gas analysis system (True One 2400, Parvo Medics, Salt Lake City, UT, USA). After each trial participants were given a 5-minute break while researchers changed their shoes behind a barrier.

We calculated metabolic rate (running economy) over the last two minutes of each trial, based on the measured rates of oxygen uptake and carbon-dioxide production using the Peronnet & Massicotte equation [28]. In the last 30s of each trial we collected ground reaction forces from the treadmill at 1200 Hz. A custom Python script was used to filter ground reaction force data using a low-pass, second-order, Butterworth filter with a cut-off frequency of 20 Hz. Contact time was determined using a 25 N vertical ground reaction force threshold to determine toe-offs and touch-downs, these points were then visually inspected to ensure accuracy. We then calculated step frequency, peak vertical ground reaction force, and propelling and braking impulse.

2.3.2 Biomechanics protocol

We placed retro-reflective markers on the participants' right leg on the greater trochanter, medial and lateral epicondyles, and medial and lateral malleoli. The right foot was tracked with markers on the 1st and 5th metatarsal head and base, as well as a cluster of three markers on the heel. To track the thigh and the shank segments, rigid bodies with four non-co-linear reflective markers were adhered to the lateral aspects of the thigh and shank.

Participants ran across a 100ft runway embedded with force plates (AMTI Inc, Watertown, MA) at 14 km/h. During the trials motion capture data (Oqus 3, Qualisys Inc., Gothenburg, Sweden) and ground reaction force data were continuously collected at 200 Hz and

2000 Hz, respectively. We used timing gates to verify that the participant's speed was 14 km/h ± 4%, and we visually made sure that the participants right foot landed directly on a force plate. Participants continued to perform runs until we had collected five good trials in each shoe condition.

To process the data, we first visually analyzed, and gap filled motion capture data in Qualisys. Next, using a custom Python script, ground reaction force and kinematic data were low-pass filtered using a dual-pass, with an effective 14 Hz cut-off [23]. For the knee, ankle, and MTP joints, we calculated joint angles, angular velocities, moments, powers, and work during the stance phase using an 3D inverse dynamics model custom built in Python. Finally, we normalized data to 100% of stance phase and averaged the trials in the same shoe condition within each participant.

2.4 Statistics

We used a two-tailed paired t-test to compare RE, step parameters, and peak biomechanical variables between shoes with a traditional significance level of $\alpha = 0.05$ (R, Vienna, Austria). We also used one-dimensional spatial parametric mapping (SPM) to conduct a two-tailed, paired-sample t-test ($\alpha = 0.05$) for ground reaction forces, joint angles, angular velocities, moments, and powers [29].

3. RESULTS

During analysis, one participant was removed from the metabolic protocol (n=14) and two participants were removed from the biomechanics protocol (n=13) due to data quality issues.

3.1 Shoe properties

The VF_{cut} had a bending stiffness of 7.7 Nm/rad, while the VF_{intact} had a bending stiffness of 23.1 Nm/rad in flexion. In extension, the VF_{cut} had a stiffness of 3.1 Nm/rad and the VF_{intact} had a stiffness of 11.1 Nm/rad. Vertical compression energy return was 86% in both the VF_{cut} and VF_{intact}.

3.2 Energetics and step parameters

Average metabolic rate was statistically similar in the VF_{cut} (14.17 ± 0.74 W/kg) and the VF_{intact} (14.10 ± 0.80 W/kg), but numerically 0.5% higher (Figure 2). Individual changes ranged from -3.3 to 3.3% between the VF_{cut} and the VF_{intact}, with 10 of 14 participants increasing RE in the VF_{cut} condition. Contact time was significantly shorter in the VF_{cut} (0.211 sec) compared to the VF_{intact} (0.213 sec; $p<0.001$). No significant difference was found for step frequency, braking impulse, propelling impulse, or peak vertical ground reaction force (Table 1). Vertical ground reaction forces were significantly higher in the VF_{cut} during 55-96% of stance phase ($p<0.001$). Anterior-posterior ground reaction forces were significantly lower in the VF_{cut} for 30-68% and significantly higher for 75-95% of stance phase (both $p<0.001$; Figure 3).

