applied sciences

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One Shoe to Fit Them All? Effect of Various Carbon Plate Running Shoes on Running Economy in Male and Female Amateur Triathletes and Runners at Individual Training and Race Paces

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Abstract: Carbon plate running shoes (CPRSs) have gained widespread popularity among elite and amateur runners, representing one of the most substantial changes in running gear over the past decade. Compared to elite runners, however, amateurs run at lower speeds and show more diverse running styles. This is a meaningful difference as many previous studies on CPRSs focus either on highly trained male runners and higher speeds or only on a single CPRSs manufacturer. The present study aims at bridging this gap by investigating how CPRSs from four different manufacturers affect running economy in amateurs of both sexes at their individual running speeds. For this purpose, 21 trained amateur triathletes (12 men; 9 women) completed an incremental treadmill test until volitional exhaustion, yielding running speeds at ventilatory thresholds 1 (v_{VT1}) and 2 (v_{VT2}). In a second session, subjects ran five trials of 3 × 3 min (speeds of 90% v_{VT1}, ½ (v_{VT1} + v_{VT2}), and 100% v_{VT2}), wearing one out of four different pairs of CPRSs or their own preferred non-CPRS shoes in each trial. Our results show that tested CPRS models resulted in a significant reduction in the mean energy cost of transport, compared to the non-CPRS control condition, with Cohen's d amounting to −1.52 (p = 0.016), 2.31 (p < 0.001), 2.57 (p < 0.001), and 2.80 (p < 0.001), respectively, although effect sizes varied substantially between subjects and running speeds. In conclusion, this study provides evidence that amateur athletes may benefit from various manufacturers' CPRS models at their typical running speeds to a similar degree as highly trained runners. It is recommended that amateur athletes evaluate a range of CPRSs and select the shoe that elicits the least subjective sensation of fatigue over a testing distance of at least 400–1000 m.

Keywords: energy cost of running; carbon-fiber racing shoes; advanced footwear technology; spirometry; biomechanics

Citation: Riedl, M.; von Diecken, C.; Ueberschär, O. One Shoe to Fit Them All? Effect of Various Carbon Plate Running Shoes on Running Economy in Male and Female Amateur Triathletes and Runners at Individual Training and Race Paces. *Appl. Sci.* **2024**, *14*, 11535. https://doi.org/10.3390/app142411535

Academic Editors: Gongbing Shan and Mingjiu Yu

Received: 11 November 2024
Revised: 7 December 2024
Accepted: 9 December 2024
Published: 11 December 2024

1. Introduction

Being an easily accessible physical activity, running has reached a notable degree of popularity in recent times [1,2]. It serves not only as a means of maintaining good health and fitness but also as a platform for competition organized in major and minor road, cross-country, and trail races, comprising both amateur and elite levels. In order to achieve better performances and thus faster running times, many amateur runners have adopted structured training plans, which are widely available in the present era. The advancement of research in areas such as gait analysis, running technology, and diagnostics has led to the development of a plethora of tools designed to enhance running performance [3–5]. In addition to the self-evident approach of enhancing performance by (specific individualized) physical training, improving running economy represents a key method to faster racing, as better RE leads to faster race times at the same physical fitness level.

Running economy (RE) is defined as the energy demand of human running locomotion and can be approximated in terms of the steady-state oxygen consumption ($\dot{V}O_2$; $mL \cdot kg^{-1} \cdot min^{-1}$) at a given submaximal running speed [6]. Energy cost of transport (ECT; $kcal \cdot kg^{-1} \cdot km^{-1}$) and metabolic power ($W \cdot kg^{-1}$) are also used as more accurate measures of RE, capturing differences in energy yield per volume of oxygen due to varying substrate (i.e., carbohydrates and fat) utilization [7]. Along with maximal oxygen uptake ($\dot{V}O_{2_{max}}$) and fractional utilization of $\dot{V}O_{2_{max}}$ at ventilatory thresholds, RE is one of the primary determinants of endurance running performance [8–10] and has been shown to be a strong predictor of 10 km race performance [11]. As such, effective strategies for improving RE are of high interest to all runners aiming to improve their race times and to further stakeholders of competitive sport, including coaches, sport scientists, and sport equipment manufacturers. Several interventions targeting physiological changes have been demonstrated to be effective in improving RE, such as different types of cardiovascular and resistance training, stretching, and nutritional interventions [12].

Following the release of Nike's first carbon-fiber-enhanced running shoe Vaporfly 4% in 2017, an increased focus has been placed on RE improvements elicited through optimized material properties of running footwear, giving rise to a novel category of running shoes commonly referred to as carbon-plate running shoes (CPRSs) and recently recoined by some authors to 'advanced footwear technology' (AFT) [13]. While the longitudinal bending stiffness (LBS) of CPRSs is increased through carbon-fiber-based stiffening elements ("plates") embedded in their midsoles, many of those running shoes nowadays also provide an increased cushioning because of their lightweight and resilient novel foams. The more general term AFT aims to explicitly account for the combination of both biomechanical concepts of increased stiffness and cushioning. The exact mechanisms of AFT leading to RE and performance benefits are still a topic of current debate [14–16], with suggested mechanisms comprising an altered gear ratio at the ankle joint through increased LBS [17,18], a higher degree of energy storage and return in the midsole foam [19], a reduction in negative work through stiffening of the metatarsophalangeal joint [20], a "teeter-totter" effect, i.e., supporting leverage between toe and heel parts of the shoe, resulting in a higher force acting on the heel during push-off [14], and better suited gastrocnemius muscle fiber contraction speeds for optimal power production and increased energy return via the Achilles tendon [21].

