Effects of Footwear and Fatigue on Running Economy and Biomechanics in Trail Runners

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ABSTRACT

VERCRUYSSEN, F., M. TARTARUGA, N. HORVAIS, and J. BRISSWALTER. Effects of Footwear and Fatigue on Running Economy and Biomechanics in Trail Runners. *Med. Sci. Sports Exerc.*, Vol. 48, No. 10, pp. 1976–1984, 2016. **Purpose**: This study aimed to examine the effects of footwear and neuromuscular fatigue induced by short distance trail running (TR) on running economy (RE) and biomechanics in well-trained and traditionally shod runners. **Methods**: RE, vertical and leg stiffness (K_{vert} and K_{leg}), as well as foot strike angle were measured from two 5-min treadmill running stages performed at a speed of 2.5 (with 10% grade, uphill running) and 2.77 $\mathrm{m{\cdot}s^{-1}}$ (level running) before and after an 18.4-km TR exercise (approximately 90% of maximal heart rate) in runners wearing minimalist shoes (MS), MS plus added mass (MSm), or traditional shoes (TS). Maximal voluntary contraction torque of knee extensors and perceived muscle pain were also evaluated before and after TR. **Results**: Maximal voluntary contraction values decreased after TR in all footwear conditions ($P < 0.001$), indicating the occurrence of neuromuscular fatigue. In the nonfatigued condition, runners exhibited a better RE only during level running in MS and MSm (i.e., combined effects of shoe mass and midsole geometry), in association with significant decreases in foot strike angle ($P < 0.05$). However, no significant difference in RE was observed between shod conditions after TR during either uphill or level running. Decreases in both $K_{\mathrm{vert}}/K_{\mathrm{leg}}$ and foot strike angle were more pronounced during running in MS and MSm ($P < 0.05$) compared with TS, whatever the period. Calf pain increased after TR when wearing MS and MSm compared with TS ($P < 0.05$). **Conclusions**: These findings indicated specific alterations in RE and biomechanics over time during the MS and MSm conditions compared with the TS condition. Future studies are warranted to evaluate the relationship between RE and footwear with fatigue in experienced minimally shod runners. **Key Words:** RUNNING ECONOMY, MINIMALIST FOOTWEAR, FATIGUE, MUSCULOSKELETAL STIFFNESS, FOOT STRIKE PATTERN, TRAIL RUNNING

Minimalist shoes (MS) are a new commercially available athletic footwear, gaining strong popularity in road runners and off-road athletes. In contrast with traditional shoes (TS), minimalist footwear is presumed to simulate barefoot running while wearing lightweight shoes with minimal drop and minimal heel height (35). During level running protocols, wearing MS may constitute an external strategy to improve predictors of performance such as running economy (RE), i.e., the submaximal oxygen demand for a given speed (5,11,12,31,38). In this regard, Franz et al. (11) quantified that oxygen uptake ($\dot{V}O_2$) increased by approximately 1% for each 100 g of mass added to each shoe for a given speed. Regardless of the metabolic benefit induced by the low mass of MS, Perl et al. (31) concluded that this new footwear may also permit more elastic energy storage and recoil in the longitudinal arch of the foot and hence improve RE. Moreover, wearing shoes with a flatter midsole geometry (i.e., low-drop/low-heel height) is known to induce a transition toward a midfoot strike pattern (MFS) (i.e., foot angle close to 0° at ground contact) associated with higher leg and vertical stiffness (15,16). These biomechanical changes might potentially improve RE, especially in athletes running in MS (24). To date, the relationship between RE, footwear, and spring-mass behavior has not been thoroughly investigated.

On the basis of numerous anecdotal reports, many athletes habituated to run in TS (i.e., with cushioning, high drop/heel height and mass) occasionally wear MS during racing and training without any gradual transition to this footwear. During running bouts of short duration (<10-min), the use of MS in traditionally shod runners may induce a rearfoot strike–midfoot/forefoot strike transition (i.e., more plantarflexed landing) associated with higher triceps surae activation and calf pain (14,15) but also increased ankle joint contact forces and plantar flexor muscle forces (33). This increased loading of musculoskeletal structures at the foot and ankle is particularly rapid in conventional runners wearing

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Submitted for publication November 2015.
Accepted for publication April 2016.

0195-9131/16/4810-1976/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000000981

minimalist footwear. Thus, calf/shin pain as well as injury risk may result from the increased forces produced by the triceps surae complex (15,34). In addition, Warne and Warrington (38) highlighted that a 4-wk familiarization period with minimalist footwear was necessary to allow optimal adaptation of the muscular and articular tissue and improve RE. Taking these results collectively, a detrimental effect of wearing MS could be expected on RE with increased exercise duration, particularly in subjects having limited experience with this type of footwear.

Despite the widespread use of minimalist footwear in running events, there is a lack of guidelines and evidence regarding their metabolic benefits over longer exercise duration (>60 min). All level running protocols focusing on the relationship between RE and minimalist footwear present a major methodological limitation linked to exercise duration and/or the absence of neuromuscular fatigue induced by the running task. In a recent meta-analysis, Fuller et al. (12) reported that published scientific studies were exclusively based on RE measurements during short periods (<10 min) between testing in different shoe conditions, and assumed that RE responses to footwear will be the same with increased exercise duration and fatigue. Thus, the completion of prolonged running inducing neuromuscular fatigue is of great interest in footwear protocols to further understand the mechanisms underlying the relationship between minimalist footwear and RE. Easthope et al. (6) showed that the use of a short distance trail run (i.e., 15.6 km), conducted on mountain single tracks with extensive vertical displacement, was a reliable experimental model to reproduce neuromuscular fatigue (i.e., assessed by a decrease in maximal voluntary contraction (MVC) torque) and to evaluate intervention strategies. This model using a pre-/postlaboratory setup has the additional advantage of reflecting neuromuscular fatigue produced in an ecological context and entails a short recovery time between the running bouts.

