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Do Carbon-Plated Running Shoes with Different Characteristics Influence Physiological and Biomechanical Variables during a 10 km Treadmill Run?

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Abstract: Footwear properties can influence physiological and biomechanical variables, which may lead to positive changes in distance running performance. One innovative development in running shoe technology is adding carbon fiber plates to increase midsole bending stiffness. However, there are only a few studies investigating the influence of shoe conditions on both physiological and biomechanical variables, simultaneously, when running for longer than 5 min or for distances > 1 km. Hence, the purpose of the current study was to investigate the influence of different running shoe concepts with carbon fiber plates on physiological and biomechanical parameters during a 10 km treadmill run. Twenty-three athletes participated in the study, which comprised four measurement days for each subject. On the first day, subjects performed a treadmill exhaustion test to determine maximum oxygen uptake. On the second, third, and fourth days, each subject ran 10 km at 70% of their maximum oxygen uptake in one of three shoe models. Significant differences were found between the shoe conditions for the biomechanical parameters, but not for the physiological parameters. It seems that runners adjusted their running styles to the shoe conditions during the 10 km run to reduce the load on the lower extremities without compromising their endurance performance. These results may have practical implications for runners, coaches, and shoe manufacturers.

Keywords: oxygen uptake; performance; biomechanics; footwear

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1. Introduction

Distance running performance can be influenced by a variety of shoe factors. Multiple studies have reported that certain footwear characteristics, such as shoe mass, midsole bending stiffness (MBS), and foam midsole material, can influence both physiological [1–5] and biomechanical variables [6–8]. This, in turn, may result in positive changes in distance running performance.

Running economy (RE) is a determinant of distance running performance and is defined as the rate of oxygen consumption at a given velocity of submaximal running [9,10].

Shoe mass is a frequently examined footwear property that is related to RE and performance. Greater shoe mass can lead to increased energy consumption and thus to a reduction in RE [1,11]. In 3000 m time trials, Hoogkamer et al. [1] showed that RE degrades and running time increases 0.78% for each additional 100 g per shoe. Furthermore, previous research found that heavier footwear has significant effects on biomechanical parameters such as ankle joint angles, ankle moments, and plantar pressure during running [12].

The effect of increased MBS is considered a key factor for optimizing running shoes. It is closely linked to individual runner characteristics (e.g., anthropometrics, strength capacities, running style), but also related to running speed [13,14] and the rollover feeling [15]. It has become increasingly common to use carbon fiber plates in running shoes to increase MBS to improve distance running performance [6,7]. Recent analyses have shown that these technological advances in running shoes have resulted in significant improvements in international half marathon and marathon best times among world-class athletes [16,17]. However, research shows inhomogeneous results of the effects of MBS on RE. According to the findings of Roy and Stefanyshyn [18], carbon fiber plates in running shoes can reduce the energy cost of running by approximately 1%. This varies depending on the plates' design (e.g., curved, flat, length) [19]. Recent studies have found that running with the "Nike Vaporfly 4%" can lead to an increased running economy of approximately 4% on average [6,20]. In addition to varying MBS to improve running performance, several studies have investigated the effects of midsole stiffness [5,21], midsole thickness [22] and midsole structure [23]. However, Healey and Hoogkamer [24] found that the curved carbon fiber plates only play a small role in the 4% metabolic savings generated by the "Nike Vaporfly 4%". The authors suggest that the savings likely result from a combination of and interaction between the midsole foam, shoe geometry, and plate.

From a biomechanical perspective, research shows that increased MBS reduces negative work at the metatarsophalangeal (MTP) joint and influences joint mechanics in the ankle and knee [7,25]. Furthermore, Hoogkamer et al. [7] concluded that the energy savings from the curved carbon fiber plates provided a clever lever effect on the joint ankle mechanics, a stiffening effect of the plate on the MTP joint, and superior energy storage in the midsole foam. However, current studies have reported conflicting results in terms of biomechanical variables [26]. Results of spatiotemporal parameters (e.g., ground contact time or step frequency) were inhomogeneous [6–8,20]. It can be concluded that there is currently no plausible explanation for improved running performance based on biomechanical parameters.

To the best of the authors' knowledge, there are only few studies that have investigated the influence of different footwear conditions on both physiological and biomechanical variables simultaneously during endurance runs longer than 1 km. However, it seems necessary to examine the long-term effects of the different shoe components on running performance in order to be able to explain (half-) marathon personal best times using physiological and biomechanical variables.

Therefore, the purpose of this study was to investigate the influence of different running shoe concepts with carbon fiber plates on physiological (e.g., oxygen consumption ($\dot{V}O_2$)) and biomechanical (e.g., peak tibial acceleration (PTA)) parameters in runners during a 10 km run. We hypothesized that different shoe properties (midsole bending stiffness, midsole stiffness) but similar shoe mass have an influence on a) biomechanical variables and b) physiological variables when running at 70% of subjects' maximum oxygen uptake ($\dot{V}O_2max$).

2. Materials and Methods

2.1. Participants

Twenty-three athletes without any injuries in the last six months participated in this study (mean $\pm$ SD; age: 35.2 $\pm$ 10.4 years, body height: 176.7 $\pm$ 5.1 cm, body mass: 70.3 $\pm$ 8.4 kg, weekly running distance: 45.3 $\pm$ 23.6 km). The subjects were informed about the purpose and design of the study, signed an informed consent document, and completed a form with their personalized data. All procedures were performed in accordance with the recommendations of the Declaration of Helsinki. This study was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences of the Chemnitz University of Technology (#101501815).

