

Influence of different midsole foam in advanced footwear technology use on running economy and biomechanics in trained runners

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Abstract

Background: Ethylene and vinyl acetate (EVA) and polyether block amide (PEBA) are recently the most widely used materials for advanced footwear technology (AFT) that has been shown to improve running economy (RE). This study investigated the effects of these midsole materials on RE and biomechanics, in both fresh and worn state (after 450 km).

Methods: Twenty-two male trained runners participated in this study. Subjects ran four 4-min trials at $13 \text{ km} \cdot \text{h}^{-1}$ with both fresh EVA and PEBA AFT and with the same models with 450 km of wear using a randomized crossover experimental design. We measured energy cost of running (W/kg), spatiotemporal, and neuromuscular parameters.

Results: There were significant differences in RE between conditions ($p=0.01$; $n^2=0.17$).

There was a significant increase in energy cost in the worn PEBA condition compared with new (15.21 ± 1.01 and $14.87 \pm 0.99 \text{ W/kg}$; $p < 0.05$; $ES=0.54$), without differences between worn EVA ($15.13 \pm 1.14 \text{ W/kg}$; $p > 0.05$), and new EVA ($15.15 \pm 1.13 \text{ W/kg}$; $ES=0.02$). The increase in energy cost between new and worn was significantly higher for the PEBA shoes ($0.32 \pm 0.38 \text{ W/kg}$) but without significant increase for the EVA shoes ($0.06 \pm 0.58 \text{ W/kg}$) ($p < 0.01$; $ES=0.51$) with changes in step frequency and step length. The new PEBA shoes had lower energy cost than the new EVA shoes ($p < 0.05$; $ES=0.27$) with significant differences between conditions in contact time.

Conclusion: There is a clear RE advantage of incorporating PEBA versus EVA in an AFT when the models are new. However, after 450 km of use, the PEBA and EVA shoes had similar RE.

KEYWORDS

energetic, EVA, PEBA, running performance, running shoes

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1 | INTRODUCTION

Advanced footwear technology (AFT) such as the “Vaporfly” series of Nike or similar shoe models of other companies is characterized by a very light shoe mass, a curved carbon fiber plate embedded in the midsole to increase the longitudinal bending stiffness (LBS), along with more resilient and compliant midsole foams to provide cushioning and energy return. It is known that the amount of cushioning material in the shoe,^{1,2} and the increase of LBS with a curved carbon fiber plate can influence running economy (RE)^{3,4} and performance^{5–7} accompanied by slight biomechanical changes.^{3,4}

AFT usually use different methodologies to increase the LBS (full or partial and flat or curved carbon fiber plate) and different midsole cushioning technologies. However, it has recently been shown that midsole material may be of greater role than increased LBS in improving RE in AFT⁸ showing a higher energy return from compression than from bending of the midsole.⁹ The most used midsole foams in running shoes are ethylene-vinyl acetate (EVA), thermoplastic polyurethane, and polyether block amide (PEBA). Hoogkamer et al.¹⁰ analyzed the mechanical energy return of these three midsole materials, which was 66% for an EVA midsole with air bag, 76% for a thermoplastic polyurethane midsole, and 87% for a PEBA midsole. Thus, PEBA which is less dense and lighter than traditional foams^{10,11} preserves more mechanical energy from each footfall. Low-density foam (i.e., PEBA) allows for adding more cushioning material in the midsole without adding mass and thus allowing for a taller stack height (now limited to 40 mm for competition shoes) compared with other, traditional, midsole foams (thermoplastic polyurethane or EVA). As a result, when comparing RE between different models of AFT, the best results have been observed for models using PEBA midsole foam as opposed to traditional materials (EVA or thermoplastic polyurethane)¹²; however, due to the low density, PEBA could suffer greater wear of the material with use during the run.