The first laboratory experiments examining this emerging technology repeatedly demonstrated that AFT running shoes significantly improve the RE of elite and highly trained runners at speeds of 14–18 km/h by 2.8–4.4% compared to traditional racing flats [22–24]. Several laboratory experiments examining AFT models from either Nike, Adidas, or Saucony in recreational runners at slower running speeds of 9–15 km/h reported similar RE benefits of 1.6–5.0%, indicating that runners can benefit from AFT independent of running speed [25–29]. Notably, when comparing the same AFT model at different running speeds, RE benefits appear to increase with greater running speed [28–30]. As kinetic energy is partially stored in and returned from the midsole foam, and because the optimal midsole LBS has been shown to depend on running speed [20,30], an association between running speed and RE benefit may be expected. Interestingly, this relationship appears to be present in both elite-level and amateur runners, with amateurs benefitting to a greater extent from AFT models [28]. This indicates that it is presumably not absolute running speed itself but rather relative physiological intensity that leads to greater RE benefits with increasing running speed. It is important to note that most studies evaluating running speed effects on the AFT response used a version of the Nike Vaporfly or Nike Alphafly. Different material properties of models from manufacturers other than Nike might imply that RE responses could be affected differently across a range of speeds.

To date, only one study has compared RE benefits across commercially available AFT models from different manufacturers for the same cohort of athletes [31]. The researchers report that there are significant differences between RE benefits provided by different AFT models, ranging from no benefit in the Hoka Rocket X to a 3% benefit in the Nike Air Zoom Alphafly Next% when compared to a racing flat. They concluded that Nike's AFT racing shoes clearly confer the greatest degree of improvement in economy and that this might lead to a competitive advantage. However, the researchers utilized a specific, strictly homogenous group of highly trained male runners and tested RE at only one running speed (16 km/h). As both the type of runners and running speeds are known to influence RE benefits of AFT [28], these results may possibly not be generalized to other populations or running speeds. It is conceivable that some AFT shoes, for example, might simply be better suited for recreational athletes running at slower speeds. Further, Joubert et al. [30] focused on average group-level RE improvements, which neglects inter-individual variability and should thus not be misinterpreted that every runner could expect to gain this amount of RE benefit. A different approach recently proposed by Heyde et al. [32] addresses these issues by reporting the percentage of runners likely to receive a given amount of RE improvement. Those researchers demonstrated the feasibility of their approach by showing that only 25% of recreational runners could expect to experience the 4% RE benefit from Nike's Vaporfly 4% shoe reported by Hoogkamer et al. [22].

In essence, an important finding of recent AFT research is that responses to AFT are highly individual, with large inter-individual variance in responses to different AFT models reported [25,28,32]. Individual RE responses to AFT range from no change to substantial improvement (≈6%) between different individuals wearing the same shoes [24,29]. This variability has led researchers to recommend an individualized approach to running shoe prescription [25,28]. At this time, however, there is currently no scientifically justified strategy for determining optimal AFT properties for an individual runner. Factors that seemingly influence individual RE response are running speed, foot strike pattern, ground contact time, body mass, plantar flexor strength, foot arch stiffness, joint range of motion, and training level [33].

Hence, the aim of the present study is to investigate the amount of RE benefit amateur runners can realistically expect when switching from regular training shoes to AFT running shoes, and whether this RE benefit differs significantly between models from different AFT manufacturers. An additional goal of this work is to determine whether hierarchical ranking of AFT models is appropriate when considering inter-individual variability in runners' responses to AFT. Lastly, associations between individual RE changes and factors previously shown to influence RE response when wearing AFT shoes will be explored.

2. Materials and Methods

2.1. Subjects

Twelve male (34.9 ± 8.3 years, 71.1 ± 8.5 kg, BMI 22.4 ± 1.9 kg m^{-2}, and $\dot{V}O_{2_{peak}}$ 62.0 ± 5.1 mL kg^{-1} min^{-1}) and nine female (29.1 ± 10.2 years, 62.3 ± 5.9 kg, BMI 21.8 ± 1.5 kg m^{-2}, and $\dot{V}O_{2_{peak}}$ 52.2 ± 3.2 mL kg^{-1} min^{-1}) amateur triathletes and runners participated in this study. All subjects had a weekly training mileage of at least 20 km (mean of 32.4 ± 12.0 km) and a 10 km race performance of better than 45 min (males, 36:50 ± 2:50 min) or 50 min (females, 45:06 ± 3:50 min). All participants reported to be in good health at the day of testing and to have been free of musculoskeletal injuries for at least 3 months. There were no exclusion criteria regarding shoe size, with average shoe sizes being US 9.5 ± 1.5 (27.5 ± 1.5 cm; range US 7 to US 11.5) for the males, and US 8.5 ± 0.9 (25.0 ± 0.9 cm; US 7 to US 10.5) for the females. All subjects provided written informed consent prior to participating in this study. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Engineering and Industrial Design at the Magdeburg-Stendal University of Applied Sciences under certificate number EKIWID-2023-09-001RM.

2.2. Footwear Conditions

Four current CPRS models from four different manufacturers were included in this study: Hoka Rocket X2 (HOK), Mizuno Wave Rebellion Pro (MIZ), Puma Fast-R Nitro Elite (PUM), and Saucony Endorphin Pro 3 (SAU) (Figure 1). The manufacturers provided their shoes in all sizes voluntarily and free of charge and did not receive any advantage from their support of this study. No alterations to the shoes were made, and sizes were assigned prior to testing based on individual comfort level. Each participant's pair of own preferred training shoes (OWN) was used as a comparison to derive relative RE changes. While differing mass, stiffness, and cushioning of OWN represent confounding variables that are known to influence RE, we chose this footwear condition for the control as it provides a realistic scenario for amateur and recreational athletes who may be considering switching to CPRS running shoes for competitions or high-intensity interval training. The four CPRS models differed in heel drop, mass, foam, and the shape and placement of the carbon plate (Table 1).

Figure 1. CPRS models used in this study. (**A**) Hoka Rocket X2 (HOK), (**B**) Mizuno Wave Rebellion Pro (MIZ), (**C**) Puma Fast-R Nitro Elite (PUM), and (**D**) Saucony Endorphin Pro 3 (SAU).

Table 1. Specifications of the four CPRS models used.