Therefore, the objective of the current work was to examine, in a pre-/postlaboratory setup including level and uphill treadmill running, the influence of neuromuscular fatigue involving a short distance trail run on RE, the foot strike pattern, leg pain, and spring-mass behavior in runners using minimalist or conventional shoes. We hypothesized that 1) wearing minimalist footwear compared with TS would improve RE during treadmill exercises conducted before trail running (TR), and 2) after controlling for shoe mass and TR performance, the occurrence of neuromuscular fatigue with MS would alter RE and biomechanics in traditionally shod trail runners having limited experience with minimalist footwear.

METHODS

Subjects. Thirteen well-trained and competitive male runners (age: 38.2 ± 4.8 yr; stature: 175.5 ± 4.9 cm; body mass: 68.2 ± 6.0 kg) were recruited. The sample size was calculated according to a previous study by Vernillo et al. (36) investigating the effect of muscle fatigue on RE following TR, with a statistical power of 80% and a significance at $P \leq 0.05$. Their mean maximal oxygen uptake ($\dot{V}O_{2max}$) and maximal heart rate (HR_{max}) were 62.5 ± 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ and 185 ± 11 bpm, respectively. Subjects had a mean of 6.4 ± 2.4 yr of TR practice, and their usual racing distance ranged from 20 to 45 km. The experimental group typically ran 4–6 $d \cdot wk^{-1}$ with a mean weekly running distance of 70 ± 10 $km \cdot wk^{-1}$ during the month preceding the investigation. Subjects were all traditionally shod trail runners and had no previous experience with MS, except during the 3 wk of training before testing (see Footwear and training). Athletes gave their informed written consent to participate to the study, which has been conducted according to the Declaration of Helsinki. A local ethics committee for the protection of individuals gave its approval for the project before its initiation.

Experimental design. During the first laboratory visit, subjects performed a maximal test on a motorized treadmill (Gymrol; HEF Tecmachine, Andrezieux-Boutheon, France) with a 10% slope that aimed at determining $\dot{V}O_{2max}$ and HR_{max}. The initial velocity was fixed at 7 $km \cdot h^{-1}$ and increased by 1 $km \cdot h^{-1}$ every 2 min until exhaustion. During the other laboratory visits, participants completed three prolonged run conditions on three separate days 1 wk apart. Each condition included treadmill running tests to measure RE, spring-mass behavior, and foot strike angle, as well as one isometric test to determine MVC torque, before (PRE) and after (POST) an 18.4-km TR course located about a 10-min drive from the laboratory. Based on pilot testing, the time between the end of TR sessions and the laboratory measurements was fixed at 12 min for the evaluation of the MVC torque and 15 min for treadmill running tests. These treadmill runs included two 5-min running stages in PRE- and POST-TR at two different speeds and slopes, with a 5-min rest between stages: 2.50 $m \cdot s^{-1}$ (+10% grade, uphill running) and 2.77 $m \cdot s^{-1}$ (0% grade, level running). The level speed was selected to be close to those expected in the runners of the current study for this type of distance, whereas uphill speed was chosen to reproduce the high metabolic intensity induced during the uphill sections of short distance trail races. During the prolonged footwear conditions including both laboratory tests and TR course, participants wore in a random order MS, MS plus added mass (MSm) per shoe, or TS. The running training program was substantially reduced during the experimental period. TR bouts were conducted in the south of France during the months of March and April, which corresponded to a long dry period. These runs were cancelled during rainy days to ensure similar paces between experimental conditions, and performed at the same time of day (between 10:00 a.m. and 4:00 p.m.) under similar environmental conditions (16°C–18°C, 25%–35% relative humidity).

Footwear and training. During the prolonged footwear conditions, subjects wore MS (Salomon Sense, Salomon® SAS, France), TS (Salomon XT Wings, Salomon® SAS, France), or MSm, using the Salomon Sense with added mass per shoe, which corresponded to the weight difference between MS and TS (122 ± 6 g), while maintaining the same drop/heel height ratio as the MS condition. Ankle weight belts filled with the appropriate mass of metal washers were strapped using Velcro lead strips around each ankle during the MSm condition. The mean mass per shoe was 209 ± 10 g (drop, 4 mm, and heel height, 13 mm) and 331 ± 14 g (drop, 10 mm, and heel height, 20 mm) for MS and TS, respectively. Subjects were requested to gradually increase exposure to the novel shoes (MS and TS) over a period of 3 wk during their personal training. Using their GPS watches, subjects slightly increased the running mileage with MS from the first to the third week of training before testing (i.e., approximately 2.5, 4.5, and 6.5 km, respectively; total duration over the 3 wk, <60 min). The rest of the weekly running training was performed with personal shoes and TS assigned to the experimental sessions (mileage identical to MS). These short running sessions with MS (<9.0% of the total training volume per week) allowed trail runners to optimally prepare their feet with the novel shoes on various rough surfaces and identify potential discomfort before testing.

