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A Comparison of Running Economy Across Seven Carbon-Plated Racing Shoes

Dustin P. Joubert
Stephen F. Austin State University, joubertd@sfasu.edu

Garrett P. Jones
Stephen F Austin State University

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Authors: Dustin P. Joubert* and Garrett P. Jones

PO Box 13015, Department of Kinesiology and Health Science, Stephen F. Austin State University, Nacogdoches, TX, 75962, USA

*Corresponding author: Dustin Joubert, joubertd@sfasu.edu, 936-468-1380

Abstract

Background: Advancements in running shoe technology, particularly in the Nike Vaporfly, have been shown to improve running economy. Other brands have now also developed new, advanced shoes with a carbon-fiber plate and thicker, new midsole foams. However, none of these new shoes have been compared to the Vaporfly. Therefore, we compared the effects of 7 different carbon-plated shoes and 1 traditional racing shoe on running economy.

Methods: Seven carbon-plated shoes: Hoka-RocketX (HRX), Saucony-Endorphin Pro (SEP), Nike-Alphafly (NAF), Asics-Metaspeed Sky (AMS), Nike-Vaporfly2 (NVF2), New Balance-RC Elite (NBRC), Brooks-Hyperion Elite2 (BHE2), and one traditional shoe: Asics-Hyperspeed (AHS) were tested in 12 male runners (5k best: 16.0±0.7 min) on two visits. Shoes were tested in a random sequence over 8x5-minute trials (16 $km \cdot hr^{-1}$; 5-minute rest between trials) on visit 1, and in the reverse/mirrored order for visit 2. Metabolic and running mechanics data were collected and averaged across visits.

Results: VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$; % change from AHS) was significantly different across shoes. HRX (51.67±2.07) and BHE2 (51.42±1.72) did not differ from AHS (51.71±2.02). While SEP (50.93±1.82; -1.48±0.72%) and NBRC (50.99±1.83; -1.37±0.78%) were statistically better than AHS, they were inferior to NAF (50.13±1.86; -3.03±1.48%), NVF2 (50.29±1.72; -2.72±1.02%), and AMS (50.39±1.71; -2.52±1.08%).

Conclusions: While some of the shoes tested performed better than the traditional racing shoe, only NAF and AMS matched the NVF2. From these data, it appears the running shoe market as a whole has not caught up to the advantages conferred by the NVF2.

Keywords: distance running, endurance performance, road racing, super shoes

1. Introduction

The advent of the carbon-plated running shoe, in support of the historic sub 2-hour marathon by Nike athlete Eliud Kipchoge, has resulted in an arms race across various running shoe companies in hopes of providing a similar competitive advantage to their athletes and customers. These new “super” shoes are characterized by the presence of a carbon-fiber plate in the midsole of the shoe to increase stiffness, often along with new, more responsive and thicker midsole foams to provide cushioning and enhance energy return. These advancements are purported to enhance performance by improving running economy (RE), a measure of oxygen consumption or energy utilization at a given physical workload. RE is a key determinant of endurance performance, as enhanced economy is indicative of a reduced energy cost to run at a given speed, or the ability to run at faster speeds while working at the same physiological intensity.[1, 2]

Recent analysis by Bermon et al.[3] concluded that advancements in running shoe technology contributed substantially to improvements in top times internationally in the marathon and half marathon among elites from 2016 to 2019. Similarly, Senefeld et al.[4] showed a 2% (2.8 minute) and 2.6% (4.3 minute) improvement in elite marathon race times for men and women, respectively, running at the world marathon majors in new Nike shoe technology (Vaporfly and Alphafly). An earlier analysis by the *New York Times*[5] concluded performance benefits were also conferred across a broader range of sub-elite runners, specifically in the Nike Vaporfly. While these observational, retrospective studies point towards widespread improvements in performance, much of the evidence is centered on the Nike Vaporfly and Alphafly shoes.

Similarly, there is both a scarcity of controlled, laboratory-based research on these new shoe advancements, and it is limited almost entirely to new Nike shoes. As early as 2014, Worobets et al.[6] showed that more compliant and resilient midsole foams made of thermoplastic polyurethane (TPU) improved RE by ~1% compared to traditional ethylene vinyl acetate (EVA) foam in an Adidas prototype without a carbon-fiber plate. However, much of the research since has been limited to various editions of the Nike Vaporfly, which incorporates new, thicker midsole foams made of polyether block amide (PEBA) and a full-length carbon-fiber plate.[7-10] Hoogkamer et al.[7] found ~4% improvements in RE in a Nike Vaporfly prototype across running speeds of 14-18 $km \cdot h^{-1}$, which was independently confirmed by Barnes and Kilding[8]. In addition to the increased longitudinal bending stiffness provided by the carbon-fiber plate in these shoes, the new midsole foam in the Nike Vaporfly was more compliant and resilient, returning more mechanical energy following compression.[7] This was thought to allow for the observed improvements in RE.