	HOK	MIZ	PUM	SAU
Heel drop [1]	5.0 mm	4.5 mm	7.5 mm	8.0 mm
Mass (men US 9) *	213 g	209 g	223 g	206 g
Midsole foam [1]	PEBA foam	'Mizuno Enerzy Lite/Lite+' the latter being PEBA foam	forefoot PEBA foam, heel EVA foam	'PWRRUNPB' PEBA foam
Carbon plate [1]	Carbon plate between two layers of foam	Carbon-infused nylon plate	Carbon plate named 'PWRPLATE'	S-shaped carbon plate

Abbreviations: HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, SAU = Saucony Endorphin Pro 3, PEBA = polyether block amide, EVA = ethylene and vinyl acetate copolymer. * Self-measured; [1] data taken from [34] for HOK, [35] for MIZ, [36] for PUM, and [37] for SAU.

2.3. Study Design

A randomized cross-over design was used to assess the effect of four different CPRS models on RE with participants attending two separate laboratory visits (Figure 2). The primary aim of the first visit was the determination of running speeds at ventilatory threshold 1 (v_{VT1}) and at ventilatory threshold 2 (v_{VT2}), while also serving as a familiarization period with the experimental setup. The subsequent visit was used to measure running economy in the five different footwear conditions in randomized order at the three individual running speeds v_1 = 90% v_{VT1}, $v_2 = \frac{1}{2}(v_{VT1} + v_{VT2})$, and v_3 = 100% v_{VT2}. The associated intensities of "easy" (v_1), "threshold" (v_2), and "competition" (v_3) were chosen to assess RE throughout a wide range of speeds that are typically used by runners in training and racing. The 3 min interval duration was chosen because it represents the shortest possible time after which steady-state oxygen consumption is likely to be reached, ensuring accurate RE measurement while, at the same time, keeping fatigue at an acceptable level [38]. Runners were instructed to abstain from strenuous exercise for at least 48 h prior to both laboratory visits and were encouraged to match diet and sleep patterns as closely as possible between visits 1 and 2.

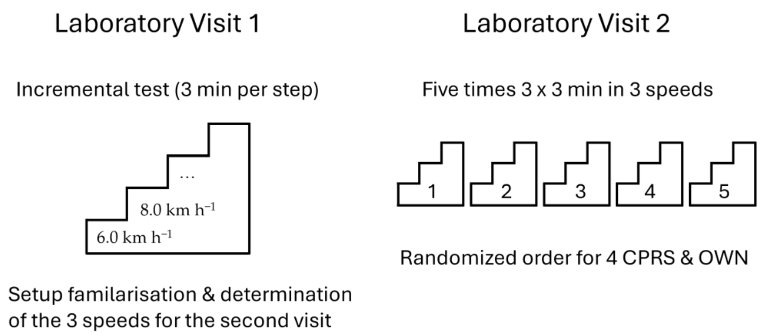

Figure 2. Schematic outline of the test design.

2.3.1. Laboratory Visit 1

During the first visit, participants' anthropometric measures and baseline physiological values were collected. Participants then put on their own training shoes (ensuring they were not AFT) and were placed on a motorized treadmill (Star Trac FreeRunner 10TRx, Core Health 6 Fitness, Vancouver, BC, Canada), which was set at a 1% incline to compensate for the absence of air drag [39]. The subjects were equipped with a heartrate monitor (Polar H10; Polar Electro Oy, Kempele, Finland) and an appropriately sized face mask (7450 Series V2 Mask; Hans Rudolph, Inc., Shawnee, KS, USA) connected to a metabolic cart (MetaMax 3B, CORTEX Biophysik GmbH, Leipzig, Germany), providing continuous breath-by-breath cardiopulmonary gas exchange measures (Figure 3). In this experimental setup, each participant completed a standardized incremental protocol defined by a starting speed of 6.0 km h^{-1} (same for all participants), 3 min stage duration, and increments of 2.0 km h^{-1} until voluntary exhaustion was reached. Upon completion of the incremental test, v_{VT1} and v_{VT2}, as well as peak aerobic capacity ($\dot{V}O_{2,peak}$), were determined. The speeds v_{VT1} and v_{VT2} were used to calculate the three running speeds v_1, v_2, and v_3 for assessing RE during visit 2. Laboratory visits 1 and 2 were separated by at least 48 h and used the same laboratory and experimental setups during both visits.

Figure 3. Laboratory setup with motorized treadmill, spirometry, subject wearing the OWN footwear condition, and researcher supervising the trial.

2.3.2. Laboratory Visit 2

During visit 2, each participant performed five trials of 3 × 3 min of treadmill running, wearing a different pair of shoes (i.e., either HOK, MIZ, PUM, SAU, or OWN) for each bout in a randomized order. Each session consisted of 3 consecutive 3 min intervals of increasing speed at v_1, v_2, and v_3 in a fixed order. Each running session was followed by 5 min of rest during which participants changed shoes. Before starting the next session, current heartrate and cardiopulmonary values were obtained to ensure a physiological state close to baseline.

2.4. Data Processing

Ventilatory thresholds 1 and 2, as well as $\dot{V}O_{2_{peak}}$, were determined by two independent experts using the Cortex MetaSoft software suite 5.5.1 before exporting the dataset for further analysis. All further data processing steps and analyses were conducted using a custom script written in MATLAB R2023a (The MathWorks Inc., Natick, MA, USA). All cardiopulmonary data were first cleaned by removing outliers that exceeded the mean of a 7-breath window by more than 2 standard deviations and then smoothed by applying a 7-breath moving average [28]. Cardiopulmonary datasets from visit 2 were split into 3 min intervals, so that for each trial 5 × 3 = 15 intervals of gas exchange data were used for further analysis. From these 15 3 min intervals, the final 60 s of data were averaged and used to determine mean oxygen consumption as the first out of two quantification approaches to RE ($\dot{V}O_2$, $mL \cdot kg^{-1} \cdot min^{-1}$). Those data were also used to calculate energy consumption by use of Pérronet and Massicotte's non-protein respiratory quotient equations [4,40]. Mean energetic cost of transport (ECT, $kcal \cdot kg^{-1} \cdot km^{-1}$) was then calculated as the second quantification approach to RE, accounting for differences in energy yield per volume of oxygen and normalized with respect to body mass and running speed. Relative RE changes (%*RE*) during each condition were then calculated by