Each running shoe model has an approximate average life depending mainly on the midsole material.¹³ Cook et al.¹⁴ tested a range of different running shoes (different compositions of EVA) in terms of continuous machine-simulated running distance. They found that, on average, the shoes retained approximately 67% of their initial shock-absorbing capacity after 160–240 km, but less than 60% after 400–800 km. Shoes were also tested at similar velocity after having been worn by volunteers during normal training, which showed smaller changes in initial shock-absorbing capacity (~30% less at 480 km) than machine-simulated running distance testing.¹⁴ Similarly, Escamilla-Martínez et al.¹³ found that the EVA midsole shoes started to deteriorate at 350 km by evaluating planar pressure distribution. Moreover, Kong et al.¹⁵ suggested

that slight modifications in the mechanical characteristics of shoes result in kinematic changes after about 320 km of running.

Importantly, mechanical tests do not predict shock during actual running because of neuromuscular adaptation.^{15,16} There are several studies that analyzed the effect of shoe use on biomechanics in traditional running shoes,^{13–15} but there is a lack of studies evaluating the effects of shoe use on RE.¹⁵ Moreover, there are no known studies that evaluate the effects of wear of different midsole materials on RE for AFT. Thus, the objective of this study was to evaluate RE and biomechanics in new and worn AFT of different midsole materials (EVA vs. PEBA). We hypothesized that PEBA midsole would have better RE than EVA midsole when both conditions are fresh; however, the PEBA midsole would suffer more wear after 450 km, which could negatively affect biomechanics and RE.

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-two male runners participated in this study. The inclusion criteria were the following: (1) participation in a running training program for at least 3 days per week during the previous 6 months without injury and (2) having a men's US 9 shoe size. Exclusion criterion was inability to run at 13 km h⁻¹ while below the onset of blood lactate accumulation of 4 mmol L⁻¹ with respiratory exchange ratio values below 1.0 during all the tests. Participants were recruited from different teams in the same city during the winter after the cross-country season had ended by contacting their coaches or contacting them directly. Data collection was conducted during the outdoor season (May–June). During the screening process, participants were asked about their foot size, previous injuries, training days, and 10-km time.

Prior to the study, all participants were informed about the testing protocols, possible risks involved, and were invited to provide written informed consent. The study was performed in accordance with the principles of the Declaration of Helsinki (October 2008, Seoul), and the experimental protocols were approved by the local ethics committee.

2.2 | Shoes characteristics

Four different prototype shoes conditions were manufactured (On running) specifically for this study and tested: (1) a new AFT with EVA midsole, (2) an AFT with EVA

midsole with a use of 450 km, (3) a new AFT with PEBA midsole, and (4) an AFT with PEBA midsole with a use of 450 km. Shoe characteristics are presented in Table 1, and all experimental conditions had a similar curved carbon fiber plate with similar LBS properties. The shoe wear process was carried out by one of the researchers. The shoes were worn by running at an average speed of 13 km/h on asphalt. The 450 km were done in 40 sessions with an average of 11.25 km/day. Both shoe models (new and worn conditions) were identical in the composition and characteristics (last, upper, color, and shape), with the aim to control a possible placebo effect.¹⁷

None of the tested shoes differed by more than 9 g. Even though additional shoe mass is known to deteriorate RE and running performance by around 1% per 100 g,^{2,18} previous research suggests that changes of up to 50 g do not affect performance at high running intensity.¹⁹ The LBS of the shoes was determined by a three-point bending test on the complete shoe (including shoe upper)^{20,21} where the forefoot of the shoe was placed on a custom-made structure with two supporting pins, 80 mm apart, to a material testing machine that measures force and displacement (Microtest, S.A., Madrid, Spain) (Figure 1). The machine was set to displace the center point of the forefoot 20 mm vertically downward at a speed of 4 mm/s, at which point it returned to its original position in the same amount of time. This was repeated 10 times for each shoe condition. The slope of the force–displacement curve (i.e., stiffness) was determined for all 10 loading cycles. The stiffness values were first averaged between 80 and 90% of each loading curve (i.e., linear portion of the force–displacement curve) and then across all 10 cycles. The shoes' hysteresis (i.e., lost energy) was determined as the difference in mechanical energy that was stored during the loading phase and that was returned during the unloading phase. The lost energy was represented as a percentage of the energy stored during

the loading phase. Note that this represents the energy lost in bending, not in vertical compression.