While those results suggest the shoes do offer a substantial advantage, it raises the question of whether or not this provides an unfair advantage.[11] Given these concerns, some suggestions have been made on the regulation of these new shoes,[12, 13] and World Athletics did rule in 2020 on new technical specifications, limiting the stack height/foam thickness to 40 mm for road racing and limiting shoes to a single carbon-fiber plate.[14] Since the release of the Nike Vaporfly, most major running shoe brands have come to market with a carbon-plated shoe of their own, with or without new proprietary midsole foams. The shoes have been promoted not just for their elite, sponsored athletes, but marketed across the ranks of competitive running. However, to our knowledge no comparative data has been published. That is to say, the Nike Vaporfly has been compared to traditional racing shoes, but not to any of its new competitors on the market. Should these advanced shoes produced now by other companies be shown to offer similar improvements in RE, things might be deemed more equitable. In the absence of any empirical evidence, we are forced to operate on the assumption that the playing field has been more or less leveled by the rest of the running shoe industry. Anecdotal evidence of large numbers of athletes gravitating towards one or two shoe brands/models,[15] athletes breaking sponsorship contracts to run in Nike shoes, or even sponsors allowing athletes to run in different brands so as to not hold their athletes back,[16] suggest that this is not a safely held assumption. Case-study data from our laboratory would suggest this as well, as the Nike Alphafly was shown to improve economy by 4%, not just relative to a traditional racing shoe, but to one of its carbon-plated competitor shoes as well.[17]

We do not necessarily think it is feasible or a good long-term approach to expect to test every new shoe that comes to market to determine if certain shoes are providing a potential advantage relative to its competitors. However, we do think that given the rapid advancements in running shoe technology over the last few years, coupled with the lack of any comparative research across various carbon-plated running shoes, an initial comparison across the broad landscape of the major brands in the running shoe industry is warranted and overdue. Therefore, the purpose of this study was to compare the effects of 7 different carbon-plated racing shoes and 1 traditional racing shoe on running economy in competitive, male distance runners.

2. Materials and methods

2.1. Subjects

Twelve trained, male distance runners who met the following inclusion criteria were recruited for the study: 1) run training of at least 3 runs per week for previous 3 months, 2) sub-17:30 5-km race performance, or equivalent race performance for distances 3 km to marathon, within the last year, 3) shoe size between 10-11 US men's sizing. Performance criteria was set so that subjects should be able to run below the lactate threshold at the tested RE speed of 16 $km \cdot hr^{-1}$. This was also confirmed by blood lactate measures, as described in the experimental design section (2.2). Subject demographics (n = 12) were as follows (mean ± standard deviation), age: 26 ± 8 years, height: 181 ± 5 cm, body mass: 68.0 ± 3.3 kg, body fat: 14.0 ± 2.2%, 5-km personal best: 16.0 ± 0.7 minutes, 5-km season best within last year: 16.4 ± 0.9 minutes. This study was approved by the Stephen F. Austin State University Institutional Review Board (2021-21220) and conducted in accordance to the ethical standards in the Declaration of Helsinki. Informed consent was obtained from all subjects prior to participation.

2.2. Experimental design

Subjects reported to the lab for 2 visits on separate days. On each visit, subjects ran in all 8 of the shoes (7 carbon-plated shoes and 1 traditional racing shoe). On visit 1, the test sequence of the shoes was randomized for each subject using a random number generator. Each subject tested the shoes in the reverse/mirrored order on visit 2. Subjects were asked to avoid exercise, caffeine, and alcohol within 24 hours of their testing visits. Additionally, they were asked to recall what they ate prior to visit 1 and to replicate this as much as possible for visit 2.

2.2.1. Shoes

Seven carbon-plated racing shoes were tested: 1) Hoka One One – Rocket X (Hoka RX), 2) Saucony – Endorphin Pro (Saucony EP), 3) Nike – Air Zoom Alphafly Next% (Nike AF), 4) Asics – Metaspeed Sky (Asics MS), 5) Nike – ZoomX Vaporfly Next% 2 (Nike VF2), 6) New Balance – Fuel Cell RC Elite (New Bal RC), 7) Brooks – Hyperion Elite 2 (Brook HE2) and 1 traditional racing shoe 8) Asics – Hyperspeed (Asics HS). Shoe specifications are provided in Table 1 and images in Figure 1. These shoes were selected as they represent the top carbon-plated racing shoes offered by many of the major brands in the running shoe industry. While we were not able to obtain every major carbon-plated racing shoe on the market due to product availability and funding limitations, we feel that the lineup obtained and tested achieved the broad goal of assessing whether or not the competitive running shoe landscape has been normalized relative the previous benefits shown to be offered by the Nike Vaporfly. To limit the effect of shoe mass on RE, the average mass of the shoes tested was 225 g and none of the tested shoes differed in mass by more than 30 g. Further, all 7 carbon-plated shoes were within 18 g of the traditional shoe (Asics HS). The Asics HS is the same racing shoe Ryan Hall wore for his still-standing, 59:43 North American half-marathon record at the Aramco Houston Half-Marathon in January 2007. All shoes were new at the beginning of the study and had not been run in previously. No shoe accumulated more than 22 km of distance during the study.

Table 1
Specifications of 7 carbon-plated shoes and 1 traditional shoe ranked by mass

Shoe	Mass (g)	Carbon Plate?	Heel Stack (mm)	Forefoot Stack (mm)	Heel-Toe Offset (mm)	Retail Price (US $)
Asics Metaspeed Sky	209	Yes	38	33	5	250
Nike ZoomX Vaporfly Next% 2	211	Yes	40	32	8	250
New Balance Fuel Cell RC Elite	221	Yes	34	24	10	225
Hoka RocketX	224	Yes	35	30	5	180
Asics Hyperspeed	227	No	30	21	9	90
Brooks Hyperion Elite 2	229	Yes	35	27	8	250
Saucony Endorphin Pro	239	Yes	39	31	8	200
Nike Air Zoom Alphafly Next%	240	Yes	40	36	4	275

Shoe mass represents average mass of the size 10, 10.5, and 11 shoes in the testing lineup. Stack height values obtained from shoe specifications listed on runningwarehouse.com. Retail prices reflect standard price listing at time of study.

