Effects of a Highly Cushioned Racing Shoe on Running Economy at Slower Running Speeds

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ABSTRACT

The Nike Vaporfly line of running shoes improve running economy by ~2.7-4.2% at running speeds of 13-18 km·hr^{-1}. It is unclear if the same benefits are conferred at slower speeds. Our purpose was to determine the effects of the Nike Vaporfly Next% 2 (VFN2) on running economy at 10 and 12 km·hr^{-1} compared to a mass-matched, control (CTRL) shoe. Sixteen runners completed 4 x 5-minute trials at both 10 and 12 km·hr^{-1} on the same day. Each shoe was tested twice at each speed in a counterbalanced, mirrored sequence. A two-way repeated measures ANOVA showed a significant shoe x speed interaction for $\dot{V}O_2$ ($p = 0.021$). At 12 km·hr^{-1}, $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) was lower (-1.4 ± 1.1%; $p < 0.001$) for VFN2 (35.8 ± 1.7) relative to CTRL (36.4 ± 1.7). This was greater in magnitude than the differences observed at 10 km·hr^{-1} (-0.9 ± 1.8%; $p = 0.065$) between VFN2 (29.4 ± 1.9) and CTRL (29.6 ± 1.9). From these data, it appears

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that the VFN2 still provides benefits to running economy at 10 and 12 km·hr^{-1}, however these benefits may be smaller in magnitude compared to previous research at faster speeds.

KEYWORDS: distance running, endurance performance, road racing, super shoes, carbon-plated, carbon plate

INTRODUCTION

Running economy (RE) can be defined as the oxygen consumption ($\dot{V}O_2$) or energy utilization required to run at a given speed. It is a key determinant of distance running performance, as improved RE allows an athlete to run faster at the same physiological intensity (Joyner & Coyle, 2008). Advancements in running shoe technology, particularly in the Nike Vaporfly line of racing shoes, have previously been shown to improve RE by ~2.7-4.2% (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2022; Whiting et al., 2021). These benefits are thought to be primarily due to the more compliant and resilient polyether block amide (PEBA) midsole foam used in the Nike Vaporfly shoes (Healey & Hoogkamer, 2021; Hoogkamer et al., 2018).

The aforementioned studies establishing the RE benefits of the Nike Vaporfly shoes all tested subjects at speeds of 13-18 km·hr^{-1}, corresponding to paces of 4:37 per km (7:26 per mile) or faster. Both Hoogkamer et al. (2018) and Barnes and Kilding (2019) examined subjects at multiple speeds from 14 to 18 km·hr^{-1} and neither observed a speed effect on the energetic benefit of the shoes. This would suggest that the benefits of the shoes may be relatively speed agnostic. However, slower speeds do have distinct effects on the kinetic and spatiotemporal characteristics of a runner's gait (McMahon & Cheng, 1990; Nilsson & Thorstensson, 1989) and may affect the runner's response to footwear with altered longitudinal bending stiffness (LBS; McLeod et al., 2020; Day and Hahn, 2020). How the substantially slower speeds may interact with the novel features of the shoes–the greater volume of compliant, resilient foam and the stiff, curved carbon fiber plate–is unknown.

To date, one study has looked at the Nike Vaporfly 4% at slower speeds (Hébert-Losier et al., 2020). The Vaporfly was compared to participants' regular training shoes (~100 g heavier) and to a traditional racing flat (~58 g lighter) at a relative speed of 60% velocity at $\dot{V}O_2$ peak, which corresponded to 11.0 ± 0.6 km·hr^{-1} on average. Running economy was improved by 4.2% in the Vaporfly compared to the much heavier training shoes. However compared to the lighter racing flat, running economy was only 1.0% better in the Vaporfly at this slower speed. Further, these differences were not statistically significant. It is unclear if the smaller benefits observed are due strictly to a lighter comparison shoe or perhaps due to the slower speeds that were tested on average in this particular study. The use of relative versus absolute speeds may also have increased the variability in responses.

