INFLUENCE OF ADVANCED FOOTWEAR TECHNOLOGY ON PERFORMANCE AND BIOMECHANICS DURING MOUNTAIN RUNNING

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The purpose of this study was to evaluate the effect of the advanced footwear technology (AFT) on performance and biomechanics during mountain running. Twelve male mountain-runners performed two running time-trials over a 5.19 km mountain circuit (1.68 km uphill, 1.56 km downhill and 1.95 km mixed) using conventional (CON) and carbon fibre plate shoes (CFP) in a randomized order (i.e., CON-CPF and CFP-CON). Total time, heart rate, RPE and biomechanical variables were registered. The AFT did not affect performance, heart rate, RPE and running power, but increased contact time and step length, decreasing step frequency in the order CON-CFP, mainly during the uphill and downhill segments. In conclusion, the AFT did not affect performance during mountain running, but the observed changes in the running biomechanics should be widely explored.

KEYWORDS: shoe, mountain races, rate of perceived exertion, running power meter.

INTRODUCTION: Factors affecting long-distance road running performance have been widely explored in the last decade (Ogueta-Alday & García-López, 2016). However, since 2017, when Nike® designed a new footwear concept (advanced footwear technology -AFT-), adding a carbon fiber plate, increasing the midsole thickness, and modifying both geometry and materials of the midsole (Nigg et al., 2021), numerous records have been broken (Muniz-Pardos et al., 2021). Recent studies have concluded that the AFT increases performance in long-distance road races by 2.0-2.6% (Rodrigo-Carranza et al., 2022), which could be due to: 1-the increase of the metatarsophalangeal joint stiffness, 2-the increase of the cushioning and comfort during running, 3-the "teeter-totter effect" (Nigg et al., 2021). Furthermore, an increase of stride length and contact time has been observed when using AFT (Rodrigo-Carranza et al., 2022).

The AFT has also been commercialized in mountain running (e.g., https://www.runnersworld.com/uk/gear/shoes/g44785342/carbon-plate-trail-shoes/), probably because the popularity of this sport has grown over the past few years, thus leading to an increase in the number of participants, competitions, and race formats (Corbí-Santamaría et al., 2023). However, the characteristics of these races are very different from those of road races, due to variations in ground conditions (soft *vs*. hard) and slope (uphill-downhill *vs*. flat), which impact running technique (Vernillo et al., 2017), and could potentially influence the effect of AFT on performance and biomechanics. To the best of our knowledge, no previous study has evaluated the effect of AFT on these variables during mountain running, which constitutes the main purpose of the present work.

METHODS: Twelve trained male mountain runners participated in this study (35.41 ± 9.48 years; 66.53 ± 6.14 kg and 1.74 ± 0.05 m). All of them had a minimum of 3 years of experience and regularly participated in mountain races of different distances. Their performance level was estimated by a maximal aerobic speed track and field test (maximal aerobic speed: 18.85 ± 1.11 km/h; VO_{2max}: 63.04 ± 5.75 ml/kg/min). All of them were informed of the benefits and risks of the investigation and written signed consent was obtained. The protocol was approved by the University Ethics Committee (REF 056-2023) and met the requirements of the Declaration of Helsinki for research on human beings.

One month before the tests, participants were required to have a new conventional mountain running shoe (CON), and 12 new carbon fiber plate mountain running shoes (CFP) from six