2.2. Footwear Conditions

Three shoes with different construction concepts were used in this study (Figure 1). The shoes, the "Puma Fast-FWD" (S1), the "Puma Fast-R" (S2) and the "Nike Vaporfly Next%" (S3) (UK sizes 8 and 10), differed in sole geometry and in the type of carbon fiber plates incorporated in the midsole material. The shoes were similar with regard to weight.

Figure 1. The test shoes used in this study. Left: "Puma Fast-FWD" (**S1**), Middle: "Puma Fast-R" (**S2**) and Right: "Nike Vaporfly Next%" (**S3**).

To quantify both midsole stiffness and midsole bending stiffness, the shoes were tested in a servo-hydraulic device (HC10, Zwick GmbH & Co. KG, Ulm, Germany) as described in Schwanitz and Odenwald [27], and Bräuer et al. [15] (Table 1).

Table 1. Characteristics of shoe conditions for men's size UK8.

	Weight [g]	Bending Stiffness [N]	Rearfoot Stiffness [N/mm]	Forefoot Stiffness [N/mm]	Rearfoot Height [mm]	Forefoot Height [mm]	Rearfoot Energy Lost [%]	Forefoot Energy Lost [%]
S1	172.4	130	284	215	25.7	26.3	21	21
S2	203.0	104	209	226	31.0	28.2	19	12
S3	183.1	107	194	180	29.2	29.4	14	15

2.3. Experimental Setup and Procedures

The study comprised four measurement days for each subject. On the first day, the subjects performed a treadmill exhaustion test to determine $\dot{V}O_2max$. During the second, third, and fourth measurement days, each subject ran 10 km in different shoe models (S1, S2, and S3) in randomized order at an individual speed based on the results of the exhaustion test. The time of the measurements could be chosen freely by the subjects. However, measurements should always take place at the same time with a minimum of one week between measurement days in order to minimize the influence of the time of day and to avoid training effects. Previous studies reported good reliability using this procedure [28,29]. In addition, inertial sensors (Opal-Sensor, APDM, Portland, OR, USA, mass 25 g) were used to record biomechanical parameters. A stationary metabolic analysis system (Metalyzer 3B, CORTEX Biophysik GmbH, Leipzig, Germany) was used to measure oxygen consumption ($\dot{V}O_2$) during running on a treadmill (h/p/cosmos® quasar 5.0, h/p/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany). Prior to data collection, the system was calibrated according to manufacturer's recommendations using ambient air and known gas concentrations. The volume was calibrated using a 3-liter syringe. Heart rate (HR) was recorded using a Polar chest strap (Polar®, H7, Kempele, Finland). The incline of the treadmill was set at 1% to compensate for air resistance for all running sessions [30,31]. To prevent falls runners wore a security belt during all treadmill tests.

2.3.1. Exhaustion Test

Subjects wore their own shoes for the exhaustion test. After a warm-up of at least 5 min at their individual pace to familiarize themselves with the treadmill, participants completed a modified ramp protocol according to [32]. The ramp test to exhaustion was performed to determine $\dot{V}O_2max$ as a baseline for the subsequent 10 km runs. After resting for 2 min, the treadmill speed was set to 8 km/h for 3 min, and velocity was then increased by 1.2 km/h every minute until volitional exhaustion or abort criteria occurred, such as cardiovascular problems or pain [33]. The highest $\dot{V}O_2$ over 30 s was considered $\dot{V}O_2max$ [34].

2.3.2. 10 km Tests

Subjects began with a 5-min warm-up trial at a self-selected speed in their own shoes. Following the warm-up, subjects completed a 10 km run with the first pair of running shoes to be tested. Following the methods of previous studies, running speed was set individually at 70% of $\dot{V}O_2$max for each subject [35,36]. Two lightweight inertial measurement units (IMU) combining a tri-axial accelerometer (measurement range 1982 m/s^2) and a tri-axial gyroscope (measurement range $\pm 2000°/s$) were used to measure biomechanical data during the 10 km tests. One IMU was attached to the shaved skin at the medial aspect and midway between the malleolus and the plateau of the right tibia using double-sided adhesive tape. Furthermore, an elastic strap and a compression sleeve for calves were used to stabilize the accelerometer and prevent excessive movements due its own weight. The sensate axis of the IMU was aligned with the longitudinal axis of the tibia according to Hennig et al. [37]. The second sensor was attached to the heel cap of the right running shoe using a sturdy lightweight sensor mount printed with a 3D printer.

2.4. Data Analysis

Raw data from the IMUs were analyzed in post-processing using MATLAB 2021a (MathWorksTM, Natick, MA, USA). Prior to all processing steps, data were filtered using a zero-lag Butterworth low-pass filter (accelerometers: 4th order at 80 Hz; gyroscopes: 4th order at 50 Hz) to remove noise. To separate the strides in continuous data, the vertical acceleration signal of the IMU mounted to the heel cap was zero-lag Butterworth high-pass filtered (80 Hz). The first peak in the filtered signal was defined as the initial ground contact of the foot [38,39].

