ORIGINAL ARTICLE

Influence of the carbon fiber plate curvature of advanced footwear technology on the running energetic cost and 3000-m performance

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Abstract

This study aimed to explore the effect of two similar commercialized advanced footwear technology models differing mainly in their plate geometry (i.e., low and high curvature plate) on the running energetic cost in both non-fatigued and fatigued states. It also sought to determine their impacts on 3000-m performance. Twelve highly trained male athletes performed four 5-min trials (two advanced technology models, two trials). In each experimental session, athletes completed a 3000-m trial which was followed by a 5-min trial to test the running energetic cost when fatigued. Athletes exhibited a lower running energetic cost when wearing the low curvature plate in a non-fatigued state ($P = 0.034$; -1.13 [-1.92 to -0.11] %), which persisted with better performance in the 3000-m trial ($P = 0.017$; -0.42 [-0.74 to -0.09] %). However, in a fatigued state, non-significant differences were reported ($P = 0.207$). The low curvature plate seems to be more effective than the high curvature plate when running at low intensity in a fresh state as well as in a maximal high-intensity effort. However, non-significant differences between plate geometries were observed when fatigue was increased.

Keywords Road shoes · Advanced footwear technology · Running economy · Running performance · Fatigue

1 Introduction

During each stride, about 80% of the overall energetic cost is oriented to meet the mechanical work demanded for the body weight support and forward propulsion [1, 2]. For this demanding task, the hip, knee and ankle joints distribute the mechanical work, although not in a uniform fashion, being of about 20, 30 and 50% [3] in the respective joints,

and raise even more to the distal joint (~70%) when the running intensity increases [4]. Accordingly, enhancing the balance of mechanical and energetic work at the ankle joint has become a relevant issue, particularly, from the perspective of footwear design through the increase of the longitudinal bending stiffness in the so-called advanced footwear technology (AFT) [5].

From the various carbon fiber-reinforced composite materials used for this aim, two mechanisms could be differentiated. On the one hand, adding elements such as a low curvature plate (LCP) within the midsole increases the ankle push-off moment [6]. This creates an increased gear ratio between the external and internal ankle moments, reducing the ankle angular velocity [6]. This reduction could optimize the force–velocity profile of the triceps surae by reducing the mean shortening velocity, an aspect that would theoretically lower the motor unit recruitment and therefore the metabolic demand [7]. Moreover, Cigoja et al. [8] reported that this footwear feature significantly engages the Achilles tendon, thereby increasing the non-taxing force generation of the triceps surae. However, athletes may experience a detrimental effect on their running energetic cost if their strength capacities are limited [6]. On the other hand, adding elements such as a high curvature plate (HCP) can reduce

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the ankle push-off moment by shortening the lever arm [9]. Additionally, Nigg et al. [10] suggest that an upward reaction force could be created at the rearfoot region when the ground reaction force travels forward during the end of the stance phase. This might create a "teeter-totter effect" that facilitates ankle plantar flexion [10], although the current evidence of this mechanism is lacking [11].

In this regard, Rodrigo-Carranza et al. [12] have performed a meta-analysis integrating those studies comparing the effect of AFT with a HCP with respect to no-plate conditions on the running energetic cost, reporting a ∼3.5% improvement. However, to the authors´ knowledge, no studies have compared the effect of AFT with different plate geometries on the running energetic cost and performance. This latter variable has been scarcely analyzed in the running footwear field as Fuller et al. [13] and later Ruiz-Alias et al. [14] highlighted. This is of particular interest for determining the effectiveness of a plate geometry since measurements of the running energetic cost are limited to intensities under the lactate threshold (LT) [15]. Superior running intensities could compromise to a greater extent the ankle plantar flexor force–velocity demands [2, 7], at which it is hypothesized that an LCP would report superior benefits than an HCP [16]. Likewise, with the onset of fatigue, it has been observed that the positive work shifts from distal to proximal joints during a prolonged run [3], and this can be delayed by increasing the longitudinal bending stiffness of the footwear [17], although it is unknown through which geometry it would be further improved.

With the continuous development of AFT, athletes nowadays have the option of using similar commercialized models differing mainly in the curvature of the plate. Therefore, this study aims (i) to explore the effect of two similar commercialized AFT models differing mainly in their plate geometry (i.e., HCP, LCP) on the running energetic cost in non-fatigued and fatigued states, and (ii) to determine their effects on the 3000-m performance.