Thus, while speed-controlled studies of the Nike Vaporfly line of racing shoes have consistently observed running economy benefits in the 2.7-4.2% range at speeds of 13 $km \cdot hr^{-1}$ and faster, these speeds are only relevant to runners completing the marathon distance in 3:15:00 and faster. Less is known regarding the RE benefits at slower running speeds. For point of reference, only 21% of the 2021 Boston Marathon field (3,227 of 15,385 finishers) and 10% of the 2021 London Marathon Field (3,709 of 35,891 finishers) completed the race under 3:15:00. Given the large percentage of runners competing in endurance events at speeds slower than 13 $km \cdot hr^{-1}$, examination of their benefits at these slower speeds is necessary for both generalization and a more comprehensive mechanistic understanding. Therefore, the purpose of this study was to compare running economy in the Nike ZoomX Vaporfly Next% 2 to a mass-matched control shoe at absolute speeds of 10 and 12 $km \cdot hr^{-1}$ in male and female runners. These speeds correspond to 3:30:00 to 4:15:00 marathon times.

METHOD

Subjects

Sixteen trained runners (8 males and 8 females) completed the study and were included in the final analysis. Initial inclusion criteria at recruitment were as follows: undertaking running training of at least 3 runs per week for previous 3 months; achieved a sub-23:30 5-km race performance within the last year; and is comfortable wearing shoe size 10, 10.5, or 11 in US men's sizing or 7, 8, 9, or 10 in US women's sizing. The established performance criteria was set to ensure participants could run at 12 $km \cdot hr^{-1}$ while below the onset of blood lactate accumulation (OBLA) of 4 $mmol \cdot L^{-1}$. This was also confirmed by blood lactate readings at the conclusion of the testing protocol. Demographic data for the 16 subjects are provided in Table 1. This study was approved by the Stephen F. Austin State University Institutional Review Board (AY2022-2140), and written informed consent was obtained from all subjects prior to participation.

Table 1. Subject characteristics

	Age (years)	Body Mass (kg)	Body Fat (%)	5-km Best (min)
Male (n = 8)	29 ± 15	68.8 ± 10.9	17.2 ± 4.7	19.1 ± 2.6
Female (n = 8)	38 ± 7	58.5 ± 7.4	23.6 ± 3.0	20.3 ± 2.2

Shoes

The experimental shoe used was the Nike ZoomX Vaporfly Next% 2 (VFN2), which at present is the most recent iteration in the previously studied Nike Vaporfly line of racing shoes. The VFN2 is composed of a PEBA midsole foam and includes a rigid carbon-fiber plate imbedded in the midsole. The control (CTRL) shoe utilized was the Asics Hyper Speed, a traditional racing flat with standard ethylene vinyl acetate (EVA) foam and no carbon-fiber plate. The average mass across all the sizes utilized for the VFN2 was 187.7 g, whereas the average mass of the CTRL shoe was 203.5 g. The difference in mass between VFN2 and CTRL for all sizes was between 15-17 g. In order to mass match the shoes, an equivalent amount of mass was added to the VFN2 shoes by placing wing nuts on the laces of the shoe.

Experimental Design and Procedures

Subjects reported to the lab for 1 visit. The study utilized a same day, crossover design where both the VFN2 and CTRL shoe were tested twice for each subject at both 10 and 12 $km \cdot hr^{-1}$. At each speed the shoes were tested in a mirrored sequence (VFN2, CTRL, CTRL, VFN2 or CTRL, VFN2, VFN2, CTRL) and the order counterbalanced across subjects. Following screening and consent, subjects tried on the test shoes to confirm proper fit and comfort. Body weight was then measured and body composition assessed via dual energy x-ray absorptiometry (GE Prodigy, Chicago, IL). Subjects then completed a 10-minute warmup at 10 $km \cdot hr^{-1}$ in their normal training shoes. In the final 5 minutes of the warmup, subjects were fitted with the headgear, mouthpiece, and nose clip used for the measurement of respiratory gas exchange (TrueOne 2400, Parvo Medics, Sandy, UT) to allow time for familiarization and adjustments prior to the test trials.