Biomechanical variables

To examine shoe rollover, the maximum angular velocity in the sagittal plane of the shoe was analyzed according to [15], and the peak angular velocity (PAV) was extracted within 200 ms after initial ground contact. The angular velocity in the frontal plane of the shoe was used to determine the peak eversion velocity (evVel) [40]. To determine the heel strike angle at initial ground contact time (HSA), the shoe orientation angle in the sagittal plane was calculated using data from the IMU mounted to the heel cap as described in Mitschke et al. [41]. The maximum IMU acceleration (within 200 ms after initial ground contact) at the tibia was used to identify peak tibial acceleration (PTA).

Physiological variables

HR and $\dot{V}O_2$ were provided by Metasoft Studio (CORTEX Biophysik GmbH, Leipzig, Germany). Relative oxygen uptake ($rel.\ \dot{V}O_2$) was calculated by dividing subjects' VO_2 by their individual body mass (kg). A standard method of assessing RE is to look at the amount of $\dot{V}O_2$ required to run a kilometer at a predefined running speed [42]. The following Equation (1) was used to determine RE:

$$RE = \frac{rel.\ \dot{V}O_2}{v_{\ 70\%\ of\ rel.\ \dot{V}O_2 max}} \tag{1}$$

For the exhaustion test, $\dot{V}O_2max$ was calculated as the mean of the highest 30 s to volitional exhaustion. For the 10 km tests, both biomechanical and physiological variables were calculated from the mean of all strides over the last 5 min of the run.

2.5. Statistical Analysis

Mean and standard deviations (mean $\pm$ SD) were calculated for the biomechanical and physiological variables. Given that the variables were normally distributed according to the Shapiro–Wilk test, a one-way analysis of variance (ANOVA) for repeated measurements followed by the Bonferroni post-hoc test was used to determine whether differences existed between the footwear conditions regarding biomechanical and physiological variables. Statistical significance was set at $\alpha = 0.05$ for all analyses. In addition, effect size (Cohen's

d) was calculated to quantify the magnitude of differences when statistical significance was found. The coefficients were interpreted as trivial (d < 0.2), small (d < 0.5), medium (d < 0.8), or large effects (d ≥ 0.8) [43].

3. Results

3.1. Exhaustion Test

Table 2 represents the results from the exhaustion test.

Table 2. Group mean ± standard deviation of the exhaustion test for physiological variables (all subjects).

	Rel. $\dot{V}O_2max$ [mL/kg/min]	v_{max} [km/h]	HR_{max} [bpm]	70% of rel. $\dot{V}O_2max$ [mL/kg/min]	$v_{70\%}$ of rel. $\dot{V}O_2max$ [km/h]	$HR_{70\%}$ of rel. $\dot{V}O_2max$ [bpm]
Mean ± SD	59.3 ± 7.8	18.5 ± 2.1	185.5 ± 10.6	41.5 ± 5.4	12.2 ± 1.6	155.2 ± 12.6

3.2. 10 km Tests

3.2.1. Physiological variables

The physiological data showed no significant differences between shoe conditions. (Figure 2a–c). For rel. $\dot{V}O_2$, the range was between 42.0 ± 5.4 mL/min/kg for S2 and 42.3 ± 5.3 mL/min/kg for S1. Similar trends were seen in RE and HR. S2 showed the best values for RE (207.8 ± 13.1 mL/kg/km) and for HR (162.1 ± 14.4 bpm), and S1 the worst values (209.5 ± 12.8 mL/kg/km), respectively (164.6 ± 16.6 bpm).