2 Methods

2.1 Experimental design

A randomized crossover design was used to explore the effect of two similar commercialized AFT models differing mainly in their plate geometry (i.e., HCP, LCP) on the running energetic cost in non-fatigued and fatigued states and on the 3000-m performance. On the first testing session, athletes performed a graded exercise test in which the LT, lactate turn point (LTP), first and second ventilatory thresholds (VT1, VT2), and the maximum oxygen uptake ($\dot{V}O_{2max}$) were determined. On the second and third testing sessions, athletes performed two 5-min trials at the speed associated with the LT/VT1, interspersed by 5-min rest, in which both footwear models were used in a randomized counterbalanced order. Then, athletes performed a 3000-m trial at the speed associated with the $\dot{V}O_{2max}$ (i.e., maximal aerobic speed [MAS]). After 10-min rest, athletes performed a 5-min trial with the footwear used in the 3000-m trial to test the running energetic cost in a fatigued state. All testing sessions were performed on a treadmill under similar environmental conditions (∼22 °C and ∼40% humidity) and time of day (±1 h) (Fig. 1).

2.2 Participants

Twelve highly trained male athletes (age: 25 ± 6 years, height: 178 ± 4 cm, body mass: 67 ± 6 kg; 3000-m
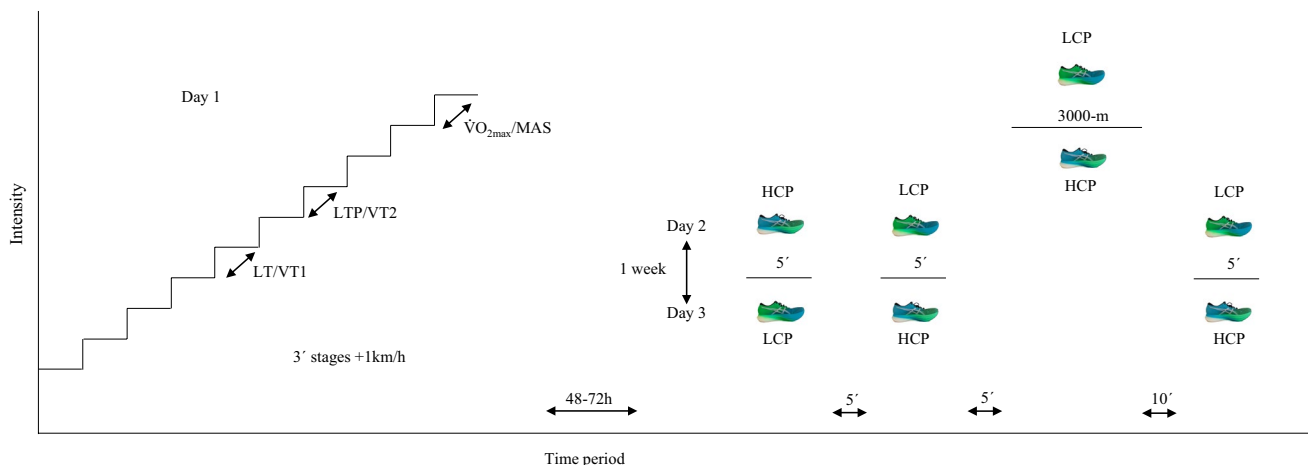

Fig. 1 Experimental design. *LT* lactate threshold, *LTP* Lactate turn point, *VT1* First ventilatory threshold, *VT2* Second ventilatory threshold, $\dot{V}O_{2max}$ Maximum oxygen uptake, *MAS* Maximal aerobic speed. *LCP* Low curvature plate, *HCP* High curvature plate