Following the warmup, subjects were seated at rest for 5 minutes before beginning the test trials in their assigned shoe sequence. Subjects first completed 4 x 5-minute trials at 10 $km \cdot hr^{-1}$, followed by 4 x 5-minute trials at 12 $km \cdot hr^{-1}$. There was a 5-minute break between each trial. All testing was performed on a level, motorized treadmill (Cardiac Science TM 55, Waukesha, WI). This treadmill is composed of a thin belt and hard, plastic deck. The span of the treadmill allows limited flex. Pilot data from our laboratory shows the percent benefits offered by the VFN2 relative to the CTRL shoe at 12 $km \cdot hr^{-1}$ do not differ when the span of the treadmill is shimmed or un-shimmed (Thornton, 2022). Treadmill speed was confirmed for each trial using a handheld digital tachometer (Peak-Meter PM6208A, Shenzhen, China). Oxygen consumption and CO_2 production were measured continuously throughout each trial and energy expenditure (kcal and $W \cdot kg^{-1}$) was determined using the non-protein based respiratory exchange ratio (Péronnet & Massicotte, 1991). The average values from the final 2 minutes of each 5-minute trial was used for analysis.

Running mechanics (cadence, vertical oscillation, ground contact time) and heart rate were measured using a previously validated (Adams et al., 2016) 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). Mechanics data were averaged from the final 4.5 minutes of the 5-minute trials, and HR averaged over the final minute.

Since each shoe was tested twice at a given speed for each subject, the average value for the two trials for each dependent variable was used for the statistical analysis. Following the final trial at the 12 $km \cdot hr^{-1}$ test speed, a capillary blood sample was obtained from the fingertip (Lactate Plus, Nova Biomedical, Waltham, MA). One subject was removed from the final analysis due to a blood lactate reading greater than 4 $mmol \cdot L^{-1}$. However, all 16 subjects included in the final data and analysis recorded a lactate reading below 4 $mmol \cdot L^{-1}$.

Statistical Analysis

A two way (shoe condition x speed) repeated measures ANOVA was used to analyze all metabolic data, which was inspected for normality and normally distributed. Significant interactions were followed up with pairwise t-tests to determine differences between shoes at a given speed. Within subject effect size (Cohen's d_z) was calculated as the average individual subject difference score divided by the standard deviation of the difference scores. Initial analysis with an independent sample t-test revealed no differences in the responses between males and females, so gender was not included in the overall statistical analysis. Significance was set an α of 0.05. Based on the more conservative effect sizes (0.75) reported in previous comparisons (Hébert-Losier et al., 2020), an a priori power analysis (G*Power, 3.1.9.7, Universität Kiel, Germany) revealed a sample size of 13 subjects would be adequate to achieve a power of 0.8 with an α of 0.05. Statistical analysis was performed in JASP (v0.14.1, University of Amsterdam, Netherlands). Running mechanics data were provided as descriptive data only. All data displayed as mean ± standard deviation.

Results

Oxygen consumption data are displayed for the individual responses and the group average between shoes at each of the tested speeds in Figure 1. As would be expected there was a main effect for speed ($F = 695.89$, $p < 0.001$). Additionally, there was a significant main effect for shoe ($F = 13.22$, $p = 0.002$). However, we also observed a significant shoe x speed interaction ($F = 6.66$, $p = 0.021$). Post-hoc pairwise t-tests showed significant differences at 12 $km \cdot hr^{-1}$, where $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$) was lower (-1.4 ± 1.1%; $p < 0.001$; $d_z = 1.26$) for VFN2 (35.8 ± 1.7) relative to CTRL (36.4 ± 1.7). This was greater in magnitude than the differences observed at 10 $km \cdot hr^{-1}$ (-0.9 ± 1.8%; $p = 0.065$; $d_z = 0.49$) between VFN2 (29.4 ± 1.9) and CTRL (29.6 ± 1.9). Energy expenditure ($W \cdot kg^{-1}$) is similarly displayed in Figure 2 where there was also a significant shoe by speed interaction ($F = 8.52$, $p = 0.011$). Energy expenditure was lower (-1.6 ± 1.2%; $p < 0.001$; $d_z = 1.31$) at 12 km·hr^{-1} for VFN2 (12.25 ± 0.60) compared to CTRL (12.45 ± 0.60), which was greater that the differences at 10 km·hr^{-1} (-0.9 ± 1.9%; $p = 0.065$; $d_z = 0.49$) for VFN2 (9.99 ± 0.70) relative to CTRL (10.08 ± 0.69). Running economy expressed as O_2 cost relative to speed (ml·kg^{-1}·km^{-1}) was as follows at 10 km·hr^{-1} (CTRL: 177.7 ± 11.3, VFN2: 176.1 ± 11.1) and 12 km·hr^{-1} (CTRL: 181.8 ± 8.4, VFN2: 179.1 ± 8.3). Heart rate and running mechanics data are summarized in Table 2.