Fig. 1 Shoes tested included 7 carbon-plated racing shoes: A) Hoka One One Rocket X, B) Saucony Endorphin Pro, C) Nike Air Zoom Alphafly Next%, D) Asics Metaspeed Sky, E) Nike ZoomX Vaporfly Next% 2, F) New Balance Fuel Cell RC Elite, G) Brooks Hyperion Elite 2, and one traditional racing shoe: H) Asics Hyperspeed

2.2.2. Test procedures

On visit 1, subjects first tried on all shoes to ensure proper sizing. Prior to beginning the RE testing trials, all subjects completed a 10-minute warmup jog in their own shoes at a self-selected pace slower than 16 $km \cdot hr^{-1}$. Subjects then completed 8 x 5-minute trials at 16 $km \cdot hr^{-1}$ wearing a different, randomly selected shoe for each trial. There was a 5-minute rest between trials to change shoes. All run testing was performed on a motorized treadmill (PPS 55 Med, Woodway, Waukesha, WI) and running speed was confirmed by a handheld digital tachometer (Peak-Meter PM6208A, Shenzhen, China). Oxygen consumption (VO_2), carbon dioxide production, ventilation, and the respiratory exchange ratio (RER) was measured throughout each trial using a calibrated metabolic cart (TrueOne 2400, Parvo Medics, Sandy, UT), and the average values in the final 2 minutes of each 5-minute trial was used to determine economy. Energy expenditure was determined with non-protein based RER equations.[18]

Running mechanics (ground contact time, cadence, ground contact time imbalances, vertical oscillation) and heart rate were also measured throughout each trial using a previously validated[19] heart rate monitor with a built-in accelerometer (HRM Tri/920 XT, Garmin, Olathe, KS). Garmin FIT files were uploaded for analysis (Golden Cheetah, v3.4). Average stride length was determined as treadmill running speed divided by average stride rate. As previously described,[20] ground contact time imbalance was calculated as the average, absolute difference in the percentage of ground contact time spent on the left vs. right foot, and the vertical oscillation ratio was calculated by dividing vertical oscillation by step length expressed as a percentage. The running mechanics data were averaged from the final 4.5 minutes of each 5-minute trial, and HR was averaged over the final minute.

These procedures were identical for both RE testing visits and the average measures across the two visits was used for analysis. The shoe testing sequence was randomized for each subject on their first visit, and that shoe sequence was tested in reverse order for each subject's second visit to eliminate any order effect. At the conclusion of the 8 trials, a capillary blood sample was obtained from the fingertip and analyzed (Lactate Plus, Nova Biomedical, Waltham, MA) to ensure the testing was performed below the onset of blood lactate accumulation (OBLA) of 4 mmol·L^{-1}.[21] Body composition was assessed via dual-energy x-ray absorptiometry (GE Prodigy, Chicago, IL).

2.3. Survey data

At the conclusions of visit 2, subjects completed a survey providing subjective feedback on the shoes. They were asked to rank the shoes in order of preference (most to least) for racing both 5 km and a marathon. Additionally, they rated each shoe on a 0- to 10-point scale for softness/cushioning (0-firm to 10-soft), energy return (0-less springy to 10-more springy), and stiffness (0-flexible to 10-rigid).

2.4. Statistical analysis

A repeated-measures ANOVA was used to compare shoe condition on the tested metabolic and mechanics variables. Continuous variables were inspected for normality and were normally distributed. Significant effects were followed up with pairwise comparisons with the Holm-adjustment for multiple comparisons.[22] Significance for all statistical test was set with an α of 0.05. Based on the more conservative effect sizes (1.73) reported in previous literature[9] comparing the Nike VF to traditional racing shoes, an a priori power analysis (G*Power, 3.1.9.7, Universität Kiel, Germany) revealed a sample size of 10 subjects would be adequate to achieve a power of 0.8 with an α, adjusted for multiple pairwise comparisons (28 possible shoe comparisons), of 0.05. While we chose to adjust α by the full 28 potential shoe comparisons for the metabolic (VO_2) data, we limited the pairwise shoe comparisons to just the Asics HS for all running mechanics variables (7 comparisons). Within subject effects sizes were calculated as the average of the individual subject difference scores divided by the standard deviation of the difference scores (Cohen's d_z).[23] Pearson correlations were determined between a shoe's average VO_2 and each running mechanics variable. Non-parametric survey data was compared across shoes with Friedman tests with significant findings followed up with Conover's post hoc tests with paired comparisons again limited to just the Asics HS. Spearman rank correlations were calculated between the average VO_2 ranking for each shoe and the subjective survey data variables. All statistical analyses were performed using classical statistics in JASP (v0.14.1, University of Amsterdam, Netherlands).

3. Results

The average VO_2 for each shoe along with the individual responses are displayed in Figure 2 and complete metabolic data in Table 2. There were significant differences across shoes for all metabolic variables.