2.3 | Design and methodology

STROBE statement checklist²² was performed. These recommendations, collected in 22 items, describe the proper way of reporting the title, abstract, introduction, methods, results, discussion, and funding.

The effect of shoe use on RE and biomechanics was evaluated using a randomized crossover experimental design. Each participant visited the laboratory for a single visit (under controlled environmental conditions: 550 m altitude, 20–23°C, 35%–37% relative humidity) in a non-fatigued state (no intense exercise in the previous 48 h). During this session, RE (oxygen and energy cost measured at metabolic steady state at a specific speed), biomechanics (spatiotemporal variables), and neuromuscular parameters (leg stiffness) were assessed with four shoes models: new and worn (450 km of use) EVA and PEBA shoe models. The sequence of the shoes was randomized for each participant using a random number generator.

First, anthropometrical variables were measured. Height was measured to the nearest 0.1 cm with a portable stadiometer (Seca, Bonn, Germany), and body mass was measured to the nearest 0.1 kg with a portable balance (Seca, Bonn, Germany), while barefoot and wearing light shorts.

Then, the participants tested all the shoe conditions, but they were not allowed to manipulate the footwear at any time and were fitted by the researchers. Prior to beginning the RE testing trials, all participants completed 10 min of jogging as a warm-up in their own shoes at a self-selected pace slower than 13 km·h⁻¹. Participants then completed 4×4 min trials at 13 km h⁻¹ with each shoe model. This speed was selected so that

TABLE 1 Shoe characteristics, comfort, and experience.

Characteristics	New EVA shoe	Worn EVA shoe	New PEBA shoe	Worn PEBA shoe
Midsole material	EVA	EVA	PEBA	PEBA
LBS (N·mm ⁻¹)	35.3±1.4	23.9±1.1	35.5±1.8	21.6±1.3
Energy return (J)	4.39±0.02	3.93±0.05	4.83±0.14	3.64±0.18
% Hysteresis	26.0±1.3	39.5±0.6	24.7±0.8	42.4±1.1
Mass (g)	234	231	226	225
Heel stack (mm)	39	39	38	38
Forefoot stack (mm)	31	31	29	29
Heel-Toe offset	8	8	9	9

Note: Mean ± SD.

Abbreviations: EVA, ethylene and vinyl acetate; LBS, longitudinal bending stiffness; PEBA, polyether block amide.



FIGURE 1 Setup of mechanical stiffness test on running shoes.

participants were able to run below of the respiratory-exchange ratio (<1) to ensure steady-state oxygen uptake (VO_2) values and also confirmed by blood lactate measures (values below 4 mmol). At the end of each trial, participants rated their perceived shoe comfort, acute muscle soreness and rating of perceived exertion on the visual analogue scale and rested 10 min before the beginning of the trials with the other models. All run testing was performed on a motorized treadmill (HP Cosmos Pulsar, HP Cosmos Sports & Medical GmbH, Nussdorf-Traunstein, Germany) that has a stiffness value around 300 kN/m.²³ During the RE trials, respiratory variables were measured using a gas analyzer (CPX Ultima Series MedGraphics, St. Paul, Minnesota, USA), which was calibrated prior to each session (CO_2 4.10%; O_2 15.92%). VO_2 values collected during the last 60 s of each 4 min bout was used to determine RE as oxygen cost of running.²⁴ The energy cost of running was calculated (W kg^{-1}) following previous calculations^{25,26} and it was the main outcome. Blood samples were collected from the fingertip in the final minute before finishing the stage for blood lactate determination (Lactate Scout, SensLab GmbH, Germany).²⁷

Main spatiotemporal outcomes during the gait cycle (contact time, step frequency, step length, and flight time) were measured for every step during treadmill running using an optical measurement system (Optojump-next,

Microgate, Bolzano, Italy) during all the running bouts, with a sampling frequency of 1000 Hz. Complementary, leg stiffness and vertical oscillation were estimated using a Stryd® device with a sampling frequency of 1000 Hz. The device uses a triaxial accelerometer that has shown an adequate reliability and excellent validity of these measures evaluated and reported by García-Pinillos et al.²⁸ The Stryd® device was paired with a Polar® watch (Vantage M GPS system; Polar, Kempele, Finland) and the information was analyzed using the Stryd Power Center program available on the web and mobile application. Data were recorded, and the final minute of each RE trial was averaged for subsequent analyses. The 1-min period provided well over the 25 steps recommended for running mechanics measurements to distinguish running technique between people.²⁹