season-best: $08:49 \pm 00:24$ min:ss; training volume: 90 ± 22 km per week; $\dot{V}O_{2max}$: 62.5 ± 6.2 ml/kg/min) participated in the study. Our sample size was based on previous studies that for an expected biological and technological error of 1.5–2.0% for measurements of the oxygen uptake [18], a sample size of 9–12 athletes enabled to discern a 1–2% mean difference between conditions (1-β: 0.6 to 0.8) [19–21]. Athletes were recruited based on shoe size (9 US) and 3000-m season-best time (< 09:30 mm:ss). The non-fatigued energetic cost trials were performed by the twelve athletes recruited. However, for the 3000-m and the fatigued energetic cost trials, three athletes were discarded after checking the exclusion criterion of maximal effort (i.e., the $\dot{V}O_{2peak}$ reached on each 3000-m trial were compared with the $\dot{V}O_{2peak}$ reached at the graded exercise test to confirm the $\dot{V}O_{2max}$ and guarantee a maximal effort in both 3000-m trials). All athletes were informed about the research purpose and procedures of the study before signing a written informed consent form. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the institutional review board (No. 2276/CEIH/2021).
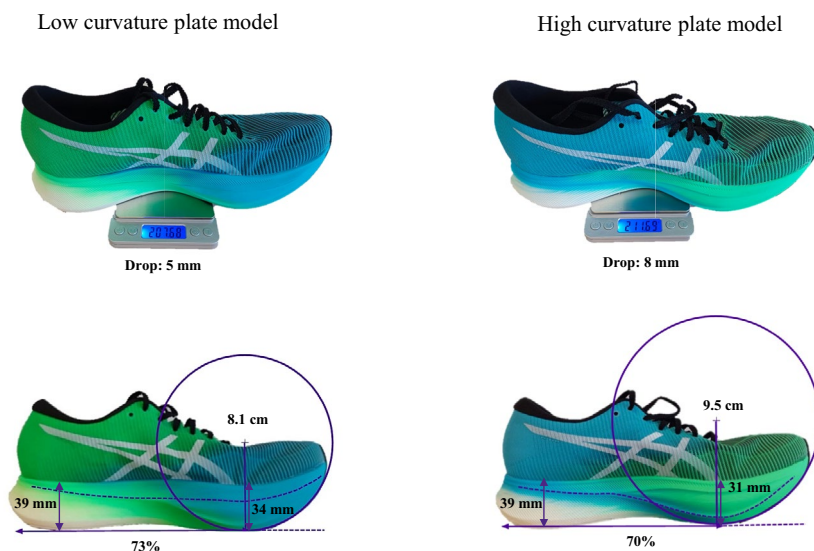
2.3 Footwear models

The Asics Metaspeed Edge + (HCP) and the Asics Metaspeed Sky + (LCP) models were used. Both AFT models present the same midsole material (i.e., Flyte Foam) and similar shoe mass (HCP: ~ 212 g; LCP: ~ 208 g). These differ in the carbon fiber-reinforced composite plate and forefoot midsole geometries (i.e., forefoot stack height, rocker and drop) (see Fig. 2 for further details).

2.4 Graded exercise test

The graded exercise test was conducted on a treadmill (WOODWAY Pro XL, Woodway, Inc., Waukesha, WI, USA). Athletes wore their own shoes. The test comprised 3-min stages with speed increments of 1 km/h, interspersed by 30-s rest in which a fingertip capillary blood sample was collected for the subsequent analysis of lactate (Lactate Scout, SensLab GmbH, Germany). The starting speed was customized according to the athlete´s training history and recent performance. Athletes were asked to exert a maximum effort. The test was finished when they could not complete a stage or declined to start a new one. The portable metabolic analyzer (COSMED K5, Rome, Italy) [22] was used to determine the VT1 and VT2, as well as the $\dot{V}O_{2max}$ and MAS. The metabolic analyzer was calibrated following the manufacturer's recommendations [22].

The blood lactate values were plotted against the running speed to determine the LT and the LTP by visual inspection [23]. The LT was established at the first breakpoint, where blood lactate concentration rises above the baseline value. The LTP was established at the second disproportionate increase in the lactate–speed relationship. The breath-by-breath data were examined to exclude errant breaths and those values outlying more than four standard deviations from the local mean were removed. Then, data were linearly interpolated to give 1-s values and then averaged into 10-s time bins. The smoothed breath-by-breath data were plotted against the running speed for determining the VT1 and VT2 [24]. The VT1 was defined as the minimal speed at which the ventilatory equivalent for oxygen exhibited a systematic increase without a parallel increase of the equivalent for carbon dioxide. The VT2 was established as the minimal

Fig. 2 Characteristics of the racing footwear models. Shoe mass: 208 (LCP) vs. 212 (HCP) grams; Rearfoot stack height: 39 mm (LCP and HCP); Forefoot stack height: 34 mm (LCP), 31 mm (HCP); Rocker axis: 73 (LCP) vs. 70 (HCP) %; Rocker radius: 8.1 (LCP) vs. 9.5 (HCP) cm; Stiffness: Extreme resistance (LCP) vs. extreme resistance (HCP) [32]. The rocker axis and radius were determined with the free-access software Kinovea [33]