RE. A standardized 10-min warm-up (i.e., level and uphill running at 2.77 and 2.08 $\text{m}\cdot\text{s}^{-1}$, respectively) was performed only in PRE-TR. Subsequently, breath-by-breath $\dot{V}O_2$ values were averaged every 10 s by the Oxycon Alpha metabolic measurement cart (Jaeger®, Germany) during 5-min level and uphill running tests conducted in PRE- and POST-TR. $\dot{V}O_2$ values were averaged over the final 2 min to calculate steady-state $\dot{V}O_2$ and RE values. Then, RE was expressed as gross energy cost ($\text{J}\cdot\text{kg}^{-1}\cdot\text{m}^{-1}$) = $\dot{V}O_2\cdot$energy equivalent$\cdot s^{-1}\cdot\text{BM}^{-1}$, where $\dot{V}O_2$ is measured in liters per minute, energy equivalent is in kilojoules per liter, speed (s) is in meters per minute, and body mass (BM) is in kilograms. The energy expenditure in joules per kilogram per meter was determined by converting the $\dot{V}O_2$ to the corresponding metabolic energy output using an energy equivalent of O_2 ranging from 21.13 to 19.62 $\text{kJ}\cdot\text{L}^{-1}$, depending on the average RER over the final 2 min of each running test. Given that substrates used to provide energy may vary with prolonged exercise, gross energy cost seems to be a more appropriate way to express RE (e.g., [36]).

Spring-mass model parameters. Spring-mass model parameters were obtained from the analysis of running kinematic variables collected during the last 30 s of RE tests using an optical system (Optojump; Microgate, Bolzano, Italy). This optical system, consisting of two bars placed opposite to each other on each side of the treadmill, transmitted an infrared light approximately 5 mm above the treadmill belt. A timer was triggered with a precision of 1 ms each time the infrared signal was interrupted by the foot, allowing to measure aerial (T_a in seconds) and contact (T_c in seconds) times for each step. For each analysis interval, 20–30 steps were sampled. Spring-mass model parameters were calculated using the computation method proposed by Morin et al. (27), including treadmill velocity (v in meters per second), T_a, T_c, subject's body mass (m in kilograms), and lower limb length (L in meters), measured as the distance from the great trochanter to the ground in a standing position. Based on this model, vertical stiffness (K_{vert} in kilonewtons per meter) was calculated as the ratio of maximal ground reaction force ($F_{\max}$ in newtons) to maximal downward displacement of the center of mass during contact (Δz in meters).

$$k_{\text{vert}} = F_{\max}/\Delta z \qquad [1]$$

with

$$F_{\max} = mg\frac{\pi}{2}\left(\frac{t_a}{t_c}+1\right) \qquad [2]$$

and

$$\Delta z = -\frac{F_{\max}}{m}\,\frac{t_c^2}{\pi^2}+g\frac{t_c^2}{8} \qquad [3]$$

Leg stiffness (K_{leg} in kilonewtons per meter) was calculated as the ratio of $F_{\max}$ to the peak displacement of the leg spring ΔL (in meters) during contact:

$$k_{\text{leg}} = F_{\max}/\Delta L \qquad [4]$$

with

$$\Delta L = L - \sqrt{L^2-\left(\frac{vt_c}{2}\right)^2}+\Delta z \qquad [5]$$

It is noteworthy that the linear spring-mass model is based on a geometrical consideration of the lower limb during the stance phase that is mainly characterized by the symmetry of the angle swept before and after midstance (e.g., [21]). During uphill treadmill running, the angle swept by the center of mass is not symmetrical around the midstance point (center of mass above the center of pressure), and thus, equations of the spring-mass model do not give correct values in K_{vert} and K_{leg}. Given that these two integrative parameters include all variables underlying the spring-mass model regulation, we restricted the analysis to K_{vert} and K_{leg} responses (e.g., [7,21]) exclusively to level treadmill running.

Isometric MVC. Participants were securely strapped into an isokinetic dynamometer (VERTEX II; Harvard Sports Inc., Compton, CA) with the knee joint angle of the right leg at 90° (full leg extension = 0°). Arms were folded and placed on the chest, avoiding any pulling from the side handles of the chair. The knee axis was aligned with the ergometer axis, and the ankle was attached to the lever arm of the ergometer. The mechanical response of the leg extensors was recorded using a force transducer (range of measurement from 10 to 200 daN, F 501 TC; TME, France). After a warm-up session in PRE-TR and following TR, participants were instructed to "extend the knee as hard and fast as possible" for the three 5-s measures of isometric MVC with a 55-s rest between attempts. The highest

MVC value achieved was used among the three attempts. According to previous studies (6,20,23), the occurrence of neuromuscular fatigue during the footwear conditions was assessed from the significant reduction in MVC between PRE- and POST-TR (i.e., percent changes from PRE).

Foot strike pattern. To quantify the foot strike pattern, each running test was filmed in the sagittal plane at a sampling frequency of 240 Hz using a high-speed camera (Casio Exilim EX-FH25, Japan). The camera was mounted on a tripod placed 1 m away from the treadmill and aligned so that the plane of the camera was parallel to the treadmill. Foot strike angle was defined as the angle between the treadmill belt and the line passing through the fifth metatarsal joint and the calcaneus, the two latter points being marked visibly on each shoe sample. Foot strike angle was visually determined by the same researcher at initial contact of the same foot with the treadmill belt. Three values in foot strike angle obtained over three consecutive steps were averaged during the last 15 s of each RE test (16). According to the classification proposed by Altman and Davis (1), it was determined that a forefoot strike pattern (FFS) = foot strike angle $< -1.6°$, MFS = $-1.6° <$ foot strike angle $< 8.0°$, and a rearfoot strike pattern (RFS) = foot strike angle $> 8.0°$. The Kinovea analysis software (version 0.8.15; Kinovea Association, France) was used to analyze all videos.