Rate of perceived exertion from 0 to 100, shoe comfort and acute muscle soreness while running with every shoe condition were recorded using a visual analogue scale.³⁰ The questions were, “how comfortable were the shoes?” and “how much acute muscle soreness do you have?” The corresponding anchor points for these scales were 0—“Not comfortable at all” to 100—“Maximal comfort”, and 0—“Absolutely no muscle soreness” to 100—“Severe acute muscle soreness”, respectively. Shoe comfort and acute muscle soreness were measurement once with each condition.³¹

2.4 | Statistical analysis

Statistical analyses were conducted using SPSS 24.0 (SPSS Inc., Chicago, IL) for Mac. Data were screened for normality of distribution and homogeneity of variance using a Shapiro–Wilk Normality Test. Repeated-measures ANOVA was conducted to compare shoe conditions. When a significant main effect for shoe was observed, a Bonferroni post-hoc test was performed. Complementarily, a paired *t*-test was performed to evaluate if the difference on RE between new and worn conditions was different between the two shoe models with different foams. Effect sizes were measured using partial eta squared in the ANOVA and values of 0.01, 0.06 and above 0.15 were considered as small, medium, and large, respectively³² and Cohen's *D* was used to compare between worn and control conditions with values of 0.2, 0.5, and above 0.8 were considered as small, medium, and large, respectively.³² Significance level for all analyses was set at $\alpha = 0.05$.

3 | RESULTS

Twenty-two male runners (mean \pm SD: 28.3 \pm 5.2 years; 65.2 \pm 5.4 kg and 168.0 \pm 34.9 cm) volunteered to participate in this study. All 22 were eligible and completed the full protocol. The average blood lactate at the conclusion of all conditions was 1.98 \pm 0.92 mmol L⁻¹ and was below 4 mmol L⁻¹ for all subjects included in the final analysis (Table 2). Respiratory–exchange ratio remained below 1.0 across all trials for all subjects (0.83 \pm 0.05, 0.84 \pm 0.06 for new and worn in EVA conditions and 0.84 \pm 0.05, 0.83 \pm 0.05 for new and worn in PEBA conditions; $p = 0.26$; $n^2 = 0.05$). There was no indication of any substantial $\dot{V}O_2$ slow component, as oxygen uptake differed by a nonsignificant 0.32% on average between Minute 3 and Minute 4 ($p = 0.64$).

Table 2 shows the results of the variables analyzed during the study for each shoe condition. Results of the ANOVA test revealed that there were significant differences between conditions for the main outcome (RE), expressed as energy cost and oxygen cost ($p = 0.01$; $n^2 = 0.17$). The Bonferroni post-hoc showed that there was a significant increase in energy cost (worse RE) in the worn PEBA condition in comparison to the new PEBA condition (15.21 \pm 1.01 and 14.87 \pm 0.99 w/kg; $p = 0.02$; ES = 0.54). RE was similar between the new (15.15 \pm 1.13 w/kg) and worn EVA (15.13 \pm 1.14 w/kg) conditions ($p = 0.47$; ES = 0.02) (Figure 2). There was a significantly larger increase in RE between new-worn conditions in the PEBA condition (0.32 \pm 0.38 w/kg) in comparison with EVA condition (0.06 \pm 0.58 w/kg) ($p = 0.01$; ES = 0.51). Moreover, RE was lower (better RE) in the new PEBA condition than the

new EVA condition (14.87 \pm 0.99 and 15.15 \pm 1.13 w/kg; $p = 0.02$; ES = 0.27).