Blood lactate at the conclusion of the final trial at 12 km·hr^{-1} was 1.54 ± 0.78 mmol·L^{-1} and was below 4 mmol·L^{-1} for all subjects included in the final analysis. RER remained below 1.0 across all trials for all subjects. There was no indication of any substantial $\dot{V}O_2$ slow component, as oxygen consumption between minute 4 and minute 5 differed by only 0.4% on average ($p = 0.412$). An ANOVA revealed no differences ($p = 0.992$) in $\dot{V}O_2$ based on the testing sequence of the shoes, which would indicate that the counterbalanced and mirrored assignment was effective.

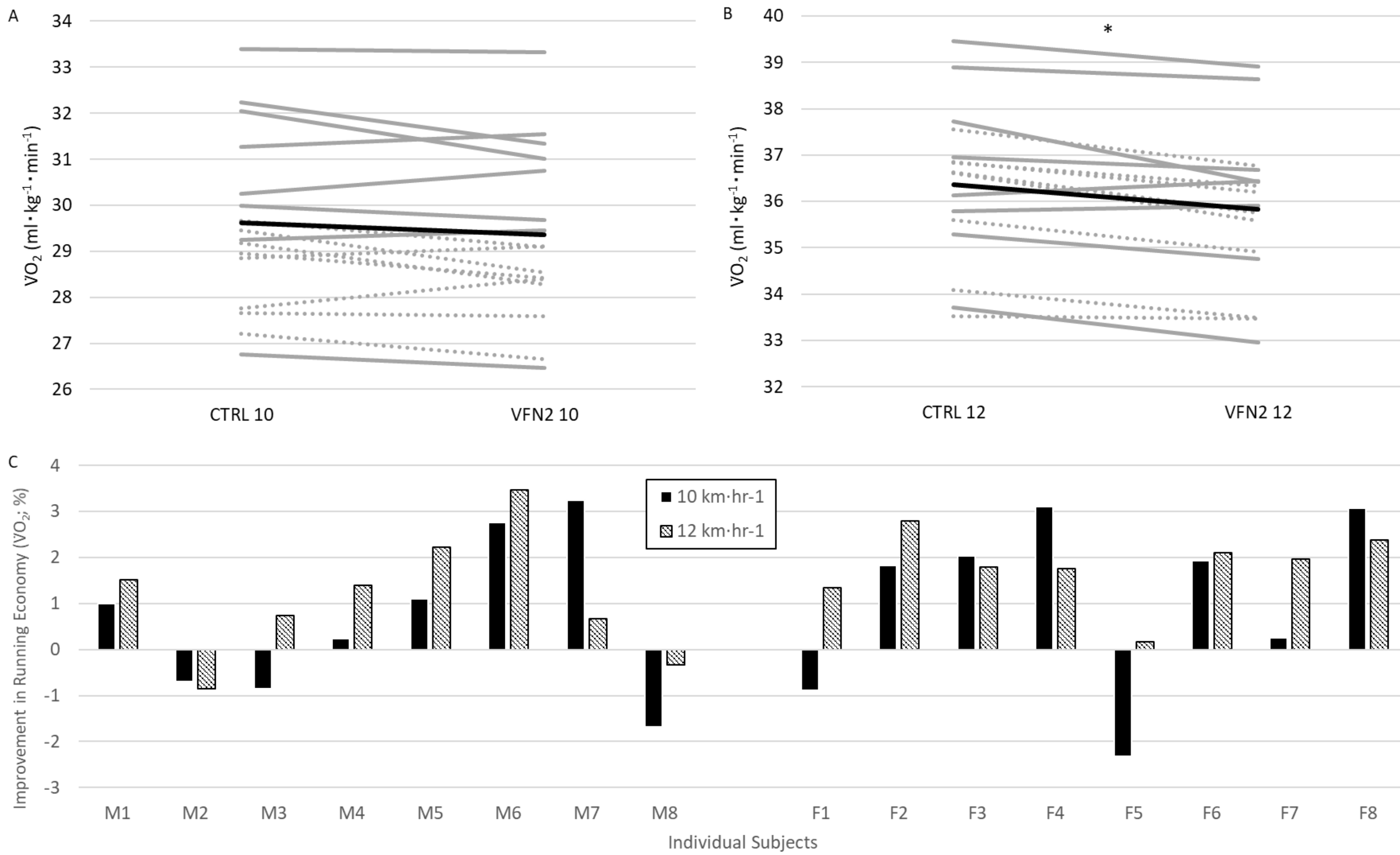

Figure 1. Oxygen consumption ($\dot{V}O_2$) at (A) 10 and (B) 12 km·hr^{-1} in the control (CTRL) shoe and the Nike ZoomX Vaporfly Next% 2 (VFN2). Black lines represent group average. Solid grey lines represent individual male subjects. Dotted grey lines represent individual female subjects. Percent improvement in running economy for the $\dot{V}O_2$ changes in the VFN2 relative to CTRL are displayed in panel C for individual male (M) and female (F) subjects at both speeds tested.