[Fig. 2]

Table 1 Average step parameters during running in Vaporfly shoes with intact (VF_{intact}) and cut (VF_{cut}) carbon-fiber plates. * indicates statistical difference between shoe conditions.

		VF_{intact} ± SD	VF_{cut} ± SD	p-value
Peak vertical GRF	BW	2.64 ± 0.20	2.64 ± 019	0.371
Braking impulse	BW sec	-0.02 ± 0.00	-0.02 ± 0.00	0.607
Propulsive impulse	BW sec	0.02 ± 0.00	0.02 ± 0.00	0.589
Contact time	sec	0.213 ± 0.014*	0.211 ± 0.014*	**<0.001**
Step frequency	steps/sec	3.00 ± 0.12	3.00 ± 0.12	0.909

SD standard deviation; BW bodyweight; SD standard deviation

[Fig. 3]

3.3 Biomechanics

Biomechanical differences were only found in MTP joint mechanics (Figure 4). MTP joint angles were more dorsiflexed in the VF_{cut} for 0-12% and 85-100% of the stance phase (p=0.013) and peak MTP joint dorsiflexion was significantly higher in the VF_{cut} (p=0.002; Table 2). This was accompanied by increased MTP joint angular velocity in the VF_{cut} between 11-21% and 77-90% of stance phase (p=0.001), and significantly more negative MTP joint power in the VF_{cut} compared to the VF_{intact} from 79-90% of stance phase (p<0.001). Negative MTP joint work was significantly higher in the VF_{cut} compared to in the VF_{intact} (p=0.008), and positive MTP joint work was significantly lower in the VF_{cut} compared to the VF_{intact} (p=0.023; Table 2).

[Fig. 4]

Table 2. Average knee, ankle, and metatarsophalangeal (MTP) mechanics while running in the intact Vaporfly (VF_{intact}) and the cut Vaporfly (VF_{cut}). * indicates statistical difference between shoe conditions

		VF_{intact} ± SD	VF_{cut} ± SD	p-value
Peak knee flexion	degrees	32.7 ± 10.0	34.2 ± 9.5	0.411
Peak knee moment	Nm	336.9 ± 32.8	336.9 ± 43.9	0683
Peak ankle dorsiflexion	degrees	17.8 ± 4.9	18.2 ± 5.7	0.738
Peak ankle moment	Nm	181.9 ± 20.8	182.5 ± 17.5	0.876
Peak MTP dorsiflexion	degrees	19.1 ± 5.3*	25.3 ± 7.8*	**0.002**
Peak MTP moment	Nm	31.6± 8.2	31.9 ± 8.4	0.875
Positive knee work	J/kg/step	0.65 ± 0.32	0.55 ± 0.16	0.190
Negative knee work	J/kg/step	-0.96 ± 0.31	-0.94 ± 0.25	0.756
Positive ankle work	J/kg/step	0.91 ± 0.18	0.85 ± 0.14	0.133
Negative ankle work	J/kg/step	-0.64 ± 0.17	-0.62 ± 0.19	0.281
Positive MTP work	J/kg/step	0.02 ± 0.01*	0.01 ± 0.01*	**0.023**
Negative MTP work	J/kg/step	-0.11 ± 0.05*	-0.15 ± 0.06*	**0.008**

SD standard deviation

4. DISCUSSION

This study sought to determine the independent effect of the curved carbon-fiber plate in the Nike Vaporfly shoe on running energetics and biomechanics. Our mechanical testing results confirm that the two shoes (VF_{intact} and VF_{cut}) had the same compression energy return, but the VF_{cut} was dramatically less stiff in flexion (~66% less stiff) and extension (~72% less stiff). Interestingly, our results show that reducing the LBS did not substantially change running economy, refuting our first hypothesis. Furthermore, we reject our second hypothesis that reduced LBS would decrease ankle dorsiflexion moment and power. Supporting our third hypothesis, MTP joint dorsiflexion angle and power were significantly larger in the VF_{cut}, however, external MTP joint moment was not significantly different between conditions.