Regarding biomechanics outcomes, there were significant differences between conditions in step length ($p < 0.01$; $n^2 = 0.25$), step frequency ($p = 0.01$; $n^2 = 0.14$), and contact time ($p = 0.01$; $n^2 = 0.28$) without changes in the other biomechanical variables ($p > 0.05$). The Bonferroni post-hoc test showed that there was a significant increase in step length in the worn PEBA condition in comparison with the new EVA condition (1.12 \pm 0.20 and 1.10 \pm 0.19 cm; $p = 0.03$; ES = 0.11). Step frequency significantly increased in worn EVA condition in comparison with the new EVA condition (163.3 \pm 6.5 and 162.1 \pm 6.5 step/min; $p < 0.03$; ES = 0.18) with no differences between PEBA conditions ($p > 0.05$). Contact time was lower in the new PEBA (0.257 \pm 0.033 s; $p = 0.04$; ES = 0.14) and worn PEBA condition (0.257 \pm 0.033 s; $p = 0.02$; ES = 0.14) in comparison with worn EVA condition (0.262 \pm 0.036 s). Vertical oscillation, flight time, leg stiffness, and subjective acute muscle soreness, comfort, and rating of perceived exertion scales did not change between conditions ($p < 0.05$). Heart rate did not change between footwear conditions ($p = 0.11$; $n^2 = 0.10$).

4 | DISCUSSION

The objective of this study was to evaluate the effects on RE and biomechanics in a new and worn AFT of different midsole materials (EVA vs. PEBA). The results of the present study provide new data about changes on RE and biomechanics when wearing new AFT of different midsole materials (EVA and PEBA) and after 450 km of use during real road running. Fulfilling our hypothesis, the main finding was that the worn PEBA shoe model had a 2.28% worse RE compared with the same new shoe model, while there were no differences between new and worn EVA shoe models after 450 km of road running. There were minor modifications on running biomechanics using both worn shoes conditions compare to new shoes conditions. Moreover, the PEBA shoe model improved RE a 1.88% together with a reduction in the contact time compared with EVA shoe model when the shoes were new.

Several studies have investigated the changes in the cushioning characteristics of running shoes, either in running^{14,33,34} or in mechanically simulated tests.^{14,35} To our knowledge, there are no known studies that evaluated the effect of shoe wears on RE or performance. Wang et al.³⁴ suggested that running shoes show a greater loss of shock absorption during mechanically repeated tests than kinematic analysis during actual running so that tests during actual running can provide more ecological information. Our study evaluated RE, which is a strong predictor of running performance in

TABLE 2 Results for variables analyzed during the study for each shoe condition.

	EVA		PEBA		Cohen's d	ANOVA	η^2
	New	Worn	New	Worn			
Energy cost (W/kg)	15.15 ± 1.13	15.13 ± 1.14	14.87 ± 0.99 \$	15.21 ± 1.01*	0.54	0.01	0.17
Oxygen cost (mL·kg ⁻¹ ·km ⁻¹)	38.28 ± 6.07	37.76 ± 5.64	37.35 ± 5.74	38.45 ± 5.64*	0.34	<0.01	0.12
Respiratory exchange ratio (RER)	0.83 ± 0.05	0.84 ± 0.06	0.84 ± 0.05	0.83 ± 0.05	0.18	0.26	0.05
Δ lactate (mmol ⁻¹)	0.25 ± 0.69	0.52 ± 0.65	0.42 ± 0.77	0.11 ± 0.56	0.41	0.15	0.08
Heart rate (bpm)	146.5 ± 12.4	146.4 ± 12.6	146.4 ± 12.3	148.4 ± 12.8	0.16	0.11	0.10
Step length (m)	1.10 ± 0.19	1.10 ± 0.19	1.11 ± 0.20	1.12 ± 0.20\$	0.05	<0.01	0.25
Step frequency (step/min)	162.10 ± 6.49	163.30 ± 6.51 *	163.22 ± 6.98	163.21 ± 6.22	0.01	0.01	0.12
Contact time (s)	0.260 ± 0.035	0.262 ± 0.036	0.257 ± 0.033 †	0.257 ± 0.033 †	0.00	<0.01	0.28
Flight time (s)	0.108 ± 0.030	0.104 ± 0.030	0.109 ± 0.030	0.109 ± 0.030	0.00	0.05	0.12
Vertical oscillation (cm)	8.25 ± 1.41	8.05 ± 1.38	8.21 ± 1.39	8.20 ± 1.19	0.01	0.15	0.08
Leg stiffness (kN·m ⁻¹)	9.57 ± 0.98	9.47 ± 1.02	9.63 ± 0.92	9.59 ± 0.98	0.04	0.08	0.10
Muscle soreness VAS (0–100)	20.3 ± 19.0	21.4 ± 18.8	18.7 ± 18.8	23.7 ± 20.4	0.25	0.28	0.05
Comfort VAS (0–100)	70.2 ± 18.8	68.45 ± 20.9	73.9 ± 14.6	73.8 ± 16.6	0.02	0.34	0.05
Rate of perceived exertion (0–100)	43.3 ± 18.1	43.62 ± 18.6	42.7 ± 17.3	45.5 ± 17.8	0.16	0.29	0.05