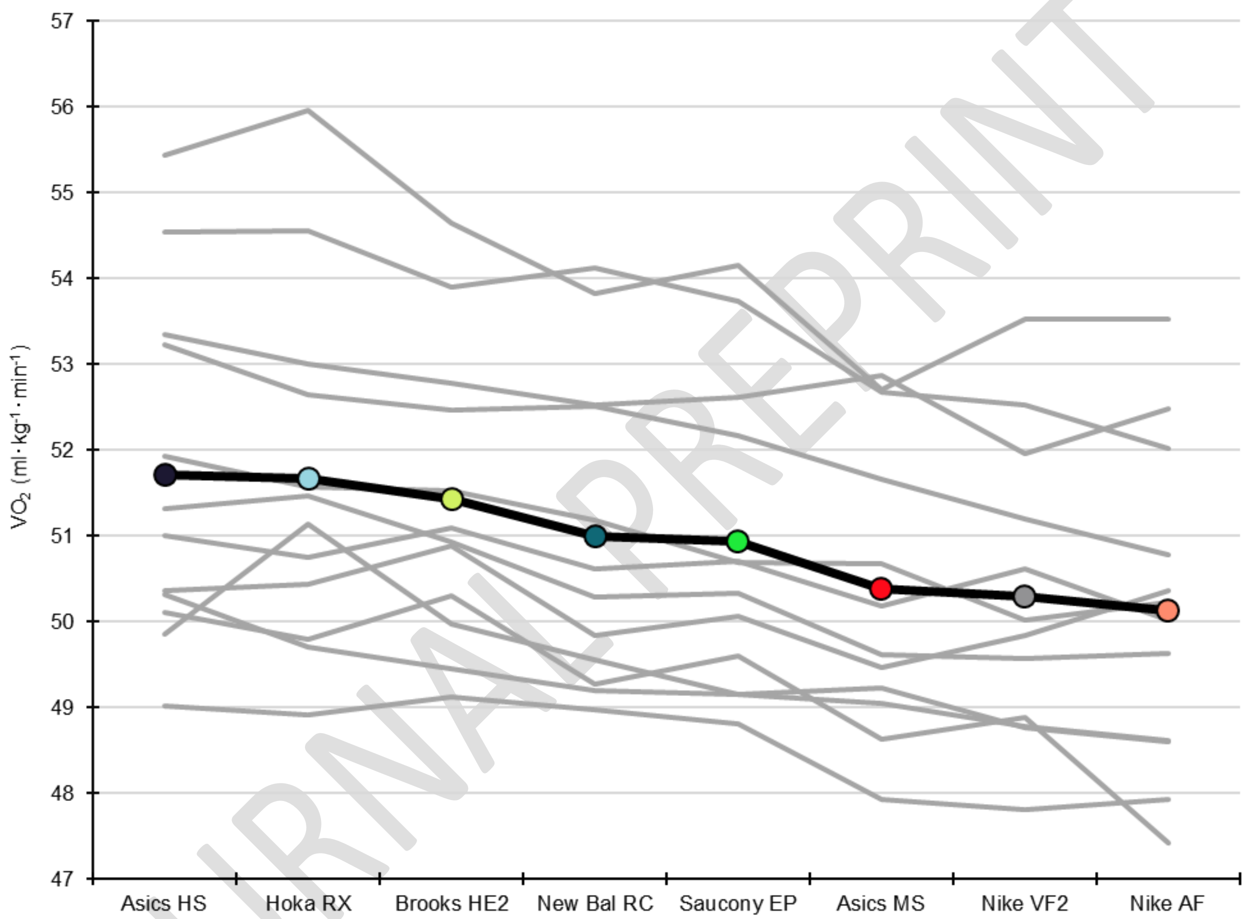

Fig. 2 Oxygen consumption (VO_2) at 16 km·hr^{-1} in 7 different carbon-plated racing shoes and one traditional racing shoe ranked from least (left) to most (right) economical. Black line depicts group average and grey lines depict individual responses. Abbreviations: AF = Alphafly; Bal RC = Balance RC Elite; EP = Endorphin Pro; HE2 = Hyperion Elite 2; HS = Hyperspeed; MS = Metaspeed Sky; RX = Rocket X; VF2 = Vaporfly 2.

Follow up pairwise comparisons showed that compared to the traditional Asics HS shoe, the Hoka RX (-0.08%) and Brooks HE2 (-0.53%) did not significantly lower VO_2. The New Bal RC (-1.37%), Saucony EP (-1.48%), Asics MS (-2.52%), Nike VF2 (-2.72%), and Nike AF (-3.03) all significantly lowered VO_2 (improved economy). However, the New Bal RC and

Saucony EP improved economy by less than 1.5% on average and were significantly worse than the Asics MS, Nike VF2, and Nike AF, which all resulted in greater than 2.5% improvements. Complete pairwise comparisons of each shoe to another is provided in Table 3. In terms of individual responsiveness, the percentage of subjects who responded with an at least 2% decrease in VO_2 relative the traditional shoe were as follows: Nike VF2 (83.3%), Nike AF (75.0%), Asics MS (66.7%), Saucony EP (25.0%), New Bal RC (25.0%), Hoka RX (0%), Brooks HE2 (0%). Likewise the percentage of subjects with an at least 3% decrease in VO_2 in a given shoe were as follows: Nike AF (58.3%), Nike VF2 (50.0%), Asics MS (25.0%), Saucony EP (0 %), New Bal RC (0%), Hoka RX (0%), Brooks HE2 (0%). Lastly, 4 of the 12 subjects (25%) responded with a greater than 4% reduction in VO_2 in the Nike AF. The Asics MS was the only other shoe to have anyone respond with a 4% improvement, limited to a single subject.