$$\%RE = \frac{RE_{OWN} - RE_{CPRS}}{RE_{OWN}} \cdot 100\%$$

with *RE* being either $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$) or ECT ($kcal \cdot kg^{-1} \cdot km^{-1}$). Positive %*RE* values indicate a RE improvement while negative %*RE* values indicate RE deterioration. Metabolic steady state was confirmed visually, and limited anaerobic contribution was assured by a respiratory exchange ratio (RER) of RER ≤ 1.0 during all trials [4,41]. Above that threshold, a substantial anaerobic lactic contribution to energy metabolism by anaerobic glycolysis is evident, corresponding to a physiological state beyond the first ventilatory threshold. In such instances, the calculation of energy expenditure based on gas exchange rates is no longer sufficient, and lactate accumulation rates should be considered as well [4]. To circumvent the necessity for additional, invasive measurements of lactate accumulation, this metabolic condition was excluded by defining the RER exclusion criterion.

2.5. Statistical Analysis

All statistical analyses were performed in R Studio 2023.12 (RStudio PBC, Boston, MA, USA). Two-way repeated-measures analyses of variance (rmANOVA) with running speed and footwear condition as factorial within-subject variables were conducted to evaluate speed and footwear effects on $\dot{V}O_2$, ECT, and speed × footwear interaction effects averaged across speeds as well as separately for each speed. Post hoc pairwise comparisons with Holm correction were used to compare specific conditions when ANOVA showed significant effects. In addition, repeated measures ANOVA was conducted with time of the session as the within-subject categorical variable to evaluate whether shoe order had affected RE results. Cohen's d (d_{Cohen}) was calculated as a measure of effect size and categorized as negligible ($d_{Cohen} < 0.2$), small (0.2–0.49), moderate (0.5–0.79), and large

(≥0.8), respectively [42]. Results are presented as mean ± standard deviation (SD). The level of significance was set to 0.05 for all statistical tests.

3. Results

Incremental treadmill tests resulted in mean v_{VT1} and v_{VT2} values of 11.5 ± 1.1 km h^{-1} and 15.4 ± 1.9 km h^{-1}, respectively. Resulting mean testing speeds for RE were v_1 = 10.4 ± 1.0 km h^{-1}, v_2 = 13.5 ± 1.5 km h^{-1}, and v_3 = 15.4 ± 1.9 km h^{-1}, respectively. Two runners exceeded a respiratory exchange ratio (RER) of 1.0 during their intervals at v_{VT2} and were thus removed from further analysis because they had evidently entered a systemically anaerobic condition.

3.1. Running Economy

3.1.1. Energy Cost of Transport

As for the mixed cohort of both sexes, ECT results are summarized in Figure 4b and Table 2. ECT was not affected by the shoes' order (F = 1.666, p = 0.167), while the footwear condition significantly affected ECT averaged across intensities (F = 7.136, p < 0.001). ECT was significantly reduced by 0.03 kcal kg^{-1} km^{-1} for HOK (2.80%, p_{Holm} < 0.001, and d_{Cohen} = 0.90), 0.03 kcal kg^{-1} km^{-1} for MIZ (2.57%, p_{Holm} < 0.001, and d_{Cohen} = 0.60), 0.03 kcal kg^{-1} km^{-1} for PUM (2.31%, p_{Holm} < 0.001, and d_{Cohen} = 0.80), and 0.02 kcal kg^{-1} km^{-1} for SAU (1.52%, p_{Holm} = 0.016, and d_{Cohen} = 0.42). Reductions by HOK and SAU were large in magnitude, whereas the effects of ECT reductions by MIZ and PUM were moderate and small, respectively.

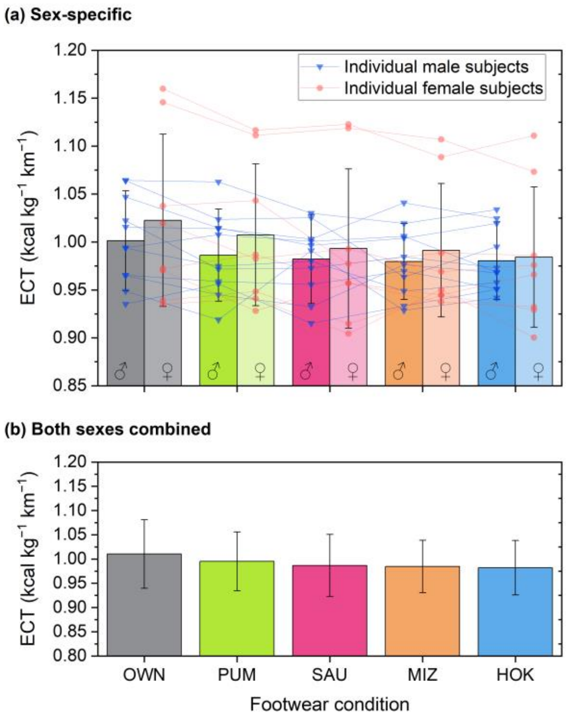

Figure 4. Energy cost of transport (ECT) in the four CPRS models studied, averaged across running speeds and ranked from the least (left) to most (right) economical. The bars show group averages while the connected symbols depict individual responses. (**a**) Sex-specific averages: Darker bar fill colours (left bar of a pair) represent mean values for the male runners whereas the lighter fill colours show female means. Blue connected down triangles (▼) depict individual male (♂) responses and red connected circles (●) individual female (♀) responses. (**b**) Averages for both sexes combined in one group. OWN: subjects' own preferred pair of running shoes, HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3.

Table 2. Energy cost of transport for each footwear condition and tested running speed, including results of repeated-measures analysis of variance (rmANOVA).