TR course. To familiarize participants with the TR course, two practice sessions were completed on the course and organized 3 wk before the experimental sessions. Red markers were placed on the ground every 200 m to track the course. The TR course consisted of four loops of a 4.6-km course (Fig. 1) comprising a climbing segment (2000-m distance, 290-m climb, 13% gradient) followed by a downhill segment (2600-m distance, −9% gradient) with repeated technical sections on rocky and root-covered paths. All athletes were equipped with the RS800CX (Polar, Kempele, Finland) fixed on the forearm for HR monitoring, elevation profile, and running time measurement. Runners were requested to perform the first footwear condition at the highest intensity on the course distance so that they could replicate the same intensity level during the two other footwear conditions. More precisely, running times were monitored and separately analyzed by uphill and downhill segments for each loop during the first footwear condition. Two average values in running time were then calculated from the four uphill and downhill segments, respectively. Subsequently, feedback was given to the subjects before the other footwear conditions, allowing them to adjust the required pace per loop over the TR course. In addition, during the first footwear condition, subjects consumed carbohydrates in the form of gel (25 g, two per runner) and energy drinks (6% CHO/600 mL of water per runner). The amount of energy drink consumed during the first footwear condition was 154 ± 65, 150 ± 75, 175 ± 41, and 180 ± 62 mL for the four loops of TR. The quantity of ingested carbohydrate gels and fluid intake was individually replicated during the two other footwear conditions. Immediately after TR and during the laboratory tests, participants were asked to indicate perceived muscle pain in the knee extensors (i.e., quadriceps) and calves on a 10-cm visual analogue scale visibly anchoring zero for "no pain" and 10 for "maximal pain" (6).

Statistical analysis. Data are expressed as mean ± SD. Two-way repeated-measures ANOVA [time (PRE, POST) × footwear (MS, MSm, TS)] were used for each treadmill running test (i.e., level and uphill running) to analyze the dependent variables (foot strike angle, K_{leg} and K_{vert}, MVC, and RE). When these analyses revealed significant differences, a Newman–Keuls *post hoc* test was applied to identify where differences lay. In addition, a one-way repeated-measures ANOVA was used to compare the dependent variables measured during and following TR (i.e., HR,

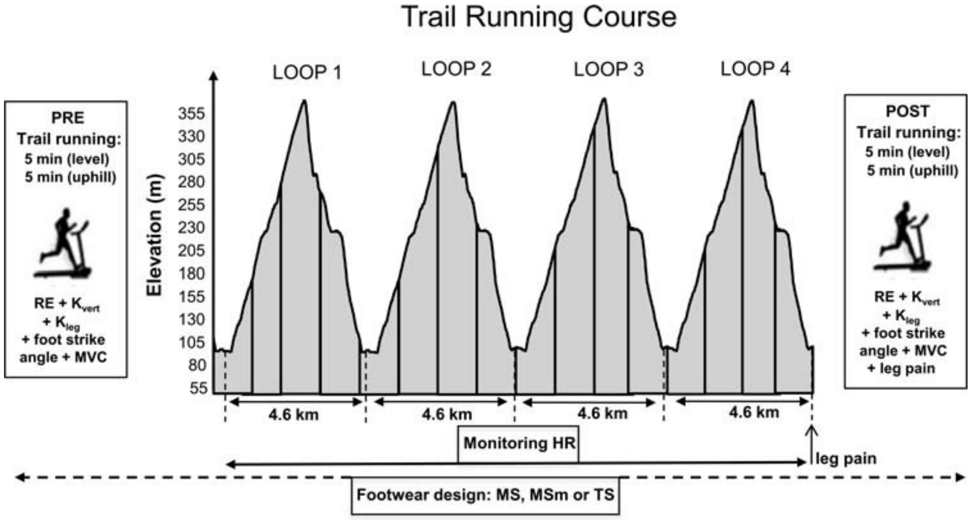

FIGURE 1—Graphic representation of experimental conditions. HR, heart rate; K_{leg}, leg stiffness; K_{vert}, vertical stiffness; MS, minimalist shoes; MSm, minimalist shoes plus added mass; MVC, maximal voluntary contraction; RE, running economy; TS, traditional shoes.

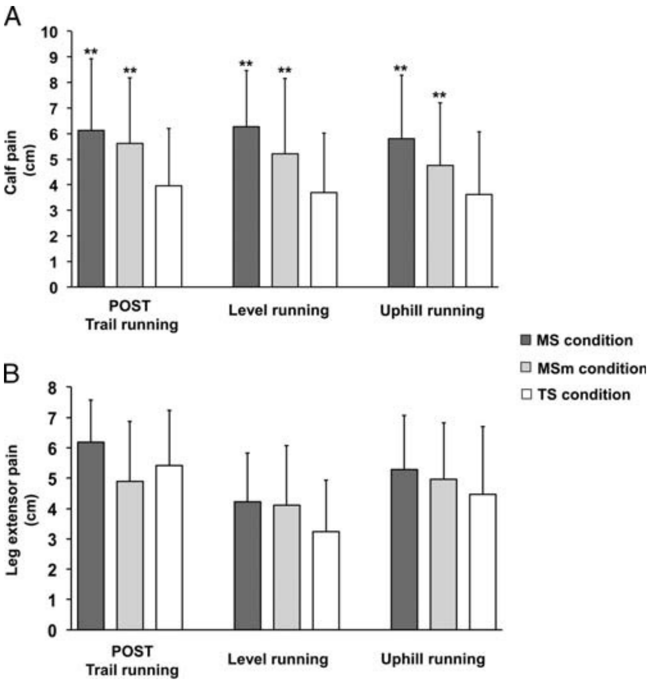

FIGURE 2—Effect of footwear on perceived calf (panel A) and leg extensor (panel B) soreness immediately after TR and during treadmill running tests (level vs uphill). **$P < 0.01$, significantly different from the TS condition for a given period. Data are presented as mean ± SD.