Note: Data are presented as mean ± standard deviation. Post-hoc analysis: * different from new condition at $p < 0.05$; \$ different from EVA-new condition at $p < 0.05$; † different from EVA-worn condition at $p < 0.05$; # different from PEBA-worn condition at $p < 0.05$.

Abbreviations: EVA, ethylene and vinyl acetate; PEBA, polyether block amide; VAS, visual analogue scale.

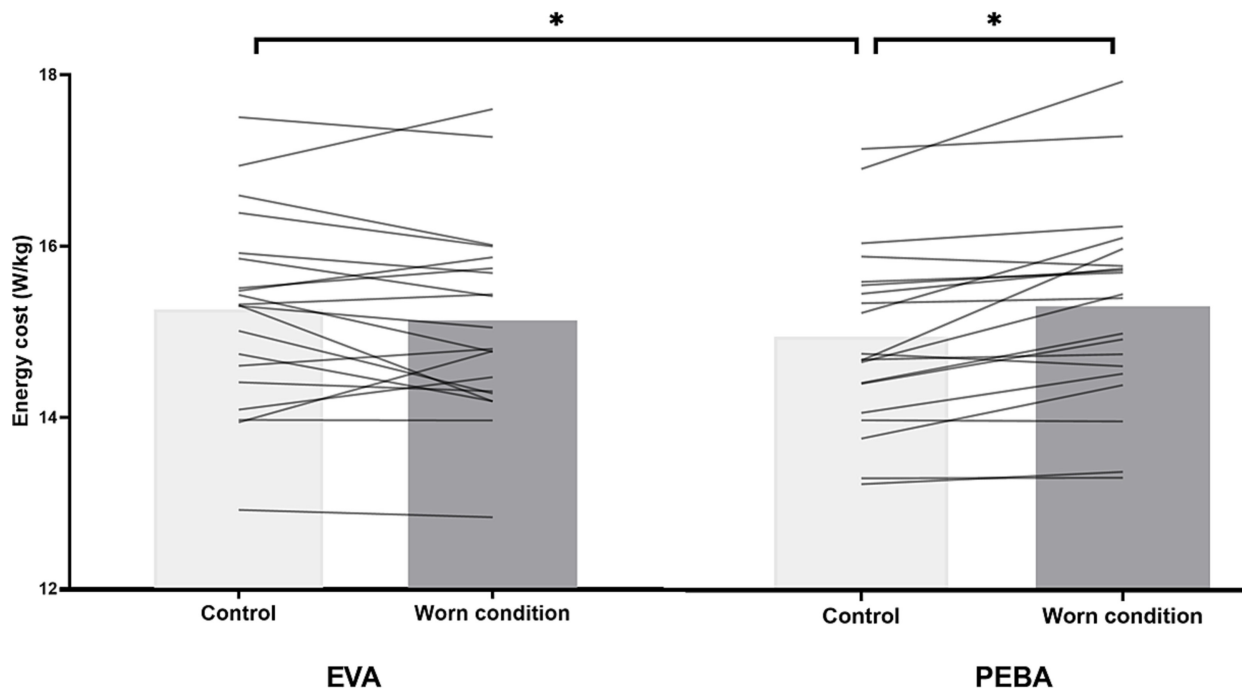


FIGURE 2 Running economy (W kg^{-1}) at 13 km h^{-1} . Bar graphs represent mean values and lines represent the individual trend with each shoe condition. $*p \leq 0.05$ during post hoc comparisons when main effect of footwear significant ($n = 22$).