Our findings are in line with previous research finding small differences in running economy between shoes with and without carbon-fiber plates [12,15,18,19]. However, most of these studies used *flat* plates, and we hypothesized the *curved* plate in the VF would result in additional savings and explain ~2% of the 4% savings reported by Hoogkamer et al. [1] and Barnes and Kilding [7]. Conversely, cutting the carbon-fiber plate only resulted in a non-significant 0.5% difference from the intact shoe. As such, our findings are in line with the data of the vast majority of studies that evaluated the effects of LBS with flat plates/insoles [14–17]. When directly comparing footwear conditions at the group level, without focusing on individual responders or the individual stiffness condition with the lowest metabolic rate, only Roy and Stefanyshyn [12] and Oh and Park [18] showed improvements in running economy (0.8 and 1.1%, respectively). Our results therefore dispute suggestions that LBS from the curved carbon-fiber plate alone is responsible for the majority of the metabolic savings, and instead suggest the savings arise from a combination of the foam, shoe geometry, and other effects of the curved carbon-fiber plate not related to bending stiffness.

These results challenge the recent suggestion that a curved plate alone can provide metabolic savings as high as 6% by acting as a teeter-totter [2,13]. The idea behind this suggested teeter-totter effect is that the curved plate would allow the foot and shoe to pivot during mid-stance to push-off in a way that the force applied at the front of the shoe results in a reaction force at the heel of the foot, and that this heel force would substantially improve running economy. In this mechanism the plate needs to provide bending stiffness in extension to enable the pivoting action. However, our current research shows that reducing the bending stiffness in both flexion and extension, does not have a substantial effect on running economy. This is not surprising because if a teeter-totter effect exists, the pivot action can be expected to slow the center of pressure velocity under the foot, and additional push-off force would be needed to land on top of the teeter-totter during the next stance, which both would deteriorate running economy. Better understanding the contributions from the highly compliant and resilient foam, as well as the shoe geometry, would further our understanding of how the plate independently contributes to the energy savings.

Biomechanical differences were found at the MTP joint; however, these changes did not translate to the ankle or knee. Predictably, cutting the carbon-fiber plate allowed for greater MTP joint dorsiflexion and dorsiflexion angular velocity. This is in line with previous studies finding decreased MTP joint dorsiflexion with both flat [15,16,25], and curved [23] plates, compared to controls. Interestingly, we did not find differences in MTP joint moment. However, it is important to note that we calculated the external MTP joint moment, which is a combination of the foot and the shoe. Although we cannot quantify it with our current data, it is likely that the VF_{intact} contributed more to the external moment than the VF_{cut}, which would result in a larger internal MTP joint moment in the VF_{cut}. Further, MTP joint negative power and negative work were significantly lower in the intact shoes (VF_{intact}). While decreasing negative work at the MTP joint has been discussed as an important feature of a carbon-fiber shoe [12,27], we show here that it alone likely has a small effect on overall metabolic energy cost.

We anticipated that cutting the plate would result in lower ankle dorsiflexion velocity and decreased ankle moment. Instead, we did not see any differences at the ankle joint. These findings are different from Hoogkamer et al. [23] who first assessed the VF and found differences in peak ankle dorsiflexion, moment, and work; however, they compared the VF to control shoes with different midsole foam and geometry. Together, these finding suggests that their results are due to differences between shoes other than the LBS of the curved carbon-fiber plate. Similar to Hoogkamer et al. [23], we did not find any differences in knee joint mechanics. Other gross biomechanical measures, i.e., step frequency, peak vertical ground reaction force, braking impulse, and propelling impulse were not significantly different between conditions. Finally, we found a small, but significant difference in contact time between the VF_{cut} and VF_{intact}, where contact time in the VF_{cut} was 1% shorter than the VF_{intact}. Previous research has shown that metabolic rate is inversely related to contact time [30], and therefore the 1% difference in contact time may cause running economy differences in the VF_{intact} vs. VF_{cut}. This is because muscles must produce force to support body weight, however, with a shorter contact time that force must be produced in a shorter period of time, requiring more metabolic energy.