muscle pain, and running time). For each ANOVA analysis, effect sizes were calculated using partial eta squared (ηP^2). Because this measure is likely to overestimate effect sizes, values were interpreted according to Ferguson (8) as having no effect if $0 \leq \eta P^2 < 0.05$, a minimum effect if $0.05 \leq \eta P^2 < 0.26$, a moderate effect if $0.26 \leq \eta P^2 < 0.64$, and a strong effect if $\eta P^2 \geq 0.64$. An alpha of $P \leq 0.05$ was considered statistically significant.

RESULTS

TR, muscle torque, and leg pain. During the TR bouts, no significant variation in running time was observed between the three footwear conditions (6688 ± 671, 6695 ± 554, and 6668 ± 445 s for the MS, MSm, and TS conditions, respectively). Similarly, mean HR responses were not significantly different between the experimental conditions (88.8% ± 4.6%, 88.4% ± 2.7%, and 87.8% ± 4.2% HR_{max} for the MS, MSm, and TS conditions, respectively). MVC values decreased moderately from PRE- to POST-TR among the three footwear conditions (−15.4% ± 11.4%, −13.7% ± 10.4%, and −14.4% ± 10.5% for the MS, MSm, and TS conditions, respectively, $P < 0.001$, $\eta P^2 = 0.63$). As shown in Figure 2A, only calf pain increased moderately during the MS and MSm conditions compared with the TS condition, immediately after TR ($P = 0.034$, $\eta P^2 = 0.35$), during level running ($P = 0.004$, $\eta P^2 = 0.37$), or during uphill running ($P < 0.001$, $\eta P^2 = 0.43$).

RE and footwear. During level running, a moderate effect of footwear was observed in PRE-TR on RE values, which increased during the TS test compared with the other footwear tests ($P = 0.032$, $\eta P^2 = 0.41$, Fig. 3A). During

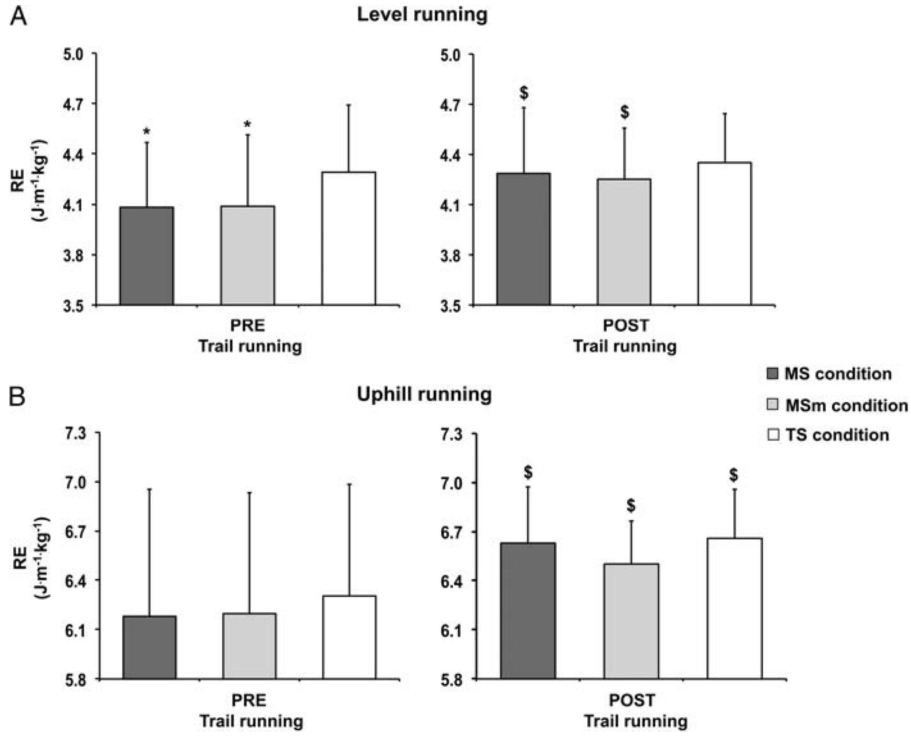

FIGURE 3—Effect of footwear on RE during level (panel A) and uphill (panel B) running tests conducted in PRE- and POST-TR. *$P < 0.05$, significantly different from the TS condition for a given period. \$$P < 0.05$, significantly different from PRE-TR for a given footwear condition. Data are presented as mean ± SD.

TABLE 1. Physiological variables and foot strike pattern responses to footwear during level and uphill treadmill running in PRE- and POST-TR.