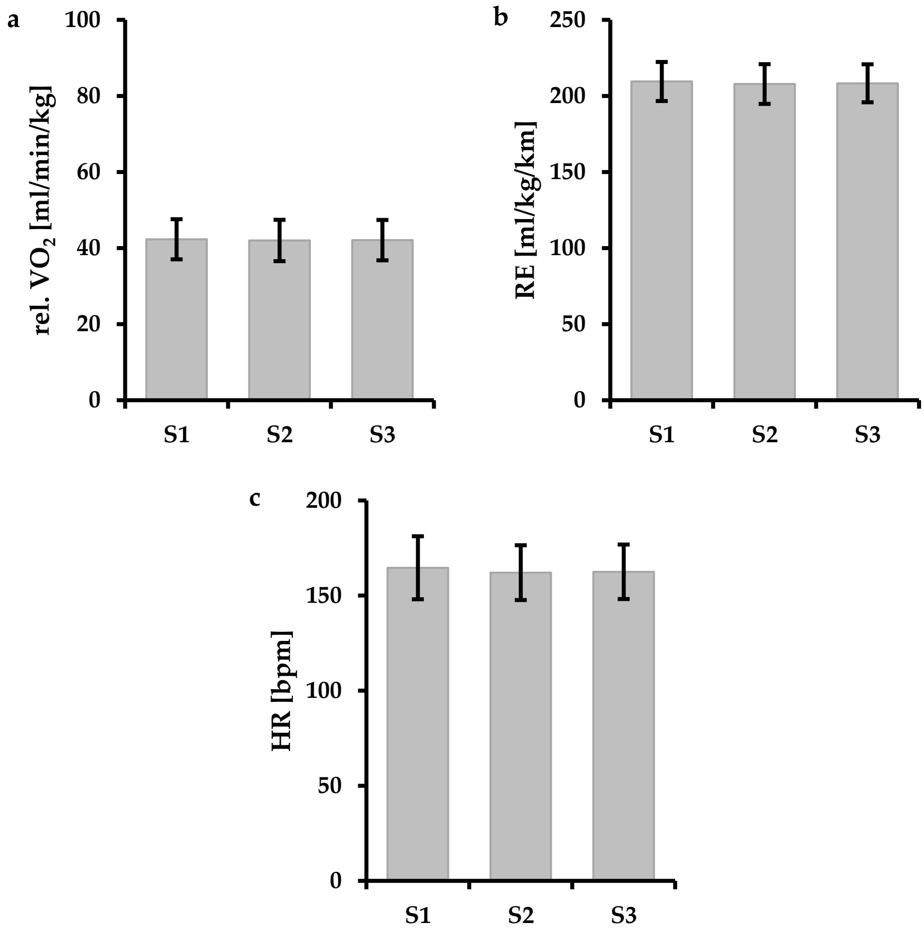

Figure 2. Comparison of shoe conditions. Panel (**a**): relative oxygen consumption (rel. $\dot{V}O_2$); Panel (**b**): running economy (RE), and Panel (**c**): heart rate (HR). No statistical differences were found for any variables between shoe conditions.

3.2.2. Biomechanical Variables

Figure 3 shows the results for biomechanical parameters of the 10 km tests. For PAV, the ANOVA revealed significant differences ($p = 0.004$) and a small effect (d = 0.45) between S1 (757.8 ± 105.2 deg/s) and S3 (814.1 ± 142.7 deg/s) (Figure 3a).

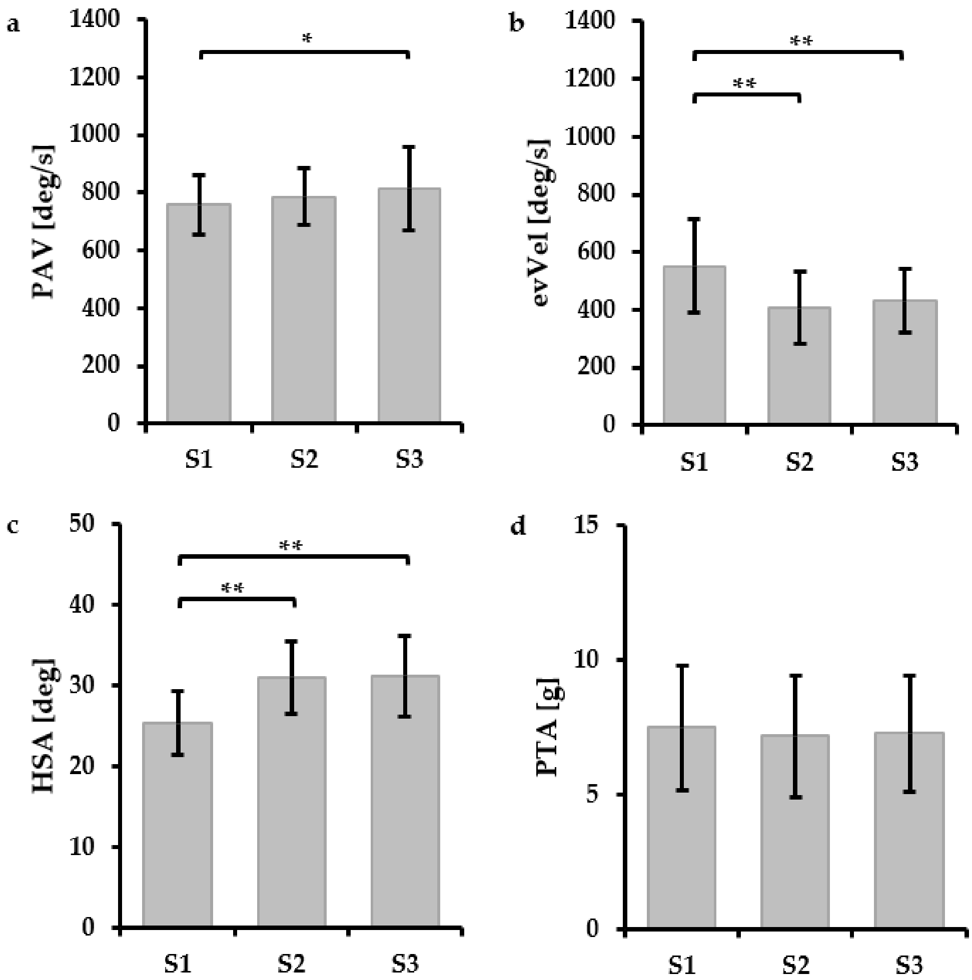

Figure 3. Comparison of shoe conditions for: (**a**) peak angular velocity (PAV); (**b**) maximum eversion velocity; (**c**) heal strike angle and (HSA); and (**d**) peak tibial acceleration (PTA). Significant differences between shoe conditions are marked with * ($p < 0.05$) and ** ($p < 0.001$).

When comparing evVel, highly significant differences ($p < 0.001$) and large effects (d ≥ 0.8) were found between S1 (552.1 ± 162.2 deg/s) and S2 (407.3 ± 124.9 deg/s) and between S1 and S3 (431.5 ± 111.4 deg/s); ($p < 0.001$; d ≥ 0.8) (Figure 3b).

The analysis of HSA revealed the lowest value for S1 (25.2 ± 4.0 deg) and the highest value for S3 (31.1 ± 5.1 deg) (Figure 3c). The ANOVA showed highly significant differences between S1 and S2 ($p < 0.001$) and between S1 and S3 ($p < 0.001$). Cohen´s d showed large effects (d ≥ 0.8) for both significant pairwise comparisons. No significant differences were found for PTA when comparing shoe conditions (Figure 3d). The values were 7.5 ± 2.3 g for S1, 7.2 ± 2.3 g for S2 and 7.3 ± 2.2 g for S3.