	Energy Cost of Transport ($kcal \cdot kg^{-1} \cdot km^{-1}$)								
Speed	**OWN**	**HOK**	**MIZ**	**PUM**	**SAU**	**rmANOVA**			
	Mean ± SD	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	**Mean ± SD**	F	p		η^2
v_1	1.01 ± 0.08	0.99 ± 0.06	0.99 ± 0.06	1.00 ± 0.06	0.99 ± 0.08	2.375	0.060		0.02
v_2	1.00 ± 0.07	0.97 ± 0.06	0.98 ± 0.05	0.98 ± 0.06	0.97 ± 0.06	3.514	0.011	*	0.026
v_3	1.02 ± 0.06	0.99 ± 0.06	0.99 ± 0.06	1.00 ± 0.06	0.99 ± 0.06	8.497	<0.001	*	0.048
Ø	1.01 ± 0.07	0.98 ± 0.06	0.98 ± 0.05	1.00 ± 0.06	0.99 ± 0.06	7.136	<0.001	*	0.028

Abbreviations: SD = standard deviation, η^2 = generalized eta squared, and * = statistical significant ($p < 0.05$). HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3.

Although peak oxygen uptake per body mass was higher for the men than for the women, gender had no impact on the order of ECT reductions ($p > 0.59$, two-way ANOVA with the factors sex and footwear condition), yielding equivalent results for men and women with footwear condition being the only significant influence ($p < 0.001$, ${\eta_g}^2 = 0.04$). No interaction effect between sex and footwear condition was found ($p > 0.59$). In view of these results, the following analyses will focus on the mixed cohort of both sexes.

When considering footwear effects on ECT at individual running speeds, there were no significant differences in the energy cost of transport between footwear conditions at v_1 ($F = 2.375$, $p = 0.060$). At v_2, in contrast, ECT was significantly affected by the footwear condition ($F = 3.514$, $p = 0.011$), with significant reductions in ECT by 0.03 kcal kg^{-1} km^{-1} for HOK (2.71%, $p_{Holm} = 0.028$, and $d_{Cohen} = 0.78$) and 0.02 kcal kg^{-1} km^{-1} for SAU (2.40%, $p_{Holm} = 0.023$, and $d_{Cohen} = 0.81$) as compared to OWN. Reductions by HOK were moderate in magnitude, whereas SAU showed a large effect. MIZ ($p_{Holm} = 0.230$, $d_{Cohen} = 0.53$) and PUM ($p_{Holm} = 0.230$, $d_{Cohen} = 0.55$) did not significantly affect ECT at this speed. At v_3, footwear condition significantly affected ECT ($F = 8.497$, $p < 0.001$) with significant reductions of 0.03 kcal kg^{-1} km^{-1} by HOK (3.32%, $p_{Holm} < 0.001$, and $d_{Cohen} = 1.56$), 0.03 kcal kg^{-1} km^{-1} by MIZ (3.23%, $p_{Holm} < 0.001$, and $d_{Cohen} = 0.97$), 0.02 kcal kg^{-1} km^{-1} by PUM (1.86%, $p_{Holm} = 0.015$, and $d_{Cohen} = 0.61$), and 0.03 kcal kg^{-1} km^{-1} by SAU (2.83%, $p_{Holm} < 0.001$, and $d_{Cohen} = 1.17$). The effects of HOK, MIZ, and SAU were large in magnitude, while the effect magnitude for PUM was moderate.

3.1.2. Effect of Running Speed on RE Response

Two-way rmANOVA revealed a significant main effect of running speed on $\dot{V}O_2$ ($F = 353.838$, $p < 0.001$), whereas running speed did not affect ECT ($F = 3.975$, $p = 0.057$). There was no significant footwear condition × speed interaction effect ($F = 0.540$, $p = 0.719$). However, effect sizes of differences in $\dot{V}O_2$ as compared to OWN increased with running speed from moderate to large for HOK, from small to moderate for MIZ, and from small to large for SAU. Likewise, with increasing running speed, effect sizes of differences in ECT compared to OWN grew from moderate to large for HOK, from small to large for MIZ, from small to moderate for PUM, and from moderate to large for SAU (Table 3).

Table 3. Changes (Δ) and relative changes in energy cost of transport during CPRS conditions compared to own training shoes and pairwise comparison results.

			Change Compared to OWN					
			Energy Cost of Transport ($kcal \cdot kg^{-1} \cdot km^{-1}$)					
Footwear	**N**	**Speed**	**Δ**	**%**	p_{Holm}		d_{Cohen}	**Effect Size**
HOK	19	v_1	0.02	2.38	0.114		0.65	moderate
	19	v_2	0.03	2.71	0.028	*	0.78	moderate

Table 3. *Cont.*

			Change Compared to OWN					
			Energy Cost of Transport (kcal·kg^{-1}·km^{-1})					
Footwear	**N**	**Speed**	**Δ**	**%**	p_{Holm}		d_{Cohen}	**Effect Size**
MIZ	19	v_1	0.02	2.38	0.555		0.43	small
	19	v_2	0.02	2.10	0.230		0.53	moderate
	19	v_3	0.03	3.23	<0.001	*	0.97	large
	57	Ø	0.03	2.57	<0.001	*	0.60	moderate
PUM	19	v_1	0.01	0.89	1.000		0.20	small
	19	v_2	0.02	1.80	0.230		0.55	moderate
	19	v_3	0.02	1.86	0.015	*	0.61	moderate
	57	Ø	0.02	1.52	0.016	*	0.42	small
SAU	19	v_1	0.02	1.68	0.311		0.53	moderate
	19	v_2	0.02	2.40	0.023	*	0.81	large
	19	v_3	0.03	2.83	<0.001	*	1.17	large
	57	Ø	0.02	2.31	<0.001	*	0.80	large

Abbreviations: * = Statistical significant ($p < 0.05$). HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3.

3.2. Inter-Individual Variability

Effects of CPRSs on measures of RE showed considerable inter-individual variability (cf. Figure 4a). Mean effects of CPRSs on ECT ranged from −1.7 to 6.5% for HOK, −2.5 to 9.4% for MIZ, −2.2 to 4.9% for PUM, and −4.5 to 5.8% for SAU among individuals. In summary, 21% of all subjects reached their individually best relative reduction in ECT wearing HOK, 32% wearing MIZ, 16% wearing PUM, and 32% wearing SAU, respectively.