trained runners.¹⁸ Our RE results suggest that in AFT, PEBA midsoles suffers greater degradation than EVA midsoles over 450 km of road running with a similar pattern of RE deterioration among all runners when comparing the worn-PEBA condition with the new-PEBA condition, while the worn-EVA condition had a wide variability among participants compared with new-EVA (Figure 2). This may be due to the different composition of the material. PEBA is a polyether, which is less dense and therefore lighter material than traditional EVA, that achieves a higher energy return.¹⁰ In our study, the PEBA and EVA condition had a similar shoe mass, so the differences between conditions had to be due to the difference between materials and the higher energy return of PEBA compared with EVA.¹⁰ The PEBA condition ceased to improve the RE after 450 km. This may be because PEBA being a less dense material the compression and the wrinkling between the air cells that compose the material could be greater,³⁵ showing a slightly greater difference in energy returned to bending between the new and worn condition in the PEBA condition than in EVA (Table 1).

However, of all the energy return that materials achieve in mechanical testing, only a limited percentage of mechanical energy return is found to be used to improve RE.^{33,36} Energy return sometimes occurs at the wrong time, frequency, location, and direction during running, thereby compromising the ultimate effect on performance. Have been showed that the magnitude of mechanical energy

return of midsoles in traditional running shoes with modified LBS (48.2% vs. 62.2%) had no effect on RE in shoes of equal mass.³⁷ Therefore, although PEBA midsoles have a higher energy return than EVA midsoles, it seems that not all the differences between the shoes can be explained by the difference in energy return and could possibly also be due to the interaction between the midsole material and the embedded curved carbon fiber plate.³⁸ Based on a recent meta-analysis by our research group, footwear with a curved carbon fiber plate and with the plate embedded in the midsole improved RE more than footwear with flat plates and stiff insoles.⁴ It could be that an embedded plate is more effective in PEBA than EVA foam.

Kong et al.¹⁵ investigated the effect of shoe degradation (new and worn running shoes) on running kinetics and kinematics measured using a force platform and video motion analysis. They found that as shoe cushioning capability after about 320 km of running decreased, runners modified their running biomechanics to maintain constant external loads. Although our study did not measure kinetics data, our results are in concordance with the modification of running kinematics when the AFT is worn.

Runners tend to adjust the kinematics to reduce the impact force during running, typically increase leg stiffness, when running on compliant surfaces and decrease leg stiffness on hard surfaces.³⁹ The differences in leg stiffness are primarily due to reduced contact time⁴⁰ produced by increased ground impact forces⁴¹ and muscle

activity,⁴² which are also related to improvements in RE.⁴³ The LBS test showed that the worn conditions of both materials were more compliant to longitudinal bending; however, it was not enough to make a significant difference in leg stiffness, although a decreasing trend is shown for both materials in the worn conditions (Table 2). Thus, the slight changes in running kinematic as increased step length and reduced contact time in PEBA conditions in comparison with EVA condition could be the small mechanisms causing the higher efficiency in the new PEBA condition. It is known that in runners of similar level (with shoes of similar LBS) less contact time is relation with better RE, characterized by earlier propulsive subphase and more economical energy transfer during the propulsive.⁴⁴

Moreover, the worn EVA condition showed a significant increase in step frequency in comparison with the new EVA; however, the worn EVA condition and the new EVA showed similar RE. It is known that the best strategy to limit the negative effects of excessive vertical oscillation or excessive stride length on RE is to increase the stride frequency,^{43,45} thus achieving the same distance with more steps and maintaining the same running efficiency, as opposed to increasing stride length to maintain running speed, which would mean greater muscles activation and also increasing the braking phase worsening the RE.