4. Discussion

The aim of the present study was to investigate the influence of different running shoe concepts with carbon fiber plates and different material properties on both physiological and biomechanical variables during a 10 km treadmill run. To provoke great influence on the examined parameters, shoes with different materials and geometries, but similar weights were used. We hypothesized that these distinctly different footwear conditions influence (a) biomechanical and (b) physiological variables.

The biomechanical results show that the subjects adjusted their running style in response to the different shoe properties. Therefore, hypothesis (a) was confirmed.

PAV (757.8 ± 105.2 deg/s) and HSA (25.2 ± 4.0 deg) were significantly lower in S1, compared to S2 and S3. In addition, evVel (552.1 ± 162.2 deg/s) was significantly higher in S1 in contrast to the other shoes. Contrary to the mentioned parameters, PTA was not influenced by shoe conditions. In general, no significant differences were found for the biomechanical variables when comparing S2 and S3. It appears that running in the shoe with the highest midsole stiffness in the rearfoot and the lowest rearfoot height (Table 1) led to a distinct adjustment of the running style as a mechanism of shock absorption during the landing phase. The results HSA and PAV were consistent with the findings of Heidenfelder et al. [44]. The authors found significantly lower values for the shoe with the flattest construction and the lowest cushioning. Additionally, Law et al. [45] also demonstrated that a shoe with thinner midsoles can lead to lower HSA due to reduced cushioning and subsequently to greater discomfort [46]. For evVel, a similar trend as in our study was found by other authors. For example, the lowest evVel for the shoe with the highest rearfoot cushioning and the highest evVel for the shoe with the hardest midsole was observed by Sterzing et al. [47] when comparing six shoes differing in midsole hardness, and by Mitschke et al. [40] when comparing three shoes with different midsole properties when running at different velocities. It seems that runners reduced HSA and PAV and increased evVel to protect the lower extremities from impact forces during the landing phase when running in flatter shoes with less cushioning. In the current study, this led to PTA values that were similar for all three shoe conditions. This is in contrast to most studies that found higher values for PTA or force rising rates (measured with force plates) when running in harder shoes [47–49]. However, most of these data were examined on short-term measurements on treadmills (<5 min), short outdoor tracks (<400 m), or based on only a few steps in the laboratory. In our study, subjects ran 10 km at 70% of their $\dot{V}O_2$max, and they had approximately 9 km to adapt their running style to each shoe condition to optimize the load on lower extremities. Therefore, longer runs may generate more realistic results.

In contrast to the biomechanical parameters, no significant differences were found between shoe conditions for any physiological parameters. Therefore, hypothesis (b) had to be rejected.

In this study, shoe conditions varied distinctly (Table 1) in terms of MBS, rearfoot and forefoot cushioning, as well as rearfoot and forefoot height. However, shoe mass was similar. Numerous studies have shown that different shoe characteristics, such as foam midsole material, MBS, and shoe mass, can influence running performance as well as biomechanical variables. Studies investigating the influence of shoe mass on physiological variables report lower energy consumption and better RE when running in shoes with lower mass [1,50]. It has been reported that weight differences between shoes of more than 100 g per shoe lead to longer running times [1] and increased oxygen uptake of approximately 1% [50]. To avoid effects of shoe mass on physiological parameters, shoes with similar mass were used in the present study—the difference between the lightest shoe (S1: 172.4 g) and heaviest shoe (S2: 203.0 g) was approximately 30 g. Thus, the focus in this study was on the influence of footwear characteristics on the physiological parameters of MBS and cushioning.

The influence of MBS on physiological parameters has been examined in several studies. However, the findings are not consistent. On the one hand, an increase in MBS leads to a decrease in energetic cost of running or improved RE [6,13,18]. In contrast, Sakaguchi et al. [51] reported no positive effects on RE when increasing MBS. Furthermore, Healey and Hoogkamer [24] proposed decreasing MBS by cutting the carbon fiber plate of the "Nike Vaporfly 4%" (six medio-lateral cuts) did not significantly affect RE. In a study by Roy and Stefanyshyn [18], three identical shoes were used to investigate the influence of RE when adjusting MBS by inserting carbon plates with differing stiffness. The authors found a "U-shaped" curve relationship between MBS and RE and concluded that a running shoe with medium MBS improves RE compared to more flexible or stiffer MBS. In the present study, MBS ranged from 104 to 130 N/mm. Comparing the reported MBS values with the aforementioned studies is difficult because of the different test procedures used to determine MBS. We found no significant differences in physiological variables between shoe conditions. However, our data shows the same tendency as found by [6,13,18]. Shoes S2 and S3 (lower MBS) showed lower HR, rel. $\dot{V}O_2$, and RE than S1 (highest MBS). One reason for similar performance results may be the additional influence of midsole stiffness.

Adjusting the midsole stiffness to enhance running performance has been investigated in several studies [5,21,52]. However, adjusting midsole stiffness is also controversial. For example, Frederick et al. [53] reported lower oxygen consumption while running in shoes with softer midsoles. In contrast, Bosco and Rusko [54] provided data showing greater values for oxygen consumption when running in shoes with softer midsoles compared to harder shoes. Additionally, Mitschke et al. [21] found no significant differences in rel. $\dot{V}O_2$ or HR when running below and slightly above the individual ventilatory threshold in distinctly different shoe conditions (cushioning and energy loss). Our results show that neither MBS nor midsole properties influenced physiological variables in our study.