4.1 Limitations and future directions

Ideally, we would have compared identical VF shoes with and without a plate, however, as such shoes are not available, cutting the plate was the next best option. We tried to remove the plate, but this was not possible without irreparable damage to the midsole. As the plate was still in the shoe, it was likely still interacting with the foam and contributing to medio-lateral bending stiffness. Further, only the forefoot and midfoot sections of the plate were cut, this choice was made because we believe forefoot and midfoot bending stiffness are most important, and because the plate was very close to the insole in the rearfoot. While we believe the plate in the rearfoot likely has little effect, it is possible it still contributes to the shoe’s effectiveness for example by spreading forces under the feet out over a larger foam area. Therefore, this study can only comment on the role of the plate in LBS, as it may still be contributing in other ways. Future studies should aim to assess identical shoe models with and without an embedded, curved carbon-fiber plate. Note people have been studying this with flat insoles, however, combined, the literature suggests that curved plates might provide a superior advantage (for discussion see Ortega et al. [20]).

Further, our shoes were only tested on males running at 14 km/h. Previous research has suggested that the effect of LBS on running economy may be speed dependent ([14], for review see [20]). However, because both Hoogkamer et al. [1] and Barnes and Kilding [7] found that metabolic savings in the VF shoes were consistent across speeds from 14 to 18 km/h, we believe that our speed of 14 km/h was adequate to test our hypotheses. Additionally, this study was only performed on males. Barnes and Kilding [7] found that metabolic savings in the VF shoes were not significantly different between males and females, but differences in sex, body mass, leg length and shoe size can theoretically differently affect the relative influence of the plate on running mechanics and energetics, which should be addressed in future research.

Finally, when mechanically testing our shoes we used two different methods for quantifying flexion and extension stiffness. Because the plate is embedded within the foam, our three-point bending testing of the VF_{intact} in flexion resulted primarily in displacement due to foam deformation, rather than longitudinal bending. Therefore, we decided to use an industry standard flex tester (Shoe Flexer, Exeter Research Inc., Brentwood, NH) for measuring flexion, and a three-point bending test for measuring extension. These tests were sufficient for showing that cutting the plate effectively reduced the LBS for flexion and extension; however, care is advised when comparing stiffness values between different testing methods (for discussion see

[20]). Future work should aim to improve external validity and standardization of footwear longitudinal bending stiffness assessment so reported values can be compared across the literature.

As carbon-fiber plates become increasingly popular in running shoe innovation, it is important to understand how they affect running economy and joint mechanics, and how this could contribute to improved performance. Future studies should continue to address specific features of shoes by systematically assessing one feature at a time to further our understanding on how different features alter running economy and running biomechanics.

4.2 Conclusion

While multiple studies have assessed the effects of increased LBS and carbon-fiber plates on running economy, this study is the first to directly assess the role of a curved carbon-fiber plate in two identical shoes. We found that reducing LBS, in both flexion and extension, only altered running economy by a non-significant 0.5%. In line with this, we found small biomechanical changes at the MTP joint. Overall, we suggest that the curved carbon-fiber plate alone has minimal impact on the 4% savings in the VF, instead those likely result from a combination and interaction of the highly compliant and resilient midsole, shoe geometry, and other effects of the curved carbon-fiber plate not related to bending stiffness.

Acknowledgements

We thank the subjects for participating, Sam Zeff for helping with mechanical testing, Sam Carey for helping cut the shoes, and Justin Ortega, Dale Haavind-Berman, Emily Laughlin, Annie Lye, and Adam Lee for help with data collections.

Authors' Contributions

LH helped with the research design and carried out the data collections, data analysis, and drafted the manuscript; WH conceived of the research idea and design, and helped to draft the manuscript. All authors have read and approved the final version of this manuscript.

Funding

No sources of funding were used to assist in the preparation of this article.

Conflicts of interest / Competing interests

Wouter Hoogkamer has received research grants from Puma North America and Saucony.