Table 2
Running economy and heart rate data for male runners (n = 12) at 16 km·hr^{-1} in racing shoes ranked from worst (left) to best (right)

	Asics HS	Hoka RX	Brooks HE2	New Bal RC	Saucony EP	Asics MS	Nike VF2	Nike AF
VO_2* (ml·kg^{-1}·min^{-1})	51.71 ± 2.02‡	51.67 ± 2.07‡	51.42 ± 1.72‡	50.99 ± 1.83†‡	50.93 ± 1.82†‡	50.39 ± 1.71†	50.29 ± 1.72†	50.13 ± 1.86†
O_2COT* (ml·kg^{-1}·km^{-1})	193.9 ± 7.6‡	193.7 ± 7.8‡	192.8 ± 6.5‡	191.2 ± 6.9†‡	191.0 ± 6.8†‡	189.0 ± 6.4†	188.6 ± 6.5†	188.0 ± 7.0†
Energetic Cost* (w·kg^{-1})	17.74 ± 0.78‡	17.72 ± 0.77‡	17.63 ± 0.66‡	17.48 ± 0.71†‡	17.44 ± 0.71†‡	17.24 ± 0.66†	17.21 ± 0.65†	17.16 ± 0.67†
Heart Rate* (beats·min^{-1})	167.6 ± 11.4‡	167.3 ± 11.4‡	166.9 ± 11.4	165.6 ± 11.4†	166.6 ± 11.6	165.4 ± 11.7†	165.2 ± 11.7†	164.4 ± 12.1†

All data represented as mean ± standard deviation. *$p < .001$ across shoe condition. †sig. difference from Asics HS. ‡ sig. difference from Nike VF2.
Abbreviations: AF = Alphafly; Bal RC = Balance RC Elite; EP = Endorphin Pro; HE2 = Hyperion Elite 2; HS = Hyperspeed; MS = Metaspeed Sky; O_2COT = oxygen cost of transport; RX = Rocket X; VF2 = Vaporfly 2; VO_2 = oxygen consumption.

Table 3
Oxygen consumption (ml·kg^{-1}·min^{-1}) across shoe conditions (mean ± SD) at 16 km·hr^{-1} with pairwise comparisons showing percent differences and effect sizes

n = 12	**Asics HS** 51.71 ± 2.02	**Hoka RX** 51.67 ± 2.07	**Brooks HE2** 51.42 ± 1.72	**New Bal RC** 50.99 ± 1.83	**Saucony EP** 50.93 ± 1.82	**Asics MS** 50.39 ± 1.71	**Nike VF2** 50.29 ± 1.72
Hoka RX 51.67 ± 2.07	-0.08 ± 1.04 % d_z: 0.08 p = 1.000						
Brooks HE2 51.42 ± 1.72	-0.53 ± 0.90 % d_z:0.61 p = 0.420	-0.44 ± 1.13 % d_z: 0.41 p = 1.000					
New Bal RC 50.99 ± 1.83	-1.37 ± 0.78 % d_z: 1.69 p = 0.002*	-1.28 ± 1.19 % d_z: 1.04 p = 0.035*	-0.84 ± 0.78 % d_z: 1.07 p = 0.035*				
Saucony EP 50.93 ± 1.82	-1.48 ± 0.72 % d_z: 2.00 p < 0.001*	-1.39 ± 1.20 % d_z: 1.15 p = 0.026*	-0.96 ± 0.51 % d_z: 1.89 p < 0.001*	-0.11 ± 0.58 % d_z: 0.20 p = 1.000			
Asics MS 50.39 ± 1.71	-2.52 ± 1.08 % d_z: 2.17 p < 0.001*	-2.43 ± 1.55 % d_z: 1.48 p = 0.005*	-2.01 ± 1.08 % d_z:1.82 p = 0.001*	-1.17 ± 0.93 % d_z: 1.22 p = 0.019*	-1.06 ± 0.98 % d_z: 1.06 p = 0.035*		
Nike VF2 50.29 ± 1.72	-2.72 ± 1.02 % d_z: 2.53 p < 0.001*	-2.63 ± 1.30% d_z: 1.93 p < 0.001*	-2.20 ± 0.62 % d_z: 3.59 p < 0.001*	-1.36 ± 0.99 % d_z: 1.35 p = 0.010*	-1.25 ± 0.64 % d_z: 1.94 p < 0.001*	-0.19 ± 0.96 % d_z: 0.20 p = 1.000	
Nike AF 50.13 ± 1.86	-3.03 ± 1.48 % d_z: 2.01 p < 0.001*	-2.94 ± 1.60 % d_z: 1.80 p = 0.001*	-2.51 ± 1.31 % d_z:1.94 p < 0.001*	-1.68 ± 1.48 % d_z: 1.12 p = 0.028*	-1.57 ± 1.33 % d_z: 1.18 p = 0.024*	-0.51 ± 1.24 % d_z: 0.41 p = 1.000	-0.32 ± 1.10 % d_z: 0.29 p = 1.000

Data represented as percentage difference (mean ± SD) between column and row shoe conditions. Cohen's d_z within subject effect size. p-value with Holm adjustment for multiple pairwise comparisons of VO_2 between shoes.
Abbreviations: AF = Alphafly; Bal RC = Balance RC Elite; EP = Endorphin Pro; HE2 = Hyperion Elite 2; HS = Hyperspeed; MS = Metaspeed Sky; RX = Rocket X; VF2 = Vaporfly 2.

There was no relationship between metabolic cost and shoe mass ($r^2 = 0.0118$). Complete running mechanics data is shown in Table 4. Pearson correlations between the average VO_2 and the running mechanics variables for a given shoe showed significant relationships for the following variables: cadence: $r(6) = 0.729$, p = 0.040, stride length: $r(6) = -0.716$, p = 0.046, vertical oscillation: $r(6) = -0.747$, p = 0.033. We attempted to explore some of the individual subject responsiveness by assessing the relationship in percent change in VO_2 relative to the various running mechanics variables for the three top shoes (Asics MS, Nike AF, Nike VF2). However, we did not find any meaningful relationships ($r^2 < .25$, data excluded for brevity). This is likely because the majority of our subjects responded well to these top three shoes.