It seems that runners adjusted their running styles, especially the foot strike pattern, during the 10 km run at 70% of rel. $\dot{V}O_2$max to reduce the load on lower extremities. However, RE, HR, or rel. $\dot{V}O_2$ were not affected by the adapted running styles. Running at higher velocities (e.g., at 75 or 80% $\dot{V}O_2$max) could lead to greater differences in biomechanical and physiological parameters.

This study has a few limitations that should be mentioned. First, our test group consisted mainly of recreational runners with a wide range of running speeds for the 10 km tests (8.0 to 14.2 km/h), since RE improvement be speed dependent [14]. The runners in this study preferred stiffer shoes when running velocities over 17 km/h. Future studies should focus on high-level runners who can achieve the required running speed. Second, in our study we did not collect data about the perception of footwear. Since there is evidence relating to improved running economy when wearing more comfortable compared to less comfortable footwear [55], follow-up studies should include subjective measurements. Third, compared to outdoor running, running on the treadmill shows some differences in terms of biomechanical parameters, such as sagittal foot strike angle or knee flexion at foot strike [56]. These small differences could be due to insufficient experience running on a treadmill, surface stiffness, and differences in air resistance, and result in limited transferability to outdoor measurements, since there is evidence that RE differs between treadmill and track running [57]. Future studies should be conducted under field conditions to achieve more realistic results.

5. Conclusions

Our study found that running at 70% of rel. $\dot{V}O_2$max in shoes with different characteristics impacts biomechanical parameters, but does not influence physiological parameters. It seems that runners adapt their running style to different shoe conditions to reduce impact forces during landing without compromising their endurance performance. Our test conditions were limited to a laboratory setting when using a stationary metabolic analysis system. Therefore, subsequent studies based on this methodology and using mobile spirometry in combination with the IMUs should be performed under field conditions to obtain more realistic information, since running kinematics differ under laboratory conditions.

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References

1. Hoogkamer, W.; Kipp, S.; Spiering, B.A.; Kram, R. Altered Running Economy Directly Translates to Altered Distance-Running Performance. *Med. Sci. Sports Exerc.* **2016**, *48*, 2175–2180. [CrossRef] [PubMed]
2. Dinato, R.C.; Cruz, R.; Azevedo, R.A.; Hasegawa, J.S.; Silva, R.G.; Ribeiro, A.P.; Lima-Silva, A.E.; Bertuzzi, R. Footwear designed to enhance energy return improves running economy compared to a minimalist footwear: Does it matter for running performance? *Braz. J. Med. Biol. Res.* **2021**, *54*, e10693. [CrossRef] [PubMed]
3. Hébert-Losier, K.; Finlayson, S.J.; Driller, M.W.; Dubois, B.; Esculier, J.-F.; Beaven, C.M. Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *J. Sport Health Sci.* **2022**, *11*, 275–284. [CrossRef]
4. Joubert, D.P.; Jones, G.P. A comparison of running economy across seven highly cushioned racing shoes with carbon-fibre plates. *Footwear Sci.* **2022**, *14*, 71–83. [CrossRef]
5. Worobets, J.; Wannop, J.W.; Tomaras, E.; Stefanyshyn, D. Softer and more resilient running shoe cushioning properties enhance running economy. *Footwear Sci.* **2014**, *6*, 147–153. [CrossRef]
6. Hoogkamer, W.; Kipp, S.; Frank, J.H.; Farina, E.M.; Luo, G.; Kram, R. A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. *Sports Med.* **2018**, *48*, 1009–1019. [CrossRef]
7. Hoogkamer, W.; Kipp, S.; Kram, R. The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. *Sports Med.* **2019**, *49*, 133–143. [CrossRef]
8. Hunter, I.; McLeod, A.; Valentine, D.; Low, T.; Ward, J.; Hager, R. Running economy, mechanics, and marathon racing shoes. *J. Sports Sci.* **2019**, *37*, 2367–2373. [CrossRef]
9. Conley, D.L.; Krahenbuhl, G.S. Running Economy and Distance Running Performance of Highly Trained Athletes. *Med. Sci. Sports Exerc.* **1980**, *12*, 357–360. [CrossRef]
10. Barnes, K.R.; Kilding, A.E. Strategies to Improve Running Economy. *Sports Med.* **2015**, *45*, 37–56. [CrossRef]
11. Fuller, J.T.; Bellenger, C.R.; Thewlis, D.; Tsiros, M.D.; Buckley, J.D. The Effect of Footwear on Running Performance and Running Economy in Distance Runners. *Sports Med.* **2015**, *45*, 411–422. [CrossRef] [PubMed]
12. Hoitz, F.; Vienneau, J.; Nigg, B.M. Influence of running shoes on muscle activity. *PLoS ONE* **2020**, *15*, e0239852. [CrossRef] [PubMed]
13. Willwacher, S.; König, M.; Braunstein, B.; Goldmann, J.-P.; Brueggemann, P. The gearing function of midsole longitudinal bending stiffness in running. *Footwear Sci.* **2013**, *5*, S109–S111. [CrossRef]
14. Day, E.; Hahn, M. Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent. *Footwear Sci.* **2020**, *12*, 3–13. [CrossRef]
15. Bräuer, S.; Kiesewetter, P.; Milani, T.L.; Mitschke, C. The 'Ride' Feeling during Running under Field Conditions—Objectified with a Single Inertial Measurement Unit. *Sensors* **2021**, *21*, 5010. [CrossRef]
16. Bermon, S.; Garrandes, F.; Szabo, A.; Berkovics, I.; Adami, P.E. Effect of Advanced Shoe Technology on the Evolution of Road Race Times in Male and Female Elite Runners. *Front. Sports Act. Living* **2021**, *3*, 653173. [CrossRef]
17. Senefeld, J.W.; Haischer, M.H.; Jones, A.M.; Wiggins, C.C.; Beilfuss, R.; Joyner, M.J.; Hunter, S.K. Technological advances in elite marathon performance. *J. Appl. Physiol.* **2021**, *130*, 2002–2008. [CrossRef]
18. Roy, J.-P.R.; Stefanyshyn, D.J. Shoe Midsole Longitudinal Bending Stiffness and Running Economy, Joint Energy, and EMG. *Med. Sci. Sports Exerc.* **2006**, *38*, 562–569. [CrossRef]
19. Nigg, B.M.; Cigoja, S.; Nigg, S.R. Effects of running shoe construction on performance in long distance running. *Footwear Sci.* **2020**, *12*, 133–138. [CrossRef]