Ethics approval

All test protocols were approved by the University of Massachusetts Internal Review Board (1741 and 1789)

Consent to participate

All participants gave written consent to participate in this research study

Consent for publication

All authors have given consent for publication

References

1. Hoogkamer W, Kipp S, Frank JH, Farina EM, Luo G, Kram R. A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. *Sports Medicine*. 2018;48(4):1009-1019. doi:10.1007/s40279-017-0811-2
2. Nigg B, Cigoja S, Nigg S. Effects of running shoe construction on performance in long distance running. *Footwear Science2*. 2020;0(0):1-6. doi:10.1080/19424280.2020.1778799
3. Burns GT, Tam N. Is it the shoes? A simple proposal for regulating footwear in road running. *British Journal of Sports Medicine*. 2020;54(8):439-441. doi:10.1136/bjsports-2018-100480
4. Frederick EC. No evidence of a performance advantage attributable to midsole thickness. *Footwear Science*. 2020;12(1):1-2. doi:10.1080/19424280.2019.1690327
5. Longman J. Do Nike's New Shoes Give Runners an Unfair Advantage? *New York Times*. https://www.nytimes.com/2017/03/08/sports/nikes-vivid-shoes-and-the-gray-area-of-performance-enhancement.html?_r=0. Published 2017.
6. Muniz B, Shaun P, Konstantinos S, Fergus A, Bosch A, Pitsiladis Y. Recent Improvements in Marathon Run Times Are Likely Technological , Not Physiological. *Sports Medicine*. 2021;(0123456789). doi:10.1007/s40279-020-01420-7
7. Barnes KR, Kilding AE. A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes. *Sports Medicine*. 2019;49(2):331-342. doi:10.1007/s40279-018-1012-3
8. Hunter I, McLeod A, Valentine D, Low T, Ward J, Hager R. Running economy, mechanics, and marathon racing shoes. *Journal of Sports Sciences*. 2019;37(20):2367-2373. doi:10.1080/02640414.2019.1633837
9. Hébert-Losier K, Finlayson SJ, Driller MW, Dubois B, Esculier JF, Beaven CM. Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *Journal of Sport and Health Science*. 2020;00:1-10. doi:10.1016/j.jshs.2020.11.012
10. Kipp S, Kram R, Hoogkamer W. Extrapolating metabolic savings in running: Implications for performance predictions. *Frontiers in Physiology*. 2019;10(FEB):1-8. doi:10.3389/fphys.2019.00079
11. Hoogkamer W, Kipp S, Spiering BA, Kram R. Altered running economy directly translates to altered distance-running performance. *Medicine and Science in Sports and Exercise*. 2016;48(11):2175-2180. doi:10.1249/MSS.0000000000001012
12. Roy JPR, Stefanyshyn DJ. Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine and Science in Sports and Exercise*. 2006;38(3):562-569. doi:10.1249/01.mss.0000193562.22001.e8
13. Nigg BM, Cigoja S, Nigg SR. Teeter-totter effect: A new mechanism to understand shoe-related improvements in long-distance running. *British Journal of Sports Medicine*. 2020;0(0):1-2. doi:10.1136/bjsports-2020-102550
14. Day E, Hahn M. Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent. *Footwear Science*. 2019;0(0):1-11. doi:10.1080/19424280.2019.1696897