Low curvature plate model   High curvature plate model

Drop: 5 mm   Drop: 8 mm

8.1 cm   9.5 cm

39 mm   34 mm   39 mm   31 mm

73%   70%

speed at which the increase of both ventilatory equivalents occurs. Both methods (i.e., lactate and ventilatory measures) were used to determine each intensity domain landmark, although the ventilatory analysis was always prioritized. The $\dot{V}O_{2max}$ and MAS were determined as the highest 30-s rolling mean value and the speed associated, respectively. Two independent researchers followed the aforementioned procedure and reached a final agreement to establish each intensity domain landmark, the running speed at which the energetic cost was tested (i.e., LT/VT1), the initial pace to establish in the 3000-m trial (i.e., between VT2/LTP and MAS), and maximal effort criterion to reach in each 3000-m trial (i.e., $\dot{V}O_{2max}$).

2.5 Running energetic cost

Athletes performed two 5-min trials at the speed associated with the LT/VT1 (15.6 ± 1.0 km/h or $80.2 \pm 7.6\%$ $\dot{V}O_{2max}$), interspersed by 5-min rest, in which both footwear models were used in a randomized order, and counterbalanced on the following testing session. After the 3000-m trial, athletes rested for 10-min and completed a third 5-min trial with the footwear used in the 3000-m trial. The mean oxygen uptake and dioxide production of the last 2-min of each trial were used to calculate the energetic cost (W/kg) using the Brockway equation [25]. A steady metabolic state was required to compare each footwear condition (Respiratory exchange ratio [RER] < 1.0) which was met for each day and condition (HCP day 1: 0.91 ± 0.06; LCP day 1: 0.90 ± 0.07; HCP day 2: 0.89 ± 0.08; LCP day 2: 0.90 ± 0.07; LCP post 3000-m: 0.85 ± 0.08; HCP post 3000-m: $\pm 0.85 \pm 0.08$). The mean biological and technological error for the energetic cost of running was determined with the data obtained on days 1 and 2 (i.e., 1.7%). This one was calculated as follows: standard deviation (SD) (Day 1 and Day 2) / $\sqrt{2}$, and expressed as a % of the mean (Day 1 and Day 2).

2.6 3000-m trial

The 3000-m trial was performed on a treadmill. Based on the results of the graded exercise test, the starting velocities of the 3000-m trials were proposed to be at MAS, or in consensus with the athlete according to their severe intensity domain range (i.e., between LTP/VT2 and MAS). Athletes were asked to exert maximum effort and to self-regulate their pace. With a thumb-up or -down signal, the athletes indicated to the researcher whether to modify their pace ± 0.5 km/h. The $\dot{V}O_{2peaks}$ reached on each 3000-m trial were compared with the $\dot{V}O_{2peak}$ reached at the graded exercise test to confirm the $\dot{V}O_{2max}$ and guarantee a maximal effort in both 3000-m trials.

2.7 Statistical analysis

Descriptive statistics are represented as mean $\pm$ SD. The normal distribution of data and homogeneity of variances were confirmed through the Shapiro–Wilk test and Levene's tests, respectively. A paired-sample *t*-test was used to compare the running energetic cost and 3000-m performance between both AFT models. Data analysis was performed using the software package SPSS (IBM SPSS version 25, SPSS Inc., Chicago, IL., USA). Statistical significance was set at $P < 0.05$.

3 Results

3.1 Running energetic cost

There was a significant difference in the running energetic cost ($P = 0.034$) (Table 1). Athletes exhibited a lower running energetic cost with the LCP model (-0.20 ([-0.35 to -0.02] W/kg; -1.13 [-1.92 to -0.11] %). After completing the 3000-m trial, the running energetic cost was not significantly different between footwear models ($P = 0.207$) (Fig. 3).

3.2 3000-m performance

There was a significant difference in the 3000-m performance ($P = 0.017$) (Table 1). Athletes exhibited a lower time with the LCP model (-2.33 [-4.14 to -0.53] sec; -0.42 [-0.74 to -0.09] %).

4 Discussion

The results revealed that athletes exhibited a lower running energetic cost with the LCP model in a non-fatigued state and better performance in the 3000-m trial. However, non-significant differences were observed between models in the running energetic cost in a fatigued state.