		Level Running			Uphill Running		
		MS	MSm	TS	MS	MSm	TS
$\dot{V}O_2$ ($mL \cdot min^{-1} \cdot kg^{-1}$)	PRE	33.5 ± 3.2*	33.6 ± 3.6*	35.2 ± 3.2	45.6 ± 3.8	46.3 ± 3.3	46.7 ± 3.6
	POST	35.4 ± 3.2***	35.4 ± 2.3***	36.0 ± 2.3	48.9 ± 2.2***	48.3 ± 1.4***	48.9 ± 2.0***
RER	PRE	0.85 ± 0.04	0.84 ± 0.03	0.85 ± 0.03	0.92 ± 0.07	0.90 ± 0.07	0.91 ± 0.06
	POST	0.79 ± 0.04***	0.79 ± 0.04***	0.81 ± 0.05***	0.85 ± 0.04***	0.86 ± 0.06***	0.86 ± 0.05***
Foot strike angle (°)	PRE	3.0 ± 9.7**	3.3 ± 9.0**	8.4 ± 9.7	−1.2 ± 3.2	−1.6 ± 3.1	0.4 ± 5.1
	POST	4.2 ± 10.2**	4.5 ± 9.6**	8.3 ± 11.0	−0.1 ± 4.7	−0.8 ± 3.9	1.1 ± 5.9

Values are presented as mean ± SD.
*$P < 0.05$, significantly different from the TS condition for a given period.
**$P < 0.01$, significantly different from the TS condition for a given period.
***$P < 0.05$, significantly different from PRE-TR for a given footwear condition.

uphill running, RE responses were not significantly different among the footwear tests, regardless of the period analyzed ($P > 0.05$, $\eta P^2 = 0.12$, Fig. 3B). In addition, a moderate effect of time (i.e., fatigue effect) was found for RE during level running ($P = 0.001$, $\eta P^2 = 0.47$), with an increase in RE values (i.e., alteration) during the MS and MSm tests in POST-TR. Similarly, RE values increased moderately after TR during uphill running ($P = 0.029$, $\eta P^2 = 0.51$) in all footwear tests. Finally, there was a strong effect of fatigue on RER during level and uphill running ($P < 0.001$, $\eta P^2 = 0.68$ and $\eta P^2 = 0.67$, respectively), with a decrease in RER after TR regardless of the footwear test (Table 1).

Running biomechanics and footwear. A small to moderate effect of footwear was observed on K_{vert} ($P = 0.030$, $\eta P^2 = 0.23$) and K_{leg} ($P = 0.031$, $\eta P^2 = 0.47$), with higher values in these variables during the TS test compared with the other footwear tests in PRE- and POST-TR (Fig. 4). Similarly, a small to moderate effect of fatigue was also found for K_{vert} ($P = 0.012$, $\eta P^2 = 0.29$) and K_{leg} ($P = 0.011$, $\eta P^2 = 0.48$), with decreased K_{vert} and K_{leg} over time regardless of the footwear test. Moreover, a moderate effect of footwear was identified on foot strike angle only during level running in PRE- and POST-TR ($P = 0.004$, $\eta P^2 = 0.38$, Table 1). Foot strike angle was significantly lower during the MS and MSm tests compared with the TS test, characterized by a significant flatter foot position at ground contact in PRE- and POST-TR.

DISCUSSION

The main finding of this study indicated that after a short distance trail run (approximately 110 min) inducing neuromuscular fatigue, traditionally shod runners exhibited no metabolic advantage of wearing minimalist footwear, characterized by similar responses in RE between shod conditions regardless of the treadmill slope. The pre-/postlaboratory setup used in the current work allowed us to evaluate and compare between testing running biomechanics and RE

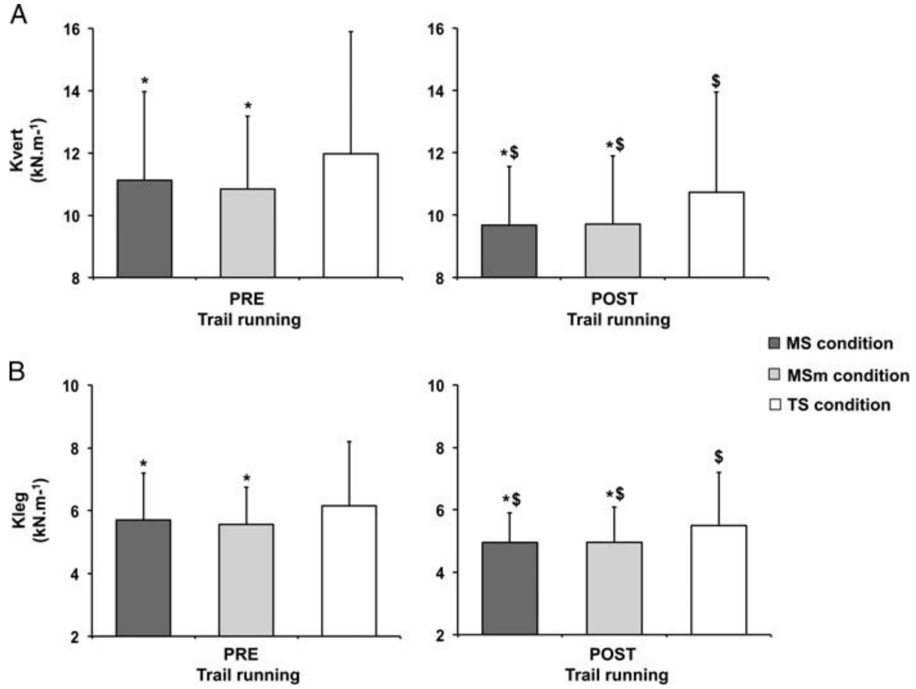

FIGURE 4—Effect of footwear on vertical stiffness (K_{vert}, panel A) and leg stiffness (K_{leg}, panel B) during level treadmill running conducted in PRE- and POST-TR. *$P < 0.05$, significantly different from the TS condition for a given period. $$P < 0.05$, significantly different from PRE-TR for a given footwear condition. Data are presented as mean ± SD.

responses close to those induced within the real constraints of short distance TR.