different manufacturers were provided to them in a randomized order. They were also required to use both types of shoes (i.e., CON and CFP) during running training, covering a distance of 50 to 100 km before the tests. All the shoes were weighted, and the CFP shoes' mass was similar to the CON shoes (296.3 ± 20.3 *vs.* 295.3 ± 28.6 g, P>0.05 and pη^2 = 0.001). The heel height (30.0 ± 5.0 *vs.* 26.5 ± 3.5 mm, P<0.05 and pη^2 = 0.354) and the forefoot height (24.4 ± 4.4 *vs.* 20.0 ± 4.1 mm, P<0.01 and pη^2 = 0.477) was higher in the CFP shoes than in the CON ones, without differences in the drop (5.7 ± 1.0 *vs.* 6.5 ± 1.5 mm, P>0.05 and pη^2 = 0.017).
The tests consisted of two 5.19 km mountain running time-trials (Set 1 and Set 2), with 30 minutes of rest in-between, using the two different types of shoes (CON and CFP) in a randomized order (Table 1). The participants were encouraged to run as fast as possible for each trial. The trail was located at an elevation ranging from 1,190 to 1,457 m above the sea level, and had an elevation gain of +305 m. It had three different sections: 1.68 km uphill, 1.56 km downhill and 1.95 km mixed. In general, the circuit followed well-marked trails and roads. The type of terrain, without having a high technical difficulty, represented the most common trails in mountain races (i.e., grass, loose stone, gravel and mud). The tests took place in autumn (November) and the weather conditions of that day were measured (temperature: 11°C; humidity: 92%; wind: 20 km/h WSW). The warm-up was standardized to take place 18 min before the first set and the re-warm-up 10 min before the second set. During the 30-minute recovery period, participants changed the shoes model and had the option to rehydrate with 250 cl of water and 250 cl of an isotonic drink.
The heart rate was registered during each set using a chest strap (Polar® H10, Polar Electro Oy, Finland) and one heart rate monitor (Polar® Vantage V2, Polar Electro Oy, Finland). This device was also used to register GPS coordinates, obtaining finishing time, section times and maximum pace. The running power, step frequency, step length, contact time, leg stiffness and vertical oscillation of the center of gravity were obtained using a running power meter (Stryd® Power meter, Stryd Inc., USA). This device has been recently validated to obtain spatiotemporal parameters of running (Rodríguez-Barbero et al., 2024). The RPE was measured using a Borg's 0–10 scale, and the participants had two familiarization sessions with this scale before the tests.
The results are expressed as mean ± SD. The SPSS+ statistical software was used (v. 26.0, IBM Corp., USA) for the data analysis. Two-way analysis of variance (ANOVA) with repeated measures was used to analyse the effect of the Shoe (i.e., CON and CFP) and the Set (i.e., 1 and 2) on the studied variables. The partial eta squared (pη^2) was calculated to measure the effect size (small: 0.01–0.059, moderate: 0.06–0.137, large: >0.137), as previous studies did (Corbí-Santamaría et al., 2023).

RESULTS: Table 1 shows that the shoes did not affect performance (*i.e.,* time), heart rate or running power, but had moderate to large influence on RPE, maximal pacing and some of the biomechanical variables (*i.e.,* step frequency, step length, contact time and vertical oscillation of the centre of gravity). The set had moderate to large influence on all the analysed variables except on the maximal heart rate. On the contrary, the combined effect of set and shoes was trivial to small in half of these variables (time, average and maximal heart rate, average and maximal power, leg stiffness) and moderate to large on RPE, maximal pacing, step frequency, step length, contact time and vertical oscillation of the centre of gravity. Complementary, the combined effect of set, shoes and segment was moderate only for the step frequency, which decreased when changing from CON to CFP shoes (and not from CFP to CON shoes), mainly during the uphill and downhill segments.
The performance and the RPE of the six participants that performed the two sets in the CON and CFP order were 1619.7 ± 164.7 and 1661.7 ± 175.3 s, and 8.9 ± 0.5 and 9.3 ± 0.5, respectively. For the six participants that performed the two sets in the CFP and CON order these variables were 1584.0 ± 140.0 and 1614.3 ± 122.4 s, and 9.1 ± 0.5 and 9.1 ± 0.5, respectively. Figure 1 shows that the order CON-CFP and CFP-CON affected differently the contact time, step frequency and step length when comparing sets 1 and 2.

Table 1: Results when using both conventional (CON) and carbon plate shoes (CFP) in the two-running time-trial sets (Set 1 and Set 2). Influence of the shoes (Shoe), the set (Set) and their interaction (Set x Shoe). Moderate and large effect sizes are highlighted in bold.

	SHOE		SET		Shoe	Set	SetxShoe
Variable	**CON**	**CFP**	**Set 1**	**Set 2**	**($p\eta^2$)**	**($p\eta^2$)**	**($p\eta^2$)**
Time (s)	1617.0±138.4	1622.8±156.5	1601.8±146.8	1638.0±146.3	0.016	**0.550**	0.032
Average heart rate (bpm)	163.2±16.1	163.0±17.4	164.8±16.8	161.5±16.5	0.004	**0.631**	0.010
Maximal heart rate (bpm)	174.0±15.3	173.7±16.3	173.8±15.5	173.8±16.1	0.024	0.000	0.024
RPE (0-10 scale)	9.0±0.5	9.2±0.5	9.0±0.5	9.2±0.5	**0.110**	**0.110**	**0.123**
Maximal pacing (s/km)	177.7±13.3	180.5±11.5	178.0±12.8	180.2±12.1	**0.184**	**0.132**	**0.206**
Average power (W)	305.6±26.6	304.2±29.8	308.3±29.6	301.4±26.3	0.016	**0.381**	0.025
Maximal power (W)	510.7±46.9	499.1±57.5	524.8±43.0	484.9±53.5	0.023	**0.278**	0.031
Step frequency (spm)	166.7±9.5	164.8±10.1	166.2±10.1	165.3±9.5	**0.438**	**0.161**	**0.482**
Step length (cm)	114.2±8.8	115.6±9.4	116.1±9.9	113.7±8.0	**0.135**	**0.452**	**0.221**
Contact time (ms)	280.6±57.3	284.4±64.9	279.3±59.3	285.7±62.9	**0.091**	**0.272**	**0.120**
Leg Stiffness (kN/m)	10.7±2.6	10.7±2.6	10.9±2.7	10.5±2.6	0.000	**0.232**	0.000
Vertical oscillation (cm)	7.1±1.1	7.2±1.1	7.2±1.1	7.1±1.1	**0.265**	**0.253**	**0.326**