Although the acting mechanisms of HCP and LCP have been widely exposed in the literature [6, 10], the existing evidence of their benefits with respect to a no plate condition is inconsistent [11]. On the one hand, Rodrigo-Carranza et al. [12] conducted a meta-analysis in which those studies analyzing the effects of a HCP model (i.e., Nike Vaporfly 4%) with respect to no plate models on running economy were included, observing a mean improvement of ~3.5%. However, Healey and Hoogkamer [26] reported later that reducing the stiffness of this HCP model through 6 medio-lateral cuts did not impair the running economy with respect to the same model in its intact state, suggesting that metabolic savings result from the interaction of the rest of the

Table 1 Effect of the footwear models on the running energetic cost at the intensity associated with the first ventilatory threshold previously and after performing the 3000-m trial and on running performance

	Variable	HCP	LCP	Δ	Δ (%)	*P*-value
Running energetic cost (W/kg)	Pre (*n* = 12)	17.7 ± 2.0	17.5 ± 2.0	− 0.20 (− 0.35 to − 0.02)	− 1.13 (− 1.92 to − 0.11)	0.034
	Post (*n* = 9)	17.2 ± 2.4	17.6 ± 2.2	0.41 (− 0.28 to 1.11)	2.38 (− 1.63 to 6.45)	0.207
Running energetic cost (W/kg/km)	Pre (*n* = 12)	68.0 ± 6.1	67.3 ± 6.0	− 0.72 (− 1.35 to 0.09)	− 1.05 (− 1.99 to − 0.10)	0.029
	Post (*n* = 9)	65.5 ± 8.0	67.0 ± 6.4	1.56 (− 1.17 to 4.31)	2.75 (− 1.40 to 6.88)	0.225
Running performance (sec and ml/kg/min)	3000-m (*n* = 9)	560 ± 31	558 ± 31	− 2.33 (− 4.14 to − 0.53)	− 0.42 (− 0.09 to − 0.74)	0.017
	$\dot{V}O_{2max}$ (*n* = 9)	60.7 ± 7.2	61.4 ± 8.0	− 0.63 (− 4.18 to 2.92)	− 1.04 (− 6.92 to 4.81)	0.688

HCP high curvature plate, *LCP* low curvature plate, $\dot{V}O_{2max}$ maximum oxygen uptake; Δ: (HCP - LCP)/HCP + *100

footwear features (i.e., midsole foam, geometry). On the other hand, Rodrigo-Carranza et al. [12] also conducted a subgroup analysis for those studies analyzing the effect of LCP models with respect no plate models on running economy, observing non-significant differences. In this regard, Willwacher et al. [27] stated that the potential cause of not responding to this footwear feature could be related to how athletes adapt their running form to an increased lever arm at the ankle joint. Specifically, they observed that some athletes increased their ankle joint moments while keeping push-off times, meanwhile others decreased ankle joint moments while increasing push-off times [27].

According to the existing evidence, it was necessary to determine the potential discrepancies and similarities between plate geometries to further understand the plate effectiveness. To do so, it was also of paramount importance to address their comparison in two contexts scarcely analyzed in the running footwear science field [13–15], at high-intensity efforts, and under fatigue. The methodological requirements of running economy measurements (i.e., intensities under the LT/VT1) in conjunction with testing different footwear conditions within a session (i.e., long recovery periods to change footwear) results in a submaximal assessment context, which differs from the AFT use in competition.

In this regard, athletes significantly improved their 3000-m times when using the LCP with respect to the HCP. The potential sources of such differences could be related to the greater ankle joint moments and the resulting changes in the muscle function, which could be operating at a lower shortening velocity [28]. Although the 3000-m improvements were a matter of few seconds, it resulted in worthwhile differences from the practical standpoint and was comparable to the effects of other footwear features. In this regard, Hoogakmer et al. [29] reported a ∼ 0.8%

improvement in 3000-m performance when reducing the shoe mass by 100 g in a group of recreational runners. Likewise, Rodrigo-Carranza et al. [30] observed that an HCP provided an improvement of ∼ 0.8 to 0.9% in 3000-m performance with respect to the same model without a plate in a group of recreationally and highly trained athletes.

Likewise, athletes displayed a better running economy when using the LCP with respect to the HCP, although after the 3000-m trial, no significant differences were observed between conditions. In this regard, it should be noted that the running economy deteriorates with the onset of fatigue, which seems to be related to a redistribution of the lower limbs' work from distal to the more demanding proximal joints [17]. Although an LCP has been shown to delay the onset of work redistribution with respect to a no plate condition during a prolonged run (i.e., 10-km at 90% of the LT) [17], no significant improvements were seen in our study with respect to the HCP. Further explorations with regard to the fatigue conditioning stimulus are required to fully understand the plate's role in this function.