RE, footwear, and spring-mass behavior. Although contradictory results have been reported after prolonged off-road running (22), neuromuscular fatigue may be associated with an impairment in RE over time. The alteration in RE with exercise duration is a well-known phenomenon, possibly resulting from changes in the running pattern, neuromuscular performance, or substrate turnover (2,29,36). A decrease in RER implying changes in substrate mobilization (i.e., toward free fatty acid oxidation) is often suggested to partly account for the RE alteration during prolonged running (e.g., [2]). In the present work, increased or unchanged RE ($J \cdot kg^{-1} \cdot m^{-1}$) during level and uphill treadmill running was observed among the three footwear conditions in POST-TR despite the significant decline in RER (Table 1), thus minimizing the potential role of metabolic changes in the RE response. In POST-TR, increased RE during level and uphill treadmill running might have been influenced by the high metabolic intensity (approximately 90% HR_{max}) sustained over the loops of the TR course as well as the occurrence of fatigue induced by prior muscular recruitment involved during prolonged eccentric (downhill) or concentric (uphill) muscle actions (e.g., [30]). However, acute RE responses during the overall footwear conditions were different between uphill and level treadmill running. Altered RE during level running was exclusively observed in the MS and MSm conditions (Fig. 3A), suggesting that for these shod conditions, RE responses seem to be more specific during level ground compared with uphill running.

Our findings relative to level running demonstrated no relationship between RE, footwear, and spring-mass model parameters either in PRE- or POST-TR. Although RE responses to footwear vary with fatigue, we reported lower values in K_{leg} and K_{vert} during the MS and MSm conditions compared with the TS condition (Fig. 4), independently of the fatigue effect. When focusing on the PRE-TR period, our results seem contradictory with those previously reported during running exercises of shorter duration (i.e., 5–10 min), showing higher K_{leg} and K_{vert} in runners using MS (5,19). One explanation for these differences could be the specificity of MS used in the studies and, notably, changes in mass, drop, shock absorption, and flexibility (16,35). Interestingly, the discrepancy in spring-mass model parameters between shod conditions was maintained in POST-TR, with subjects exhibiting more pronounced decreases in K_{leg} and K_{vert} in the MS and MSm conditions (Fig. 4). To date, little information is available concerning the mechanical alterations in running gait in response to footwear with fatigue. Recently, Lussiana et al. (19) reported a significant reduction in K_{leg} over time (after 50 min of level treadmill) only in the MS condition. In this investigation, the lack of training with MS within the cohort of subjects has been suggested to explain changes in running biomechanics with increased exercise duration. Given that traditionally shod runners were recruited in the present study, it is reasonable to assume that modifications in K_{leg} and K_{vert} during the MS and MSm conditions were at least in part related to the footwear condition and may have reflected some mechanical alterations probably due to the lack of long-term practice with MS (see Methods).

Furthermore, it is noteworthy that decreased K_{leg} and K_{vert} were found over time in all footwear conditions. These findings are in accordance with those reported during exhaustive treadmill runs of short duration (e.g., [32]), but different to those induced over a 24-h treadmill run (26) or after a 5-h hilly running bout (10). In TR over longer distances, it is known that runners modify their running patterns toward higher values in K_{leg} and K_{vert} and adopt a “smoother and safer running style” as a consequence of the high quantity of foot strike produced during running (e.g., [27]). Thus, the alterations in spring-mass behavior depend on not only the characteristics of running studied, including distance, intensity, treadmill, or field protocols, but also the type of footwear used during running (MS vs TS). Finally, K_{leg} and K_{vert} were not quantified during uphill treadmill running because of the limits of the macroscopic sine wave spring-mass model with increasing incline (see Methods). Alternative and complex ultrasonography methods have been recently used either to assess the behavior of Achilles tendon during uphill and level running (28) or to analyze the relationship between RE and triceps surae tendon stiffness (e.g., [9]). This recent mechanistic approach seems to be useful in future running protocols to better understand the impact that wearing MS may have on the triceps surae complex as neuromuscular fatigue occurs on different treadmill slopes.

RE, footwear, and foot strike pattern. In the current study, additional findings specific to level running indicated a significant shift from an RFS pattern in the TS condition to an MFS pattern in the MS and MSm conditions independently of the fatigue effect (Table 1). This transition in the strike pattern observed in POST-TR suggests that the MFS pattern when wearing MS was predominant during the TR course and led trail runners to produce continuously repeated and nonhabitual calf contractions, possibly inducing a greater Achilles tendon stress (9,15,17) compared with the TS condition. This hypothesis is consistent with specific muscle pains reported during the MS and MSm conditions. Significant increases in calf pain were identified in POST-TR only in the MS and MSm conditions, whereas no change in quadriceps pain was found between shod conditions (Fig. 2). Calf pain is commonly observed in traditionally shod runners adopting an MFS pattern (14,15) and/or wearing MS during a long period of training (15,34). In addition, previous investigations have shown an increased activation of plantarflexor muscles with the MFS pattern not only when wearing MS (e.g., [14]) but also during uphill running (e.g., [30]). Taken together, these results suggest that the use of MS and MSm resulting in nonhabitual changes in the foot strike pattern associated with higher calf pain might have accentuated the strain in the plantarflexor muscles, partially accounting for the RE alteration with fatigue.