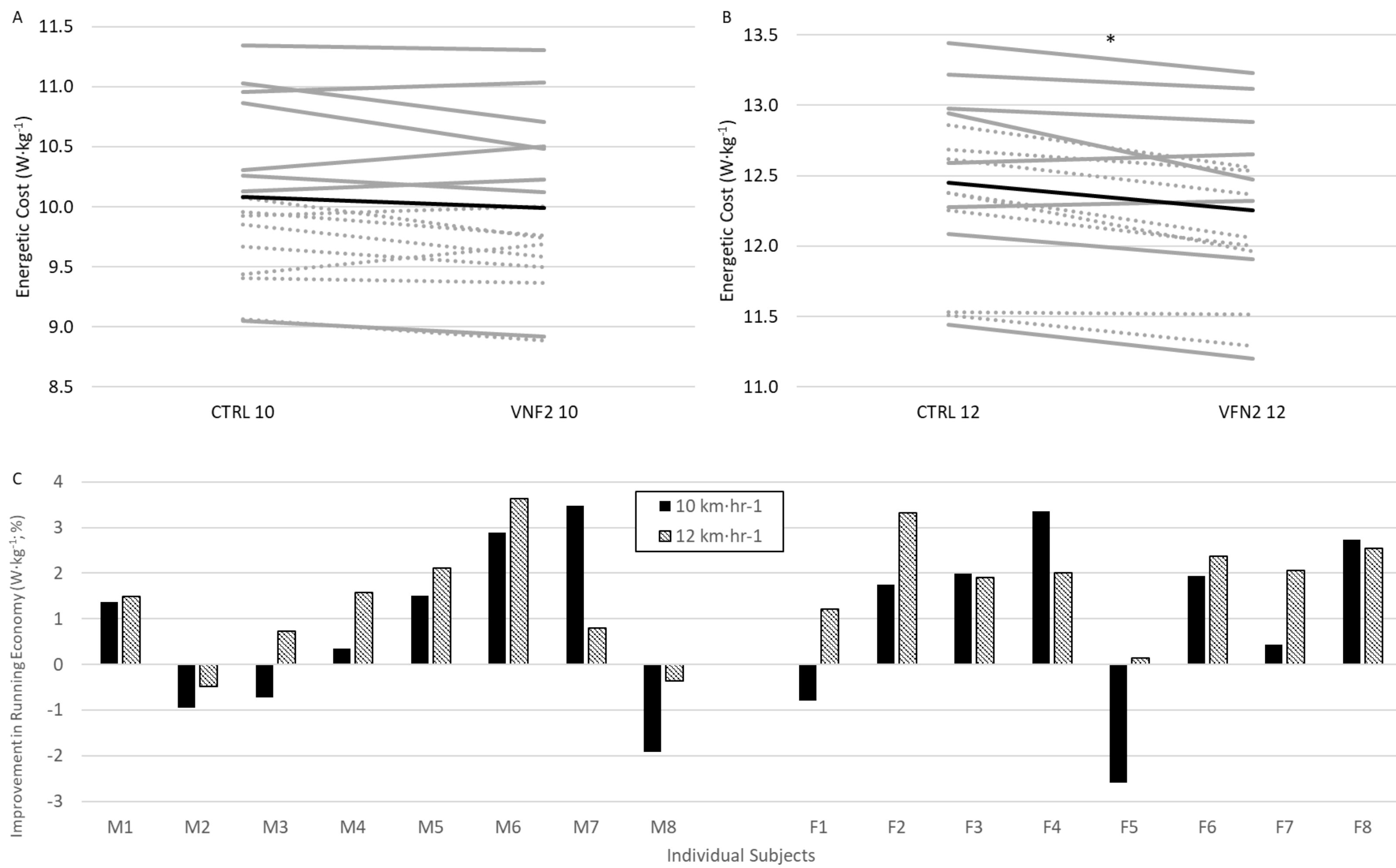

Figure 2. Energy expenditure (W·kg^{-1}) at (A) 10 and (B) 12 km·hr^{-1} in the control (CTRL) shoe and the Nike ZoomX Vaporfly Next% 2 (VFN2). Black lines represent group average. Solid grey lines represent individual male subjects. Dotted grey lines represent individual female subjects. Percent improvement in running economy for the W·kg^{-1} changes in the VFN2 relative to CTRL are displayed in panel C for individual male (M) and female (F) subjects at both speeds tested.

Table 2. Heart rate and running mechanics characteristics of trained runners (n = 16) across shoes at two different running speeds

	10 km·hr^{-1}		12 km·hr^{-1}	
	CTRL	VFN2	CTRL	VFN2
Heart Rate (beats·min^{-1})	137 ± 10	136 ± 10	155 ± 10	154 ± 10
Step Frequency (steps·min^{-1})	173.2 ± 8.9	172.3 ± 8.4	178.3 ± 9.3	177.2 ± 9.3
Vertical Oscillation (cm)	8.1 ± 1.5	8.3 ± 1.6	8.4 ± 1.5	8.5 ± 1.5
Ground Contact Time (ms)	266 ± 19	267 ± 19	244 ± 18	245 ± 17

CTRL control shoe; *VFN2* Nike Vaporfly Next% 2

Discussion

These findings are unique as this is the first study to compare the running economy benefits of Nike Vaporfly line of racing shoes to a mass-matched control shoe at fixed speeds slower than 13 km·hr^{-1}. Whereas previous investigations have shown running economy benefits in the range of 2.7-4.2% at speeds of 13-18 km·hr^{-1} (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2022; Whiting et al., 2021), these data suggest that the benefits may be reduced at 12 km·hr^{-1} (1.6%) and 10 km·hr^{-1} (0.9%). Furthermore, the previous studies that tested subjects at multiple faster speeds (14-18 km·hr^{-1}) observed the magnitude of the running economy benefit to be consistent, independent of the tested speed (Barnes & Kilding, 2019; Hoogkamer et al., 2018). Here, however, we observed the energetic benefits of the shoes to be speed-dependent, with the running economy improvements less at 10 km·hr^{-1} (0.9%) than at 12 km·hr^{-1} (1.6%), and less than this lab previously observed at 16 km·hr^{-1} (2.7%) (Joubert & Jones, 2022).