It is also important to acknowledge certain limitations. First, despite our initial sample size was adequate for identifying 1–2% differences between conditions [19–21], the exclusion of three participants due to meeting the criterion of maximality possibly weakened our statistical power, affecting the accuracy of performance and running economy measurements under fatigue. Second, adding a control condition (without plate) would have provided an intriguing comparative to fully understand the performance implications of this footwear feature. However, no commercialized AFT models maintaining the same design without a plate were available. In addition, arranging a third maximal testing session for the highly-trained athletes recruited presented logistical challenges due to their competition schedules. Third, a single trial was performed in the fatigued state in
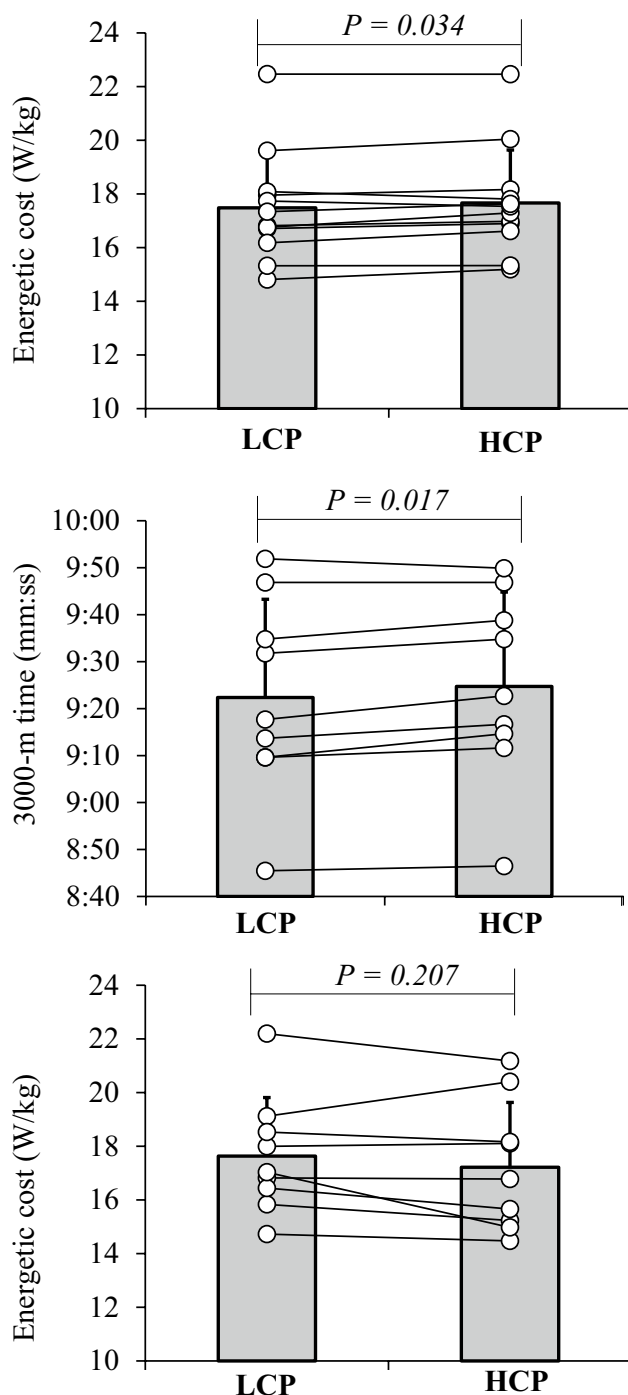
Fig. 3 Group and individual responses to the racing footwear models on the running energetic cost tested previously and after performing the 3000-m trial and on running performance. *LCP* low curvature plate, *HCP* high curvature plate. *Athletes did not meet the maximal effort criterion

pursuit of the athletes' comfort which restricted us to conducting an individual analysis [31]. This is a relevant issue given the comparison of a single trial could result in different outcomes compared to when multiple trials are averaged due to biological and technological errors [31]. Therefore, only the group response was here reported. Lastly, only highly trained male athletes were recruited, limiting the extrapolation of these results to other populations, such as recreational runners, who may respond differently to AFT [30].

5 Conclusion

The LCP model reduced the running energetic cost in a non-fatigued state, and these benefits persisted in the 3000-m trial. However, in a fatigued state, no significant differences between plate geometries were observed. From a practical standpoint, these results suggest a promising perspective on the individualized use of running shoes.

Declarations

Conflict of interest The authors declare no conflict of interest.

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