Table 4
Running mechanics data for male runners (n = 12) at 16 $km \cdot hr^{-1}$ in 7 carbon-plated shoes and 1 traditional shoe.

	Hoka RX	Saucony EP	Nike AF	Asics MS	Nike VF2	New Bal RC	Brooks HE2	Asics HS	*p*
Contact Time (ms)	204 ± 9	205 ± 9	206 ± 9	206 ± 9†	205 ± 8	204 ± 10	203 ± 9	204 ± 9	.001*
Cadence ($steps \cdot min^{-1}$)	175.8 ± 10.5	175.5 ± 10.3	174.6 ± 10.4†	175.5 ± 10.5	175.8 ± 10.3	175.7 ± 10.8	176.1 ± 10.6	176.5 ± 10.3	< .001*
Stride Length (m)	3.04 ± 0.18	3.05 ± 0.18	3.06 ± 0.18†	3.05 ± 0.18	3.04 ± 0.18	3.05 ± 0.19	3.04 ± 0.18	3.03 ± 0.18	< .001*
Vertical Osc. (cm)	10.0 ± 1.7	10.0 ± 1.7	10.2 ± 1.7	10.1 ± 1.7	10.0 ± 1.7	10.0 ± 1.7	10.0 ± 1.7	9.9 ± 1.6	.062
Vertical Osc. Ratio (%)	6.55 ± 0.77	6.56 ± 0.75	6.60 ± 0.76	6.58 ± 0.78	6.54 ± 0.76	6.56 ± 0.77	6.54 ± 0.75	6.53 ± 0.74	.398
Contact Time Imbalance (%)	2.0 ± 1.9	2.0 ± 1.9	1.8 ± 1.7	2.0 ± 2.1	2.0 ± 1.9	1.8 ± 2.1	1.7 ± 2.0	2.0 ± 2.3	.377

All data represented as mean ± standard deviation. *p < .05 across shoe condition. †sig. difference from Asics HS.
Abbreviations: AF = Alphafly; Bal RC = Balance RC Elite; EP = Endorphin Pro; HE2 = Hyperion Elite 2; HS = Hyperspeed; MS = Metaspeed Sky; Osc. = oscillation; RX = Rocket X; VF2 = Vaporfly 2

In fact, there were only three subjects who showed a less than 2% reduction in VO_2 on average for the Nike VF, Asics MS, and Nike AF relative to the traditional Asics HS. That is not to say there was not a range of responsiveness, as subjects ranged from 1% to 4% improvement in economy on average. The metabolic and mechanic characteristics of the top 50% of responders in terms of economy improvements and the lower 50% of responders is provided in Table 5. While the purpose and design of the study was not to make statistical conclusions for these types of comparisons, these descriptives do allow for some subsequent points of discussion.

Table 5
Metabolic and mechanics characteristics of high and low responders

	Asics HS	Top 3 Shoes	% Difference
VO_2 (ml·kg^{-1}·min^{-1}) Upper 50	52.8 ± 2.0	50.9 ± 1.8	-3.6 ± 0.3
VO_2 (ml·kg^{-1}·min^{-1}) Lower 50	50.7 ± 1.5	49.7 ± 1.6	-1.9 ± 0.7
Contact Time (ms) Upper 50	201 ± 8	202 ± 8	0.8 ± 1
Contact Time (ms) Lower 50	208 ± 8	209 ± 9	0.4 ± .4
Cadence (steps·min^{-1}) Upper 50	174.0 ± 5.4	172.6 ± 5.2	-0.8 ± 0.9
Cadence (steps·min^{-1}) Lower 50	179.0 ± 13.8	178.1 ± 13.9	-0.5 ± 0.5
Vertical Oscillation (cm) Upper 50	10.4 ± 1.3	10.6 ± 1.2	1.9 ± 3.3
Vertical Oscillation (cm) Lower 50	9.5 ± 2.0	9.6 ± 2.1	1.0 ± 1.2

All data represented as mean ± standard deviation. Upper 50: top 50% of responders (n=6) in terms of economy improvements. Lower 50: bottom 50% of responders (n=6).
Abbreviations: HS = Hyperspeed; Top 3 = Average of Asics Metaspeed Sky, Nike Vaporfly 2, and Nike Alphafly; VO_2 = oxygen consumption.

Friedman test revealed significant differences across shoes for all of the subjective survey variables (softness/cushioning, energy return, stiffness/rigidity, 5 km race preference, marathon race preference). However, post hoc comparisons revealed that only the Nike AF, Nike VF2, and Asics MS differed in their energy return rating, stiffness/rigidity rating, and marathon shoe preference compared to the Asics HS. The Nike VF2 and Asics MS were more preferred relative to the Asics HS for 5 km race preference. Spearman correlations comparing the VO_2 rankings of the shoes to the subjective survey variable rankings were significant for all variables, but the relationship with softness/cushioning: $r_s(6) = 0.952$, p = 0.001 and energy return: $r_s(6) = 0.929$, p = 0.002 was stronger than stiffness/rigidity: $r_s(6) = 0.810$, p = 0.022. Likewise, marathon shoe preference: $r_s(6) = 0.905$, p = 0.005 was more strongly related to the VO_2 rankings than 5 km shoe preference: $r_s(6) = 0.833$, p = 0.015.