Hébert-Losier et al. (2020) did show that the Nike Vaporfly improved running economy by only 1% on average when subjects were tested at 60% velocity at $\dot{V}O_2$peak (11.0 ± 0.6 km·hr^{1}) relative to a minimal racing flat that was 58 g lighter. Traditionally, economy is impaired by ~1% for every 100 g of additional shoe mass (Frederick, 1984). Adjusting for the lighter mass of the control shoe in the Hebert-Losier et al. (2020) study, we might expect economy to be an additional 0.58% better in the Vaporfly, or ~1.6%, relative to a mass-matched control shoe at the slower speed tested. This is consistent with our present findings using a mass-matched control shoe at a fixed speed of 12 km·hr^{-1}. More recently, Black et al. (2022) showed a highly cushioned Nike prototype shoe (specific model not named), improved economy relative to a control shoe that was 30-40 g heavier in an incremental exercise test ranging from 10 to 15 km·hr^{-1}. However, only the average economy improvement (~3%) across all speeds was reported. While the highly cushioned shoe utilized in their study did improve economy relative to the heavier control shoe at speeds of 10-12 km·hr^{-1}, it does appear from graphical presentation of their data that the benefits of the highly cushioned were smaller in magnitude at slower speeds than faster speeds. However, given that the authors did not disclose the names of the prototype shoes tested and did not report the specific magnitude of the benefits at the various speeds, it is difficult to draw further conclusions from this comparison.

Why the apparent decrease in benefit at lower speeds? One explanation might be that of the reduced vertical ground reaction forces experienced by the runners. The runners in this study exhibited relatively high step frequencies for the slow speeds (172-173 and 177-178 steps·min^{-1} at 10 and 12 km·hr^{-1}, respectively). In a post-hoc analysis using the contact time and step frequency captured from the Garmin HRM device with the spatiotemporal calculations presented by Morin et al. (2005), we estimated the vertical forces of the runners to be 2.1 and 2.3 times body weight (BW) at each speed. While these estimates are slightly lower than what might be typical at these speeds, i.e., 2.4–2.6 BW (Munro et al., 1987; Nilsson & Thorstensson, 1989), they may be consistent with the high native step frequencies of runners in this study. These forces are substantially lower than the 2.9–3.1 BW observed by Hoogkamer et al. (2018) at 14 – 18 km·hr^{-1}. With the foam acting as a highly-efficient elastic spring (only ~14 % energy lost), it has the potential to store and return a substantial amount of energy (Hoogkamer et al., 2018). However, the absolute amount of energy that can be recycled within the step is contingent on the kinetic input to the shoe. It may be that here at lower speeds, the runners are not completely compressing the foam and realizing the full elastic potential afforded by the shoe. Concomitantly, the forces may be low enough that the thin EVA midsole of the control shoe is not as relatively deleterious as it would be at faster speeds, as there is less absolute energy to be lost. As such, in these compliant and resilient super shoes, there may exist a "force threshold" for a runner–above which the forces of the runner fully compresses regions of the foam and the resulting energetic benefit is consistent across speeds, but below which their forces do not fully compress the foam, and the benefit is contingent on the speed and subsequent vertical forces.

Another explanation for the speed dependency may lie the runner's interaction with the rigid, curved carbon fiber plate. Running speed has been linked to an individual's response to increased longitudinal bending stiffness (LBS) in footwear, with faster speeds tending to favor stiffer footwear conditions for some individuals (Ortega et al., 2021). In a group of competitive runners assessed in three different LBS conditions at 14 and 17 km·hr^{-1}, more of the subjects improved their running economy in the stiffer conditions (Day & Hahn, 2020). Rearfoot striking runners have also demonstrated higher optimal longitudinal bending stiffnesses at 16.1 km·hr^{-1} vs. 10.4 km·hr^{-1} (McLeod et al., 2020). The role of the rigid plate in the observed energetic benefit of modern super shoes is still being elucidated (Healey & Hoogkamer, 2021), but these limited studies would suggest that the characteristically higher LBS in these super shoes might favor faster speeds for some individuals. Considering that Hoogkamer et al. (2018) did not observe a difference in running economy across speeds from 14-18 km·hr^{-1}, this would further suggest that any speed relation to the plate's effect may be one that could be more deleterious at lower speeds (below 14 km·hr^{-1}) rather than increasingly beneficial at faster speeds.