15. Madden R, Sakaguchi M, Tomaras EK, Wannop JW, Stefanyshyn D. Forefoot bending stiffness, running economy and kinematics during overground running. *Footwear Science*. 2016;8(2):91-98. doi:10.1080/19424280.2015.1130754
16. Flores N, Delattre N, Berton E, Rao G. Does an increase in energy return and/or longitudinal bending stiffness shoe features reduce the energetic cost of running? *European Journal of Applied Physiology*. 2019;119(2):429-439. doi:10.1007/s00421-018-4038-1
17. Beck ON, Golyski PR, Sawicki GS. Adding carbon fiber to shoe soles may not improve running economy: a muscle-level explanation. *Scientific Reports*. 2020;10(1):1-13. doi:10.1038/s41598-020-74097-7
18. Oh K, Park S. The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion. *Journal of Biomechanics*. 2017;53:127-135. doi:10.1016/j.jbiomech.2017.01.014
19. McLeod AR, Bruening D, Johnson AW, Ward J, Hunter I. Improving running economy through altered shoe bending stiffness across speeds. *Footwear Science*. 2020;12(2):79-89. doi:10.1080/19424280.2020.1734870
20. Ortega JA, Healey LA, Swinnen W, Hoogkamer W. Energetics and biomechanics of running footwear with increased longitudinal bending stiffness : a narrative review. *Sports Medicine*. Accepted F.
21. Fredrick EC, Clarke TE, Larsen JL, Cooper LB. The effect of shoe cusioning on the oxygen demands of running. *Biomechanical aspects of sport shoes and playing surfaces*. Published online 1983:107-114.
22. Worobets J, Wannop JW, Tomaras E, Stefanyshyn D. Softer and more resilient running shoe cushioning properties enhance running economy. *Footwear Science*. 2014;6(3):147-153. doi:10.1080/19424280.2014.918184
23. Hoogkamer W, Kipp S, Kram R. The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Medicine*. 2019;49(1):133-143. doi:10.1007/s40279-018-1024-z
24. Cigoja S, Firminger C, Asmussen MJ, Fletcher JR, Edwards B, Nigg B. Effects of midsole bending stiffness on arch deformation of the human foot during running. *Footwear Science*. 2019;11(sup1):S181-S182. doi:10.1080/19424280.2019.1606318
25. Willwacher S, Kon̈ig M, Potthast W, Brug̈gemann GP. Does specific footwear facilitate energy storage and return at the metatarsophalangeal joint in running? *Journal of Applied Biomechanics*. 2013;29(5):583-592. doi:10.1123/jab.29.5.583
26. Willwacher S, König M, Braunstein B, Goldmann JP, Brüggemann GP. The gearing function of running shoe longitudinal bending stiffness. *Gait and Posture*. 2014;40(3):386-390. doi:10.1016/j.gaitpost.2014.05.005
27. Willwacher S, Kurz M, Menne C, Schrödter E, Brüggemann GP. Biomechanical response to altered footwear longitudinal bending stiffness in the early acceleration phase of sprinting. *Footwear Science*. 2016;8(2):99-108. doi:10.1080/19424280.2016.1144653
28. Peronnet F, Massicotte D. Table of nonprotein respiratory quotient: an update. *Canadian Journal of Sport Science*. 1991;16(1):23-29.
29. Pataky TC. One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*. 2012;15(3):295-301. doi:10.1080/10255842.2010.527837

30. Kram R, Taylor CR. Energetics of running: a new perspective. *Letters to Nature*. 1990;346(July):265-267.

Figures

Fig 1. VF_{intact} and VF_{cut} shoe conditions. To create the VF_{cut} six medio-lateral cuts were made through the carbon-fiber plate. Note the black line is not the exact location of the plate, all the cuts were fully through the carbon-fiber plate.