20. Barnes, K.R.; Kilding, A.E. A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes. *Sports Med.* **2019**, *49*, 331–342. [CrossRef]
21. Mitschke, C.; Karger, K.; Milani, T.L. Differences in Mechanical Midsole Characteristics of Running Shoes Do Not Influence Physiological Variables in Aerobic and Anaerobic Running. *J. Hum. Kinet.* **2019**, *69*, 29–38. [CrossRef] [PubMed]
22. Chambon, N.; Delattre, N.; Guéguen, N.; Berton, E.; Rao, G. Is midsole thickness a key parameter for the running pattern? *Gait Posture* **2014**, *40*, 58–63. [CrossRef] [PubMed]
23. Wunsch, T.; Alexander, N.; Kröll, J.; Stöggl, T.; Schwameder, H. Effects of a leaf spring structured midsole on joint mechanics and lower limb muscle forces in running. *PLoS ONE* **2017**, *12*, e0172287. [CrossRef] [PubMed]
24. Healey, L.A.; Hoogkamer, W. Longitudinal bending stiffness does not affect running economy in Nike Vaporfly Shoes. *J. Sport Health Sci.* **2022**, *11*, 285–292. [CrossRef] [PubMed]
25. Cigoja, S.; Firminger, C.R.; Asmussen, M.J.; Fletcher, J.R.; Edwards, W.B.; Nigg, B.M. Does increased midsole bending stiffness of sport shoes redistribute lower limb joint work during running? *J. Sci. Med. Sport* **2019**, *22*, 1272–1277. [CrossRef]
26. Patoz, A.; Lussiana, T.; Breine, B.; Gindre, C. The Nike Vaporfly 4%: A game changer to improve performance without biomechanical explanation yet. *Footwear Sci.* **2022**. [CrossRef]
27. Schwanitz, S.; Odenwald, S. Long-term Cushioning Properties of Running Shoes. *Eng. Sport* **2008**, *7*, 95–100. [CrossRef]
28. Driller, M.; Brophy-Williams, N.; Walker, A. The Reliability of a 5km Run Test on a Motorized Treadmill. *Meas. Phys. Educ. Exerc. Sci.* **2017**, *21*, 121–126. [CrossRef]
29. Saunders, P.U.; Pyne, D.B.; Telford, R.D.; Hawley, J.A. Reliability and Variability of Running Economy in Elite Distance Runners. *Med. Sci. Sports Exerc.* **2004**, *36*, 1972–1976. [CrossRef]
30. Hanson, N.J.; Berg, K.; Deka, P.; Meendering, J.R.; Ryan, C. Oxygen Cost of Running Barefoot vs. Running Shod. *Int. J. Sports Med.* **2011**, *32*, 401–406. [CrossRef]
31. Jones, A.M.; Doust, J.H. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J. Sports Sci.* **1996**, *14*, 321–327. [CrossRef] [PubMed]
32. Lourenço, T.F.; Martins, L.E.B.; Tessutti, L.S.; Brenzikofer, R.; Macedo, D.V. Reproducibility of an Incremental Treadmill $\dot{V}o_2$max Test with Gas Exchange Analysis for Runners. *J. Strength Cond. Res.* **2011**, *25*, 1994–1999. [CrossRef] [PubMed]
33. Steinacker, J.M.; Liu, Y.; Reißnecker, S. Abbruchkriterien Bei Der Ergometrie. *Dtsch. Z. Sportmed.* **2002**, *53*, 228–229.
34. Robergs, R.A.; Dwyer, D.; Astorino, T. Recommendations for Improved Data Processing from Expired Gas Analysis Indirect Calorimetry. *Sports Med.* **2010**, *40*, 95–111. [CrossRef]
35. Xu, F.; Montgomery, D.L. Effect of Prolonged Exercise at 65 and 80 % of VO_2max on Running Economy. *Int. J. Sports Med.* **1995**, *16*, 309–313. [CrossRef]
36. Scharhag-Rosenberger, F.; Meyer, T.; Gäßler, N.; Faude, O.; Kindermann, W. Exercise at given percentages of VO2max: Heterogeneous metabolic responses between individuals. *J. Sci. Med. Sport* **2010**, *13*, 74–79. [CrossRef]
37. Hennig, E.M.; Milani, T.L.; Lafortune, M.A. Use of Ground Reaction Force Parameters in Predicting Peak Tibial Accelerations in Running. *J. Appl. Biomech.* **1993**, *9*, 306–314. [CrossRef]
38. Mitschke, C.; Heß, T.; Milani, T.L. Which Method Detects Foot Strike in Rearfoot and Forefoot Runners Accurately when Using an Inertial Measurement Unit? *Appl. Sci.* **2017**, *7*, 959. [CrossRef]
39. Maiwald, C.; Dannemann, A.; Gaudel, J.; Oriwol, D. A simple method to detect stride intervals in continuous acceleration and gyroscope data recorded during treadmill running. *Footwear Sci.* **2015**, *7*, S143–S144. [CrossRef]
40. Mitschke, C.; Öhmichen, M.; Milani, T.L. A Single Gyroscope Can Be Used to Accurately Determine Peak Eversion Velocity during Locomotion at Different Speeds and in Various Shoes. *Appl. Sci.* **2017**, *7*, 659. [CrossRef]
41. Mitschke, C.; Zaumseil, F.; Milani, T.L. The influence of inertial sensor sampling frequency on the accuracy of measurement parameters in rearfoot running. *Comput. Methods Biomech. Biomed. Eng.* **2017**, *20*, 1502–1511. [CrossRef] [PubMed]
42. Foster, C.; Lucia, A. Running Economy: The Forgotten Factor in Elite Performance. *Sports Med.* **2007**, *37*, 316–319. [CrossRef] [PubMed]
43. Cohen, J. A Power Primer. *Psychol. Bull.* **1992**, *112*, 155–159. [CrossRef] [PubMed]
44. Heidenfelder, J.; Sterzing, T.; Bullmann, M.; Milani, T.L. Heel strike angle and foot angular velocity in the sagittal plane during running in different shoe conditions. *J. Foot Ankle Res.* **2008**, *1*, O16. [CrossRef]
45. Law, M.H.C.; Choi, E.M.F.; Law, S.H.Y.; Chan, S.S.C.; Wong, S.M.S.; Ching, E.C.K.; Chan, Z.Y.S.; Zhang, J.H.; Lam, G.W.K.; Lau, F.O.Y.; et al. Effects of footwear midsole thickness on running biomechanics. *J. Sports Sci.* **2019**, *37*, 1004–1010. [CrossRef]
46. Lieberman, D.E.; Venkadesan, M.; Werbel, W.A.; Daoud, A.I.; D'Andrea, S.; Davis, I.S.; Mang'Eni, R.O.; Pitsiladis, Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **2010**, *463*, 531–535. [CrossRef]
47. Sterzing, T.; Schweiger, V.; Ding, R.; Cheung, J.T.-M.; Brauner, T. Influence of rearfoot and forefoot midsole hardness on biomechanical and perception variables during heel-toe running. *Footwear Sci.* **2013**, *5*, 71–79. [CrossRef]
48. Mitschke, C.; Kiesewetter, P.; Milani, T.L. The Effect of the Accelerometer Operating Range on Biomechanical Parameters: Stride Length, Velocity, and Peak Tibial Acceleration during Running. *Sensors* **2018**, *18*, 130. [CrossRef]
49. Heidenfelder, J.; Sterzing, T.; Milani, T.L. Systematically modified crash-pad reduces impact shock in running shoes. *Footwear Sci.* **2010**, *2*, 85–91. [CrossRef]
50. Fuller, J.T.; Thewlis, D.; Tsiros, M.D.; Brown, N.A.T.; Buckley, J.D. The long-term effect of minimalist shoes on running performance and injury: Design of a randomised controlled trial. *BMJ Open* **2015**, *5*, e008307. [CrossRef]