Figure 5 displays the percentage of subjects experiencing mean metabolic savings between 0 and 10% in the four CPRS conditions studied. In summary, ECT was reduced by at least 1% in 89.5% of all subjects wearing SAU, by 73.7% of subjects wearing HOK, by 63.2% of subjects wearing MIZ, and by 52.6% of subjects wearing PUM shoes. Reductions in ECT of 4% were exceeded by 36.8% of subjects wearing MIZ, 31.6% HOK, 15.8% SAU, and 10.5% PUM. Notably, 10.5% of subjects wearing SAU, 15.8% wearing HOK, 36.8% wearing MIZ, and also 36.8% wearing PUM experienced a *detrimental* effect on ECT instead of an improvement.

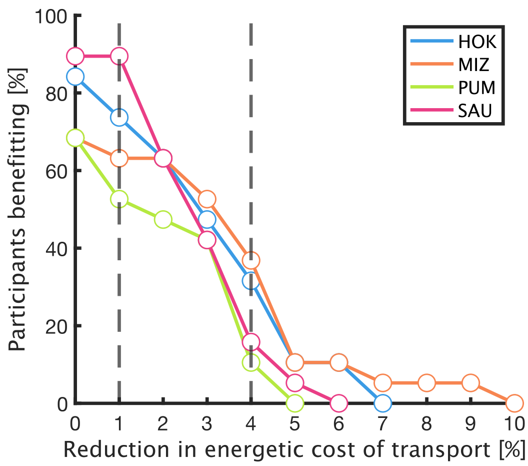

Figure 5. Percentage of subjects that experienced average metabolic savings between 0 and 10% in CPRS conditions. HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3. The dashed lines depict the thresholds of savings of 1% and 4%, respectively.

3.3. Intra-Individual Variability

Individual responses averaged across running speeds are displayed in Figure 4a (lines connecting the symbols). Relative changes in ECT experienced by individuals across different CPRS models exhibit considerable variability. This is evident both visually (lines crossing in Figure 4a) and numerically from the widened mean range of individual percentage changes in ECT across the CPRS amounting to 3.9% (thereby exceeding the highest cohort average of ECT reduction across CPRSs of 2.8% for HOK, see above). In fact, the maximum range of individual percentage ECT reductions across CPRS conditions observed for one subject was as high as 7.6% (from −4.5% in SAU to 3.1% in PUM).

Similarly, intra-individual variability between running speeds for a given CPRS proved to be substantial (Figure 6): the mean range of individual ECT percentage reductions as a function of speed amounted to 4.0% for HOK, 6.0% for MIZ, 5.4% for PUM, and 3.8% for SAU, respectively. Interestingly, the maximal range of speed-related individual ECT percentage reductions observed for one individual was 14.7% (from −9.9% at v_1 to 4.8% at v_3 for PUM). Furthermore, only 5 out of 19 subjects (26.3%) experienced their highest individual reduction in ECT for the same *CPRS* model across all running speeds (HOK 2 subjects, MIZ 1, PUM 0, and SAU 2), whereas the "individually best" CPRS model varied in relation to running speed for the majority (14 out of 19, 73.7%).

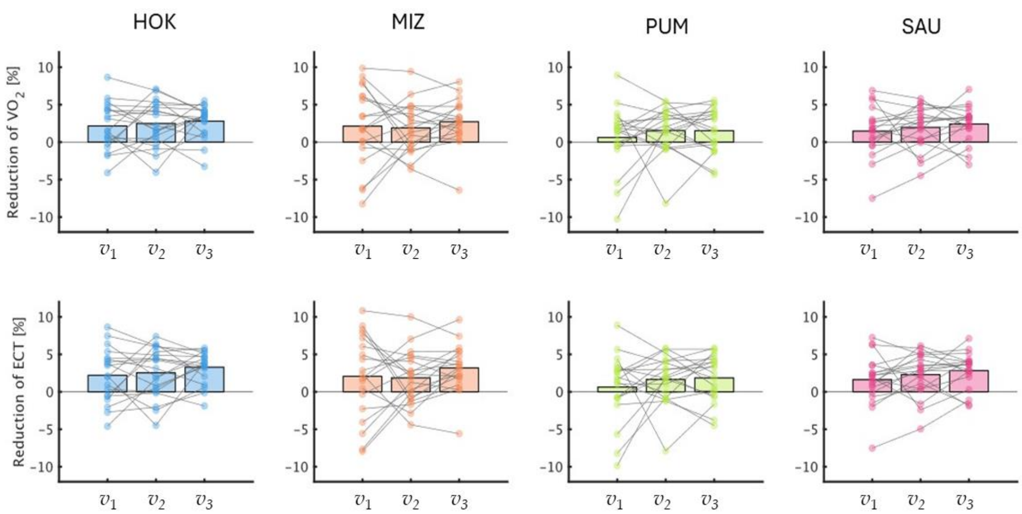

Figure 6. Relative changes in energy cost of transport (ECT) at each running speed. Connected dots represent individual runners. v_1 = speed 1, v_2 = speed 2, and v_3 = speed 3. HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3.

3.4. Correlation of RE Changes and Other Measures

Table 4 shows the Spearman's correlation coefficients between individual relative RE changes %*RE* at the three different running speeds v_1, v_2, and v_3, and additionally between individual %*RE* (averaged across the individual speeds v_1, v_2, and v_3), individual body mass, mean individual running speed, and individual $\dot{V}O_{2,peak}$. A significant correlation between %*RE* at v_1 and v_2 was found only for the SAU footwear condition (ECT: $r = 0.558$, $p = 0.018$). For speeds v_2 vs. v_3, %*RE* correlated significantly for the MIZ (ECT: $r = 0.631$, $p = 0.006$), HOK (ECT: $r = 0.575$, $p = 0.014$), and PUM (ECT: $r = 0.472$, $p = 0.05$) footwear conditions. There were no significant correlations between %*RE* for speeds v_1 vs. v_3. As for the other parameters, %*RE* showed a small negative correlation with body mass in terms of ECT ($r = -0.262$, $p = 0.049$) and with $\dot{V}O_{2_{peak}}$ (ECT: $r = -0.311$, $p = 0.022$) only for HOK. For all other CPRSs, no significant correlations were observed in this respect.