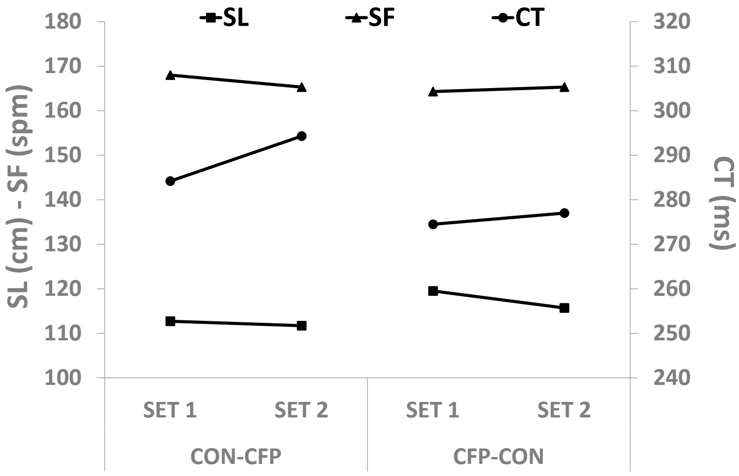

Figure 1: Step length (SL), step frequency (SF) and contact time (CT) registered during the sets 1 and 2 when using conventional-carbon fibre plate shoes (CON-CFP) and carbon plate-conventional shoes (CFP-CON).

DISCUSSION: The main findings of the present study were that AFT did not affect performance in mountain running but affected the runners' RPE and the running biomechanics. AFT increased both contact time and step length, and decreased step frequency. Performing the two time-trials (i.e., Set 1 and Set 2) in the same testing day induced fatigue on the runners during Set 2, without influence of the shoe type. The runners experienced a greater increase in their RPE during Set 2 when the order CON-CFP was used compared to CP-CON. The changes in running biomechanics were more pronounced in CON-CFP than in CP-CON.

The fact that AFT did not affect performance contrasts with previous findings in long-distance road running races, where it increased (Rodrigo-Carranza et al., 2022). This could be due to the differences between road and trail in ground characteristics (i.e., soft *vs.* hard) and slopes (i.e., uphill-downhill vs. flat). The AFT was specifically designed to flat asphalt road races, so its geometry and components must be optimized to improve performance in mountain running. The order CON-CFP during the Set 1-Set 2 produced higher changes in both RPE and running biomechanics than the order CFP-CON (Table 1 and Figure 1). This could be justified from three different perspectives. First, according to previous studies (Rodrigo-Carranza et al., 2022), the use of CFP increased the contact time and the step length, and consequently, at the same running speed, the step frequency decreased. Second, if the runners' perception of muscle soreness was lower when using CFP shoes than CON shoes in the Set 1 (it was not evaluated in the present study), as previous studies observed (Castellanos-Salamanca et al.,

2023), it could justify the differences in the RPE increase when comparing the CFP-CON order to the CON-CFP one. Third, it could be possible that the “motor perseveration” (Sombric and Torres-Oviedo, 2021) during the CFP-CON order was lower than during the CFP-CON one, which could be interpreted by the runners as a lower effort to complete the same task (i.e., running in the same circuit). Although a highest “motor perseveration” is commonly associated with a lowest motor function and a lowest adaptation of the motor tasks, and also with some pathologies and aging (Sombric and Torres-Oviedo, 2021), probably in the context of training and high sport performance its meaning could be different.
The main limitation of the study was to perform the two running sets in the same day, so the fatigue was the main independent variable affecting performance (Table 1). However, environmental conditions vary significantly in mountain races, including changes in ambient temperature and humidity. These variations affect both the runners’ effort capacity and their performance, as well as the ground mechanical characteristics and their interaction with footwear. Future studies should confirm, complement, or refuse the main findings of this work.

CONCLUSION: The AFT does not improve performance in mountain running, but it has an effect on running biomechanics, increasing the athletes contact time and step length, and decreasing the step frequency when running at the same speed. Future studies should analyze in more detail these last findings and the influence of the AFT on fatigue and muscle soreness during mountain races.

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