RER (0.92 ± 0.04) remained below 1.0 for all subjects across the trials. Blood lactate recorded at the conclusion of testing protocol (2.1 ± 0.9 $mmol \cdot L^{-1}$) was ≤ 4 $mmol \cdot L^{-1}$ for all subjects. Additionally, to confirm that there was not a substantial VO_2 slow component we examined the average VO_2 at minute 4 (50.8 ± 1.9 $ml \cdot kg^{-1} \cdot min^{-1}$) to minute 5 (51.0 ± 1.8 $ml \cdot kg^{-1} \cdot min^{-1}$) across all trials, which represented only a 0.39 ± 0.49% difference. We used an ANOVA to examine whether or not there were differences in VO_2 based on shoe testing sequence and found no differences (p = 0.946), indicating that the randomization and mirrored design was effective.

4. Discussion

Our findings are unique as this is the first study to our knowledge to compare RE between the previously established Nike Vaporfly shoe to other competitor shoes also utilizing carbon-fiber plates and thicker midsole foams. On average, RE was improved by 2.7% in the Nike VF2 relative to the traditional shoe in the present study. However, only the Nike AF (3.0%) and Asics MS (2.5%) resulted in similar improvements in RE. And while other shoes in the lineup did perform statistically better than the traditional (Asics HS) shoe, none resulted in greater than 1.5% improvements on average. These data suggest that the release of new “super” shoes by various brands across the running shoe industry has not resulted in a leveling of the playing field relative to the established Nike shoes. It is evident from our data that simply including a carbon plate or increasing the stack height in a racing shoe does not confer equal improvements in economy. This would suggest that the foam and/or interaction of the foam and the plate is crucial to the economy benefits. This is consistent with recent findings by Healey and Hoogkamer,[24] who showed that cutting the carbon plate in the Nike VF to reduce the longitudinal bending stiffness did not result in changes in RE compared to an intact version of the Nike VF, suggesting that the PEBA based ZoomX foam in the Nike VF is the critical factor. This also helps to explain the equivocal findings in the literature on the effects of increasing longitudinal bending stiffness on RE, as pointed out in recent reviews.[25, 26] Despite the widespread use of carbon-fiber plates in new racing shoes, the foam technology still varies widely. Additionally due to the use of proprietary foam names and blends, it is difficult to determine exactly what midsole foams are composed of (EVA, TPU, PEBA, etc.) across different shoe brands. Even when shoes are known to utilize similar foam materials, such as the case with the PEBA based Saucony EP and Nike VF2/AF, we see differences in economy in the current study.

In regards to the magnitude of improvement in RE in these new shoes, our findings show the Asics MS (2.5%, range 0.9-4.9%), Nike VF2 (2.7%, range 0.8-3.8%), Nike AF (3%, range 0-5.3%) all improved economy to a similar extent relative to a traditional racing shoe. In the current study the traditional racing shoe utilized (Asics HS) was heavier than the Asics MS (+18g) and Nike VF2 (+16g), but lighter than the Nike AF (-13g). Previously, Barnes and Kilding[8] found that relative to a traditional racing shoe (Adidas Adios Boost) the Nike VF improved economy by 4.2% at 16 $km \cdot hr^{-1}$, though this advantage was reduced to 2.9% when ~30-35 g was added to the Nike VF shoe to equal the mass of the traditional racing shoe. Although this reduction in economy of greater than 1% is more than would be expected for this minimal amount of additional mass, these mass adjusted improvements are similar to our current findings. This is somewhat in contrast to the magnitude of response found by Hoogkamer et al.[7] who showed 4% improvements in economy with a Nike VF prototype even when ~50g of additional mass was added to the Nike VF to equal the mass of the traditional shoe. And finally, Hunter et al.[9] showed only 2.8% improvements in the Nike VF when compared to the same control shoe that was ~35g heavier.

Traditionally, shoe mass has been inversely related to RE. It has previously been proposed for typical running shoes that for every 100 g increase in shoe mass, oxygen cost increases by ~1%.[27] This may no longer be the case given the new materials being incorporated into racing shoes. For instance, Barnes and Kilding[8] showed that the Nike VF improved economy by 2.6% compared to a track spike, despite being nearly 100g heavier. We chose not to match for shoe mass in the present study for several reasons. 1) All of the shoes tested ranged in mass by a fairly narrow range (~30 g), and all shoes were within 18 g of the traditional shoe being compared. 2) Given the multitude of shoes tested this would have required entirely separate lab visits for mass-matched trials. 3) We did not see a relationship between shoe mass and oxygen cost. 4) Of the shoes that offered substantive benefits to RE, the heaviest shoe in the lineup (Nike AF: 240 g) was the most economical and performed similarly to the lightest shoes (Nike VF2: 211 g, Asics MS: 209 g). 5) And finally, from an external validity standpoint, we contend that not matching for shoe mass has greater application. Simply adding extra inert mass, not in the form of extra foam, does not seem useful or practical. Given that these new shoes have been engineered with thicker foam with the goal of enhancing energy return, there is a tradeoff manufacturers face between adding more "springy" material vs. keeping the shoe lighter. While this tradeoff is something that a given shoe manufacturer would need to explore in the development of a shoe, when it comes to real world application, an athlete is most concerned simply with what shoe enhances economy the most among a similar, competitive, lineup of racing shoe options. This is what we have proposed and compared in the current lineup of shoes tested.

While the Nike VF2, Nike AF, and Asics MS were the top three shoes in the study in terms of improving RE, we only found a few significant differences between these shoes and the traditional Asics HS shoe in terms of running mechanics (Table 4). Ground contact time was greater in the Asics MS, cadence was lower in the Nike AF, and stride length was longer in the Nike AF. These trends however are consistent with the previously studied Nike VF.[7, 8] Furthermore, significant Pearson correlations in the present study showed that the average VO_2 across shoes was directly related to the average cadence and inversely related to average vertical oscillation and stride length. This suggests that a shoe's effectiveness in improving economy is likely related to such changes in mechanics, characterized by longer, bouncier strides.