Table 4. Spearman's correlation coefficients of percentage RE changes (%*RE*) between running speeds v_1, v_2, and v_3 and between relative RE changes and body mass, running speed, and $\dot{V}O_{2,peak}$.

		v_1 vs. v_2	v_2 vs. v_3	v_1 vs. v_3	Body Mass vs. %*RE*	Speed vs. % *RE*	$\dot{V}O_{2_{peak}}$ vs. %*RE*	%*RE* vs. %*RE*
Parameter		ECT	ECT	ECT	ECT	ECT	ECT	$\dot{V}O_2$ vs. ECT
HOK	*r*	0.441	0.575 *	0.292	−0.262 *	−0.068	−0.311 *	0.967 *
	p	0.069	0.014	0.239	0.049	0.614	0.022	<0.001
MIZ	*r*	0.418	0.631 *	0.179	−0.185	−0.058	−0.136	0.990 *
	p	0.086	0.006	0.477	0.169	0.671	0.328	<0.001
PUM	*r*	0.368	0.472 *	−0.150	−0.103	0.003	−0.049	0.974 *
	p	0.133	0.050	0.552	0.446	0.980	0.724	<0.001
SAU	*r*	0.558 *	0.437	0.001	−0.124	0.125	−0.094	0.977 *
	p	0.018	0.072	1.000	0.359	0.355	0.499	<0.001

Abbreviations: *r* = Spearman's correlation coefficient, v_1 = running speed 1, v_2 = running speed 2, v_3 = running speed 3, speed = absolute running speed (km·h^{-1}), $\dot{V}O_2$ = oxygen consumption, ECT = energy cost of transport, and %*RE* = percentage change in running economy. * Flags significant correlations. HOK = Hoka Rocket X2, MIZ = Mizuno Wave Rebellion Pro, PUM = Puma Fast-R Nitro Elite, and SAU = Saucony Endorphin Pro 3.

4. Discussion

The primary aim of this study was to evaluate the amount of RE benefit amateur athletes can realistically expect when switching running gear from their traditional training shoes to CPRSs and to compare this benefit across CPRS models from different manufactures for the same cohort. As expected, all models of CPRS significantly reduced mean ECT when compared to traditional training shoes with percentage differences from −1.52% to −2.80%. These effects are similar in magnitude to previously reported findings of CPRS/AFT effects when compared to regular running shoes [32] and racing flats [22–24]. Interestingly, all CPRSs tested showed an improvement of more than 1.5% in RE, a level not achieved by several other current manufacturers [31,43,44]. Based on mean group-level RE improvement, the CPRS models rank as follows (in the order of worst-performing to best-performing): Puma Fast-R Nitro Elite (−1.52% ECT), Saucony Endorphin Pro 3 (−2.31% ECT), Mizuno Wave Rebellion Pro (−2.57% ECT), and Hoka Rocket X2 (−2.80% ECT). Notably, regarding pairwise comparisons, only the differences between Hoka Rocket X2 and Puma Fast-R Nitro Elite were statistically significant. When considering the percentage of runners experiencing RE benefits of a given magnitude, however, rankings change and substantial differences between CPRS models become apparent. At 1% improvement, the Saucony Endorphin Pro 3 performed best with 89.5% of runners experiencing at least this amount of ECT reduction, closely matching values recently reported for the Nike Vaporfly 4% [32]. In contrast, reductions of at least 1% ECT were induced in 73.7% of runners for HOK, 63.2% for MIZ, and in 52.6% for PUM, indicating increasingly higher numbers of non-responders. Conversely, at 4% improvement, MIZ and HOK performed similarly well with 36.8% and 31.6% of runners reducing their ECT by this amount. Both CPRS models exceed values reported for the Nike Vaporfly 4% [32]. In contrast, SAU and PUM were substantially less beneficial, providing (at least) 4% of ECT reduction only to 15.8% and 10.5% of runners, respectively.

A comparison of the structural parameters of the various CPRS models, as outlined in Table 1, with the corresponding experimental RE results reveals some noteworthy insights. The PUM model is the only CPRS model to utilize solely EVA foam in the heel section, with the remaining models employing either PEBA or a combination of EVA and PEBA (e.g., the MIZ) in this region of the shoe. A recent study has indicated that footwear with PEBA foam incorporated into the midsole results in a lower ECT than footwear with EVA foam midsoles [45]. It may thus be reasonably deduced that the structural distinctiveness of the PUM shoes, which feature PEBA foam only in the forefoot section and EVA in the heel section, might have had a detrimental effect on the potential for RE improvement, given that a substantial proportion of the amateur athletes in our cohort exhibited a heel-striking running pattern. In contrast, the MIZ model features a midsole comprising layers of PEBA and EVA foams throughout the entire shoe, with a carbon plate positioned between them. Given the MIZ's top ranking in our study, it is plausible that this specific layer combination may confer an advantage in terms of improved RE compared to midsole structures with a single foam layer.

In essence, these results demonstrate the importance of reporting RE effects of CPRSs on an individual rather than group level. While the Hoka Rocket X2 did not perform best at any increment of improvement and led to the greatest RE improvement in only 4 out of 19 subjects, it consistently performed well with most subjects, resulting in only few non-responders and a large percentage of runners gaining substantial benefit. Conversely, the Mizuno Wave Rebellion Pro and the Saucony Endorphin Pro 3 performed well at opposite ends of the spectrum, with the Saucony model showing the lowest rate of non-responders and leading to greatest RE improvement in 7 out of 19 subjects, while the Mizuno model improved RE beyond 4% for the highest percentage of runners and led to greatest RE improvement in 6 out of 19 subjects. The Puma Fast-R Nitro Elite underperformed at each increment of improvement compared to other CPRS models and led to greatest RE improvement in only 2 out of 19 subjects. Interestingly, a considerable percentage of subjects (>30%) experienced detrimental effects on RE when wearing specific CPRS models (i.e., PUM and MIZ), which differs from previously published findings of CPRS models from other manufacturers [24,29] and warrants further investigation into shoe design features, including foam properties, geometry, stack height, stiffening elements, etc., which might lead to higher numbers of non-responders. In the case of MIZ, the large percentage of non-responders may be due to its peculiar heel design (cf. Figure 1) which potentially affects heel strikers differently than forefoot strikers (with the latter being less common in amateur athletes than in elite runners).