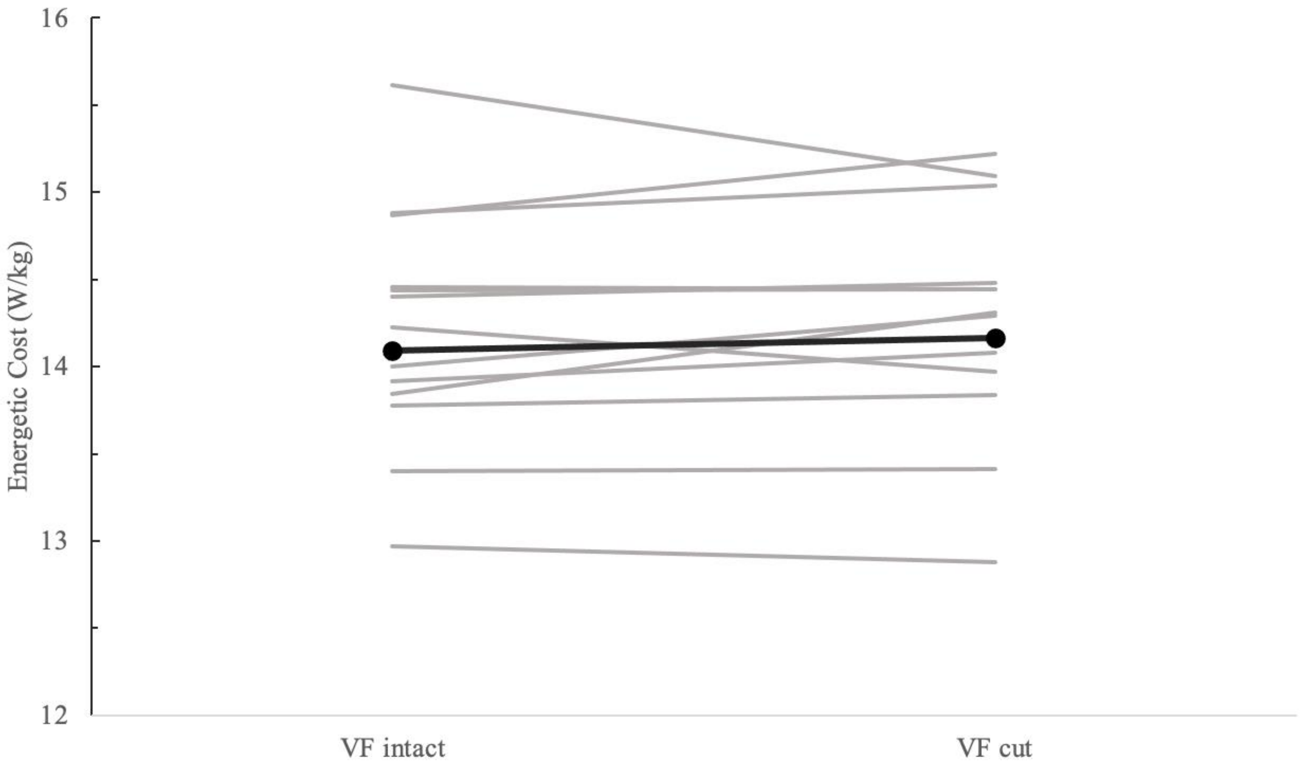

Fig 2. Running economy was similar between Vaporfly shoes with intact (VF_{intact}) and cut (VF_{cut}) carbon-fiber plates. Average metabolic rate is shown in black and individual responses are shown with grey lines. Numerically, runners had a 0.5% higher metabolic rate in the VF_{cut} than in the VF_{intact}, but this difference was not statistically significant.