51. Sakaguchi, M.; Wannop, J.; Madden, R.; Koska, D.; Stefanyshyn, D. Effects of shoe bending stiffness and surface stiffness on lower extremity biomechanics during running. *Footwear Sci.* **2015**, *7*, S4–S6. [CrossRef]
52. Nigg, B.M.; Stefanyshyn, D.; Cole, G.; Stergiou, P.; Miller, J. The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. *J. Biomech.* **2003**, *36*, 569–575. [CrossRef]
53. Frederick, E.C.; Howley, E.T.; Powers, S.K. Lower Oxygen Demands of Running in Soft-Soled Shoes. *Res. Q. Exerc. Sport* **1986**, *57*, 174–177. [CrossRef]
54. Bosco, C.; Rusko, H. The effect of prolonged skeletal muscle stretch-shortening cycle on recoil of elastic energy and on energy expenditure. *Acta Physiol. Scand.* **1983**, *119*, 219–224. [CrossRef]
55. Van Alsenoy, K.; van der Linden, M.L.; Girard, O.; Santos, D. Increased footwear comfort is associated with improved running economy—A systematic review and meta-analysis. *Eur. J. Sport Sci.* **2021**, 1–13. [CrossRef] [PubMed]
56. Van Hooren, B.; Fuller, J.T.; Buckley, J.D.; Miller, J.R.; Sewell, K.; Rao, G.; Barton, C.; Bishop, C.; Willy, R.W. Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies. *Sports Med.* **2020**, *50*, 785–813. [CrossRef]
57. Mooses, M.; Tippi, B.; Mooses, K.; Durussel, J.; Mäestu, J. Better economy in field running than on the treadmill: Evidence from high-level distance runners. *Biol. Sport* **2015**, *32*, 155–159. [CrossRef]