In regards to individual subject responsiveness, we provided some descriptive metabolic and mechanics characteristics of high and low responders (Table 5). From these data it appears that the subjects who are more responsive (indicated by greater percent reductions in VO_2) are less economical to begin with in traditional shoes, as shown by the greater VO_2 when running in the Asics HS. In this sense, it appears that the top shoes are allowing the less economical runners to close the gap in economy advantages relative to their more economical competitors. We also see that cadence tends to be higher and vertical oscillation lower in the low responders. It is unclear if this is simply a characteristic of them being more efficient runners to begin with, or if these characteristics might impact the responsiveness to the new shoes. The 4 subjects who were the lowest responders in terms of VO_2 improvement (0-2.2%) in the Nike AF, had the 4 highest cadences in the study, average 186 steps·min^{-1} compared to 170 steps·min^{-1} for the remainder of the participants. Vertical oscillation was also lower in these participants (8.48 cm) compared to the remainder of the subjects (10.77 cm). In fact, the only subject who was a complete non-responder to the Nike AF (0% improvement) was the only runner in the study who had a vertical oscillation of less than 8 cm. These things considered, we would speculate that low- or non-responders on an individual level, although rare, might be a result of naturally low vertical oscillation and high cadence running that is already considered economical,[2] but more importantly may not allow for the full energy saving benefit of these "springier" shoes to be realized. While we did not examine foot strike patterns, Hoogkamer et al.[7] did show that rearfoot strikers who ran with longer ground contact times and lower cadences (~173 steps·min^{-1}) tended to respond better to the Nike VF than faster cadence (~180 steps·min^{-1}) mid/forefoot strikers. However, future studies would need to be designed specifically for separating out high cadence/low vertical oscillation "shufflers" from low cadence/high vertical oscillation "bounders" to truly make these comparisons.

Given the difficulty in testing every new shoe available and the lack of access for most athletes to perform individualized RE testing, we attempted to explore if any subjective measures related to a shoe's RE. While we saw moderate to strong relationships across all variables, it appears that the group rankings on the softness/cushioning and energy return of the shoes was more closely related to the average VO_2 in the shoes than was the stiffness/rigidity rating. This seems reasonable as the carbon plate in the shoes likely imparts similar subjective feelings of stiffness/rigidity, but the various foam materials have a broader range of ratings and are likely more important to the economy improvements. Furthermore, marathon shoe preference ranking was more closely related to VO_2 ranking of the shoes than 5k shoe preference ranking. It is likely that runners simply gravitated to the lighter shoes when thinking about racing a 5k, but this is not necessarily in the best interest in terms of RE, as seen in the heavier, but more economical Nike AF. It is important to note that these Spearman ranked correlations were based on the group averages and do not necessarily indicate that on the individual level athletes were effective at rating which shoe would be best for them. In fact, only 2 of 12 subjects (5 km shoe preference) and 3 of 12 subjects (marathon shoe preference) selected the shoe that was most economical for them individually. While our study was not designed to draw broad conclusions on these subjective measures, the group average relationships may help shed some insight in parsing through the abundance of subjective shoe reviews that can be found online and help guide more robust investigations in this area.

Future research should continue to establish whether or not new racing shoes are comparable with the Nike VF, and the now established Nike AF and Asics MS. As far as the speeds at which these shoes might help improve economy, our study was delimited to 16 $km \cdot hr^{-1}$. However, based on previous research,[8] similar benefits would be expected from at least 14 to 18 $km \cdot hr^{-1}$. Future investigations can help elucidate the minimum speeds at which these shoes no longer confer meaningful benefits, as well as help to clarify characteristics of runners likely to be low- or non-responders. Lastly, future research can help to determine if there are benefits (decreased muscle damage, soreness, etc.) offered by these new shoe advancements that aid performance beyond that of the observed improvements in RE.

5. Conclusions

Based on our findings indicating that only the Asics MS and Nike AF offered similar RE improvements as the Nike VF2, we conclude the current competitive running shoe market is not equal and athletes choosing to race in any of the shoes shown to be inferior to these in the present lineup are likely at a competitive disadvantage. For perspective, the 2.5-3% improvement on average for the Nike AF, Nike VF2, and Asics MS is similar to or greater than the expected improvements in RE in response to several weeks to months of various plyometric or resistance training interventions.[28] Using the equation developed by Tam et al.[29] as previously described and applied,[30] a 3% improvement in RE would be expected to improve performance by ~3% at 14 $km \cdot hr^{-1}$ and ~2.6% at 20 $km \cdot hr^{-1}$. This would theoretically translate to ~25-30 seconds for a 15-17 minute 5-km runner and ~4-6 minutes for a 2.5-3.5 hour marathon runner. With this in mind, we would suggest the following to running shoe industry stakeholders. 1) If shoe companies wish for consumers to believe that their new technological advancements offer performance benefits, they should support independent testing of their products. 2) Consumers should be wary of paying high prices for “advanced” shoes that have not been proven to offer comparable benefits to the presently established shoes. 3) Elite athletes, and sub-elite athletes with access, should seek laboratory based RE testing before making decisions on racing shoes, particularly those that have not been independently tested. 4) Sport governing bodies should remain vigilant in assessing whether the competitive shoe market becomes more level over time.

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Authors' contributions

DPJ led all aspects of the project; GPJ was involved with project pilot testing and design, data collection, and manuscript review. All authors have read and approved the final version of the manuscript and agree with the order of presentation of authors.

Competing interest

The authors declare no competing interest. All shoes used for the study were purchased and no funding was provided by any shoe company.

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