Interestingly, RE responses to footwear are likely to be dictated by the combined effects of the treadmill gradient and foot strike pattern. Although contradictory findings exist on the relationship between RE and the foot strike pattern (24), it has been suggested that running on level ground with MFS and FFS patterns compared with an RFS pattern may enable a better stretch of the foot arch and a better storage and release of elastic energy from tendons, ligaments, and muscles of the lower limbs during the first part of the stance phase, thus improving RE (31). However, this mechanism of energy storage may be altered with increasing treadmill gradient despite the adoption of a FFS/MFS pattern and might explain why RE responses to footwear are different between uphill and level running especially in PRE-TR. Indeed, during uphill running, subjects exhibited similar RE (Fig. 3B) and MFS patterns (close to 0°, Table 1) among the footwear conditions. These findings are in line with a recent study reporting identical RE between MS and TS on treadmill tests with a +8% gradient compared with level ground (18). It has been postulated that the stretch-shortening cycle during uphill treadmill running is underutilized, and the ability of the muscle tendon unit to store and release elastic energy is reduced compared with level running (3,18,36). The optimal springlike action of the foot and its positive effect in terms of energy release would be possible only during level running and likely accentuated with the use of MS by modifying the foot strike pattern. Thus, wearing MS during level running protocols might optimize the energy-saving mechanisms over time. Given the specificity of TR including irregular and rocky surfaces as well as positive and negative slopes, it would be interesting to evaluate the relationship between RE and footwear from a prolonged and flat run exercise.

Finally, subjects exhibited better RE in MS or MSm compared with TS during level running in PRE-TR, suggesting a combined effect of shoe mass and midsole geometry in determining RE responses. Several studies showed a better RE in MS compared with TS either in barefoot athletes and minimalist runners (11,31) or in traditionally shod runners unaccustomed to the MS (5,37,38). These findings indicate that the metabolic advantage of wearing MS often described during running exercises of short duration (<10 min) may not be influenced by the running experience with MS. Conversely, the potential benefits of wearing MS reported during short run bouts might be strongly reduced with increased exercise duration and/or fatigue in traditionally shod runners because of the nonhabitual changes in contraction modality and force produced by the triceps surae (31).

Limitations and perspectives. The subjects of this study exhibiting limited experience with MS might have influenced the findings in POST-TR. As detailed in the Methods section, the running training with MS before testing (<9.0% of the total training volume per week) was not designed to familiarize the subjects with this type of footwear, in comparison with previous investigations reporting higher running mileages over several weeks with MS (e.g., 60%–100% of the total training volume per week) in conventional runners to induce chronic adaptations (15,25,34,38). As recently suggested (13), a reduction in RE and biomechanics alterations could be expected in traditionally shod runners practicing a long-term training (i.e., several months) with MS. There exist no consensus on what should be an appropriate follow-up period (and associated training guidelines) to investigate the long-term effects of MS. However, some practical recommendations may be proposed for traditionally shod trail runners, including a progressive program over several weeks with increasing running mileage in MS (e.g., [15,25]) and footwear using an intermediate heel height/drop ratio (between MS and TS) to permit an optimal transition to an MFS pattern and limit the "calf and tendon pains." Although the concept of MS is relatively recent in TR, further work including a control group of minimalist runners is needed to evaluate the importance of a long-term training with MS in determining RE with fatigue. Another limit is the time between the end of TR sessions and the laboratory measurements. This period may have underestimated the changes in muscle strength, RE, and biomechanics. However, our results must be interpreted as reflecting the effects of long-lasting fatigue, which may be comparable with those previously reported not only within the first 30 min after a 15.6-km TR exercise (6) but also after and during an extended period of several days consecutive to a 30-min downhill run session (4,20). In addition, the period between the sites was strictly respected among the footwear sessions, allowing us to compare dependent variables between testing from similar conditions of measurement. Finally, it would be interesting to replicate this type of fatigue protocol in a laboratory setting to evaluate the time course of RE changes and identify at which period the use of MS becomes metabolically detrimental in conventional runners.

In conclusion, the findings of this study indicated no metabolic advantage of wearing MS with neuromuscular fatigue induced by a short distance trail run in traditionally shod runners. The relationship between RE and footwear with fatigue seems to be more specific during level running compared with uphill running. During level treadmill running in POST-TR, wearing MS and MSm compared with TS is characterized by significant RE alterations associated with substantial decreases in biomechanical responses (i.e., foot strike pattern, and K_{leg} and K_{vert}) and increased calf pain. Although the metabolic benefit of wearing MS is evident in the nonfatigued condition, future studies should examine whether these benefits are maintained with fatigue in trained and experienced minimalist runners.

The authors thank the subjects for their willingness to participate in the present work. The authors would also like to extend their gratitude to Jean-Benoit Morin for his expertise in the domain of running biomechanics and D. Bishop for improving the use of English in the manuscript.

This investigation was funded by SALOMON SAS (Amer Sports, Annecy, France), which provided the different footwear products used by the subjects in the experimental sessions. The funders had no role in the study design, data collection and analysis, preparation of the manuscript, or decision to publish.

The authors report no conflict of interest.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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