Surprisingly, despite differences in RE between the new and worn PEBA conditions, there were no biomechanical changes between conditions in spite of a 39% reduction in LBS and of the increase of energy lost by hysteresis from 25% to 42% after 450 km of real road running in new PEBA versus worn PEBA condition. Previous studies have shown a reduction in shoe shock absorption capability after 240 km¹⁴ and 500 km.³⁵ Thus, the worn PEBA condition in the present study may have become less “bouncing” with use, resulting in a loss of shock attenuation capacity and a loss of rebound effect for the runner. However, it seems that the change in the properties of the worn PEBA shoes does did not cause kinematic changes. Thus, we can assume that the worse RE with the worn PEBA condition is due to the adjustments the runner has to make in order not to change his running biomechanics.

Regarding the subjective measures, there were no significant differences between the new and worn conditions for both materials. The higher LBS levels of the new conditions compared with the worn conditions did not result in greater discomfort, muscle soreness and rating of perceived exertion for runners. Overall, consistent with previous research,³⁰ where changes in comfort at the foot/shoe interface did not result in changes in RE or significant changes in biomechanical variables.

4.1 | Limitations

The present study has several limitations. The total running distance was 450 km, a longer running distance was not considered because of time constraints. The midsole characteristics of AFT, especially of EVA midsoles shoes over distances greater than 450 km remains unknown. Several studies indicate that the collapse of air cells⁴⁶ and the wrinkling of cell faces³⁵ affect the shock absorption capacity of the EVA running shoes, but perhaps the combination of EVA and carbon fiber plate results in a longer life of the EVA midsole. Stiffness and energy return measures for compression, rather than just for bending, would have allowed to further explore differences between the foams and the effects of wear. Furthermore, not all PEBA or EVA midsoles from shoe companies have the same characteristics. Importantly, the EVA and PEBA shoes evaluated in this study were separate shoe models, but with similar midsole dimensions (Table 1). Therefore, the results of the present study should not be generalized across other shoe types. The mechanical LBS test conducted in our study was performed at similar speeds from previous studies^{20,47} but substantially slower than bending speeds observed during running. Moreover, this study was done only with male runners and only at one velocity. Hence, it is possible that the present results are limited to male runners of similar competitive levels because it is known that lower limb strength levels and the contact time that the runners have during treadmill running may affect the optimal LBS between subjects.^{38,48}

4.2 | Perspective

Most major running shoe companies now have a new style of road racing shoe with a thick lightweight midsole and accompanied by a carbon fiber plate that increases the LBS of the shoe like the ones used in this study. Therefore, these results generate important new knowledge for the footwear industry. General recommendations for shoe life range between 400 and 500 km for racing shoes, such as AFT. However, our results demonstrate different changes in AFT with PEBA and EVA midsole properties after 450 km of road running, leading to changes in RE and minor kinematic adaptations. Therefore, our results suggest that shoe companies can create AFT with EVA midsole for use in training with a longer shoe life, and design AFT with PEBA for use only in competition to achieve better RE results. However, future studies should compare the wear process in shoes with PEBA midsole with a carbon fiber plate to increase LBS and without carbon fiber plate to analyze the influence of the element to increase the LBS (carbon fiber plate) on AFT wear. In addition,

since there is recent discussion about the possible risk of injury when using AFT,^{49,50} future studies should also investigate the influence of using AFT with EVA and PEBA midsole and their corresponding worn conditions on the risk of injury.

5 | CONCLUSIONS

There is a clear RE advantage to incorporating PEBA versus EVA along with a curved carbon fiber plate in AFT. However, the PEBA midsole experienced greater wear over 450km and worsened RE compared with the new PEBA condition. While for the shoes with an EVA midsole, RE was not affected when the shoe was worn for 450km. However, there were minor spatiotemporal modifications on running biomechanics using worn shoes conditions compare to new shoes conditions.

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CONFLICT OF INTEREST STATEMENT

VRC, FGM, SHM, MCSM, ARG, and JMGR have no conflicts of interest relevant to the content of this article. WH has received research grants from PUMA and Saucony. No footwear company had any influence on the conceptualization or presented in this publication.

DATA AVAILABILITY STATEMENT

The data that support the finding of this study are available from the corresponding author upon reasonable request.

PATIENT CONSENT STATEMENT

All participants were informed about the testing protocols, possible risks involved, and were invited to provide written informed consent.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

Not applicable.

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