Although body mass, running speed, and training level have been shown to influence individual RE response [33], HOK was the only footwear condition to show any significant correlation between RE response and any of the mentioned factors in the present study. A small negative correlation between body mass and ECT reduction ($r = -0.262$) indicates that lighter runners may benefit slightly better than heavier runners, while a moderate negative correlation between $\dot{V}O_{2,peak}$ and ECT reduction ($r = -0.311$) indicates that less trained runners can potentially expect greater RE improvements in this CPRS model than better trained individuals. The lack of correlation observed in this study further demonstrates that mechanisms behind the observed differences in RE response are multifactorial and of a complex nature. Future work should aim at elucidating biomechanical explanations and strategies to enable an effective prediction of individual RE response for a given CPRS model.

Notably, only small to moderate correlations were observed between the individual RE benefits for each footwear condition for running speeds v_1 vs. v_2 and v_2 vs. v_3, while they were small to even negligible for speeds v_1 vs. v_3. Although some variability may be due to the inherent measurement error of single-trial RE data [33] and gas exchange data [46], this lack of correlation between %*RE* at different running speeds highlights the importance of measuring RE across multiple running speeds. Variability across velocities may also partly explain why previous research was unable to link RE benefits to performance benefits, as RE measurements are typically undertaken at running speeds slower than during performance testing [25,27].

Given the variability in responses among individuals, it proves challenging to provide a universal recommendation regarding footwear selection. Generally speaking, it seems advisable to evaluate a range of CPRS models at the same testing occasion. In some cases, it may be beneficial to assess the suitability of different shoes over a testing distance of 400–1000 m at a competitive pace. This approach could help identify the shoe that offers the least exertion during running. However, it is important to note that this purely subjective method is not a substitute for objective spiroergometric testing.

Some limitations of this study must be noted. First, individual RE measures in the present study are based on single-trial data as each participant ran in each footwear condition at each running speed only once. This is likely to be a reason for the large intra-individual variability across running speeds seen in this study (Figure 6). Although desirable, it was not feasible to test subjects multiple times in this work due to the considerable number of combinations of footwear condition (n = 5) and running speeds (n = 3) during the limited time of CPRS availability. Measuring running economy based on single trials may be subject to reduced reliability so that intra-individual RE changes between running speeds and footwear conditions (Figure 6) should be interpreted with caution [33]. Therefore, no single-trial RE measures were used in this study for calculating mean CPRS effects (averaged across speeds and subjects) or percentage of subjects receiving certain amounts of benefit (averaged across velocities). Furthermore, as RE was assessed at speeds up to the second ventilatory threshold, a non-negligible amount of energy may have been produced through anaerobic lactic metabolism by anaerobic glycolysis, even though this was partly controlled by excluding subjects that exceeded an RER of >1.0. A small amount of the observed variation between subjects may thus have been due to lactic anaerobic contributions. By spot checking via individual lactate measurements with the maximum additional lactate accumulation observed reaching 2.0 mmol L^{-1}, an upper limit of 10% to 13% for this lactic contribution to total energy consumption could be estimated (with an additional lactate accumulation of 1 mmol L^{-1} lactate corresponding to an additional 3 mL min^{-1} kg^{-1} oxygen consumption) [4,47]. Despite the fact that using only spirometric gas exchange rates to calculate energy expenditure represents the standard practice in the current footwear literature, future research should consider lactate accumulation at running speeds close to the second ventilatory threshold to increase the accuracy of CPRS effect measurements. Moreover, this study is limited by examining only four different CPRS models. It is likely that CPRSs from other manufactures may yield different results.

5. Conclusions

The present study provides comprehensive insights into the running economy benefits amateur runners can realistically expect when transitioning from regular training shoes to carbon plate racing shoes and elucidates the variations in these benefits across different models from various manufacturers. Although all tested CPRS models offer measurable benefits, the presented findings illustrate that the extent of improvement and the proportion of athletes benefiting vary substantially across different CPRS manufactures and shoe designs. In essence, focusing only on mean group-level improvements fails to convey the nuances of the individual RE response of runners and may be misleading to consumers, which highlights the importance of presenting individual-level data when testing CPRSs with respect to their RE benefits. The finding of a substantial number of non-responders with certain models further underscores the complexity behind shoe performance interactions and the necessity for future research into design features to maximize benefit for a wider range of athletes. Future studies should aim to incorporate multiple trial measurements and try to explore the mechanisms of individual RE responses. Moreover, at running speeds close to or above the individual's second ventilatory threshold, lactate accumulation should be considered in total energy expenditure to improve accuracy, especially for middle-distance runners and sprinters. Eventually, investigating the relationship between RE improvements at various running speeds and actual performance outcomes will be crucial for translating these findings into valid practical recommendations for athletes.

Author Contributions: Conceptualization, M.R. and O.U.; methodology, M.R. and O.U.; software, C.v.D.; validation, M.R., C.v.D. and O.U.; formal analysis, M.R., C.v.D. and O.U.; investigation, M.R.; resources, M.R. and O.U.; data curation, M.R. and C.v.D.; writing—original draft preparation, C.v.D.; writing—review and editing, M.R. and O.U.; visualization, C.v.D., M.R. and O.U.; supervision, O.U.; project administration, M.R. and O.U.; funding acquisition, M.R. and O.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Department of Engineering and Industrial Design at the Magdeburg-Stendal University of Applied Sciences under certificate number EKIWID-2023-09-001RM.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: Dataset available on request to the authors.

Acknowledgments: We would like to thank all the participants in this study for their time and effort. We would also like to thank Eric Quellmalz for providing us with test shoes from four manufacturers free of charge for the duration of this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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