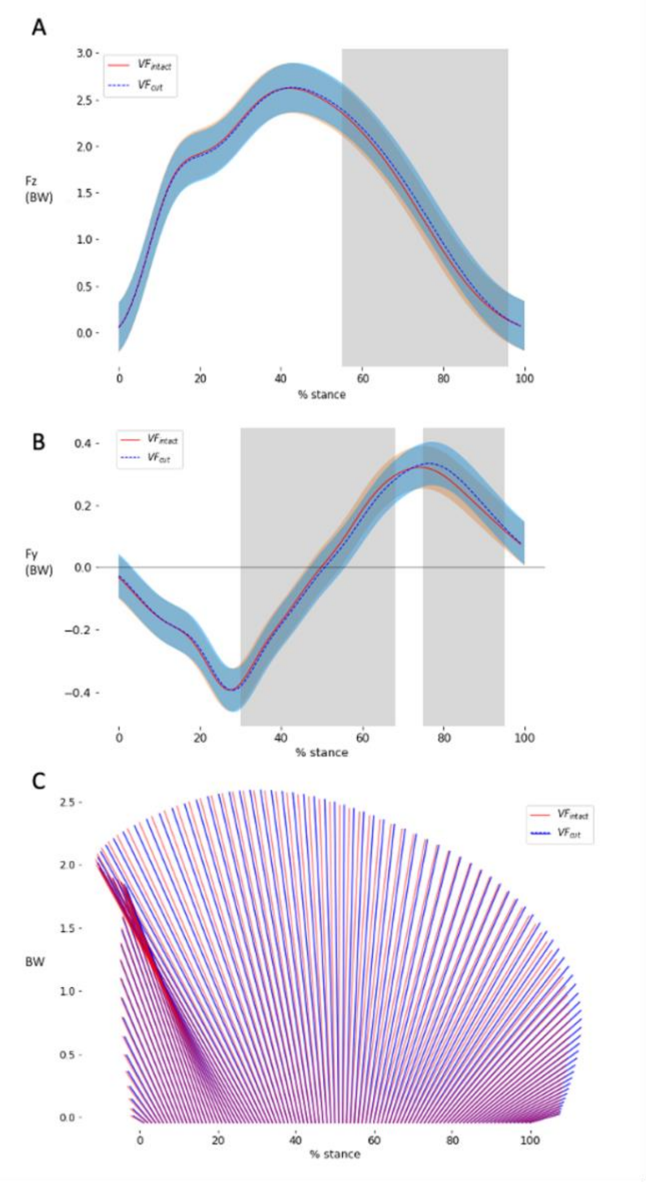

Fig 3. Ground reaction forces (GRF) in the Vaporfly shoes with intact (VF_{intact}; red) and cut (VF_{cut}; blue) carbon-fiber plates. Force traces have been normalized to body weight (BW). A) Average vertical (F_Z) GRF traces; B) anterior-posterior (F_Y) traces. Grey shaded areas represent where traces are significantly different from each other ($p<0.001$) as determined by SPM. C) Ground reaction force vectors during stance phase. Note around 60-70% of stance phase when GRF vectors appear to be the same, the VF_{cut} (blue) is 1% behind the VF_{intact} (red).

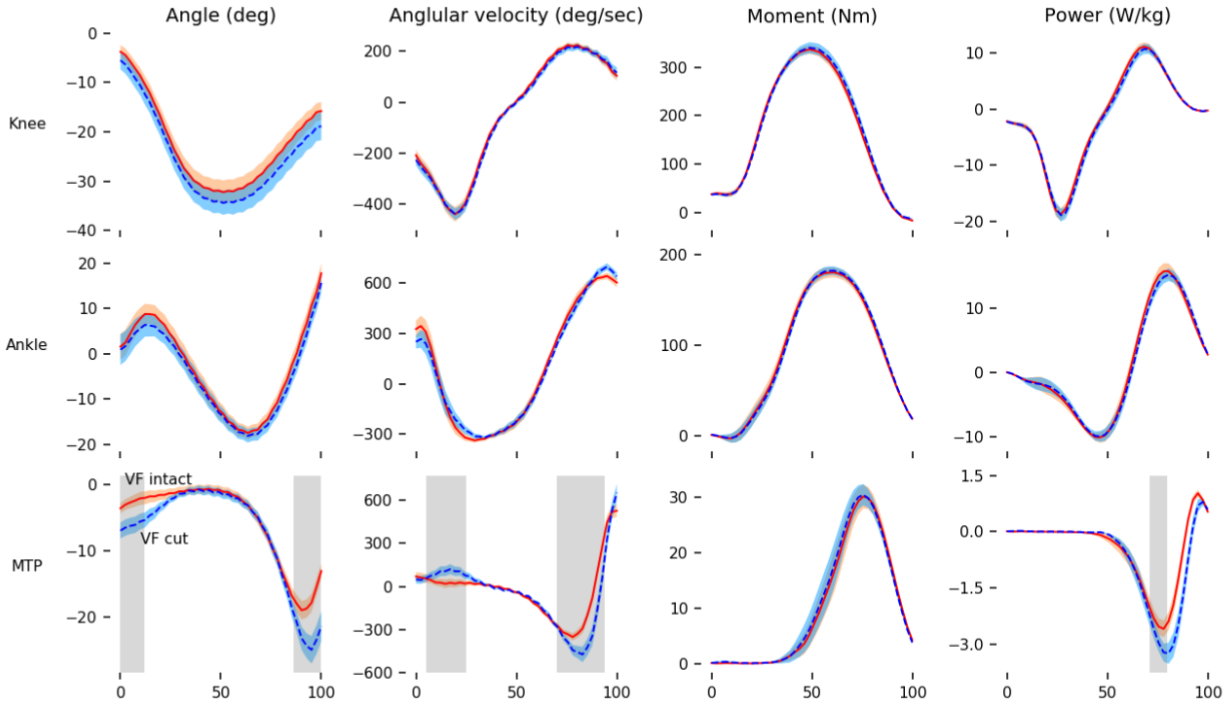

Fig 4. Joint angles, angular velocities, moments and powers for the knee, ankle, and metatarsal phalangeal (MTP) joints while running in the intact Vaporfly (solid red line) and cut Vaporfly (dashed blue line). Positive values are extension/plantarflexion. Grey regions indicate where the traces are significantly different ($p<0.05$) as determined by SPM. Traces are group averages and shaded regions represent ±1 standard error.