We recognize some potential limitations to our present study. While we chose to randomize and counterbalance the shoe testing sequence, we did not randomize the sequence of the tested speeds. In keeping with the nature of incremental exercise testing, we tested all subjects first at 10 km·hr^{-1} before progressing to 12 km·hr^{-1}. Similarly, Barnes and Kilding (2019) tested more well trained men (14 and 18 km·hr^{-1}) and women (14 and 16 km·hr^{-1}) on the same day in an incremental fashion. Despite not randomizing test speeds, they still found similar benefits in the Nike Vaporfly at both speeds. This is in contrast to our current findings that found smaller benefits at the slower 10 km·hr^{-1} speed than 12 km·hr^{-1}, which suggests that the slower speed is driving these differences rather than any sequence effect. Moreover, we did not observe any substantial slow component in the $\dot{V}O_2$ of our subjects within trials, further suggesting that the $\dot{V}O_2$ response would likely be consistent in an alternative sequence. As such, this lack of randomization in the speed sequence does not impact our overall conclusions of smaller running economy benefits observed at 10 km·hr^{-1} (0.9%) and 12 km·hr^{-1} (1.6%) compared to the 2.7-4.2% benefits previously reported at speeds of 13-18 km·hr^{-1} (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2022; Whiting et al., 2021), but it could be taken as a consideration for future study designs.

The findings in this study are particularly relevant for the majority of recreational runners who train and compete at paces within the range of speeds tested, 10 km·hr^{-1} (6:00 per km or 9:40 per mile pace) up to 12 km·hr^{-1} (5:00 per km or 8:03 per mile pace). This corresponds to an ~3:30:00 to 4:15:00 marathon finishing time, which further represents the majority of marathon racers. This large population of runners also have competitive goals and are likely to seek a race day shoe option to enhance performance. The modeling of Kipp et al. (2018) that sought to translate running economy improvements to performance time improvements suggests that the 1.6% running economy benefit at 12 km·hr^{-1} would result in a ~3 minute improvement at the marathon distance for a 3:30:00 marathon runner. The 0.9% running economy benefit observed at 10 km·hr^{-1} should translate to a ~2.5 minute improvement for a 4:15:00 marathon runner. Beyond the performance improvements attributed to these running economy benefits, some preliminary data (Kirby et al., 2019) suggests that markers of muscle damage may be also be reduced in these highly cushioned shoes, which could offer further benefits in longer duration events and might explain larger estimated improvements in performance times in a crowd sourced, big data analysis of marathon times in the Nike Vaporfly (Quealy K, 2018). How these possible benefits–a reduction in muscle trauma or fatigue–affect the performance of runners at slower speeds is unknown and yet to be explored in a well-controlled fashion. As such, it may not be mutually exclusive at slower speeds for the economy benefit to be smaller but the realized performance benefit equal or larger. The mechanisms and magnitudes of any these effects across speeds and demographics adjure for continued research into how modern super shoes are changing running. Nonetheless, from this controlled examination of the Nike Vaporfly's effect on running economy at slower speeds, we conclude that the energetic benefits of the Nike Vaporfly are lower at 10 km·hr^{-1} (0.9%) and 12 km·hr^{-1} (1.6%), than the 2.7-4.2% benefits reported at faster speeds (13-18 km·hr^{-1}) in previous studies.

Contributions

Contributed to conception and design: DPJ
Contributed to acquisition of data: DPJ, TAD
Contributed to analysis and interpretation of data: DPJ, GTB
Drafted and/or revised the article: DPJ, GTB, TAD
Approved the submitted version for publication: DPJ, GTB, TAD

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Data and Supplementary Material Accessibility

Please contact the authors for access to data.

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