Highly Cushioned Shoes Improve Running Performance in Both the Absence and Presence of Muscle Damage

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ABSTRACT

BLACK, M. I., S. H. KRANEN, S. KADACH, A. VANHATALO, B. WINN, E. M. FARINA, B. S. KIRBY, and A. M. JONES. Highly Cushioned Shoes Improve Running Performance in Both the Absence and Presence of Muscle Damage. *Med. Sci. Sports Exerc.*, Vol. 54, No. 4, pp. 633–645, 2022. **Purpose:** We tested the hypotheses that a highly cushioned running shoe (HCS) would 1) improve incremental exercise performance and reduce the oxygen cost (O_c) of submaximal running, and 2) attenuate the deterioration in O_c elicited by muscle damage consequent to a downhill run. **Methods:** Thirty-two recreationally active participants completed an incremental treadmill test in an HCS and a control running shoe (CON) for the determination of O_c and maximal performance. Subsequently, participants were pair matched and randomly assigned to one of the two footwear conditions to perform a moderate-intensity running bout before and 48 h after a 30-min downhill run designed to elicit muscle damage. **Results:** Incremental treadmill test performance was improved (+5.7%; +1:16 min:ss; $P < 0.01$) in the HCS when assessed in the nondamaged state, relative to CON. This coincided with a significantly lower O_c (−3.2%; −6 mL·kg^{-1}·km^{-1}; $P < 0.001$) at a range of running speeds and an increase in the speed corresponding to 3 mM blood lactate (+3.2%; +0.4 km·h^{-1}; $P < 0.05$). As anticipated, the downhill run resulted in significant changes in biochemical, histological, and perceptual markers of muscle damage, and a significant increase in O_c (+5.2%; 10.1 mL·kg^{-1}·km^{-1}) was observed 48 h post. In the presence of muscle damage, O_c was significantly lower in HCS (−4.6%; −10 mL·kg^{-1}·km^{-1}) compared with CON. **Conclusions:** These results indicate that HCS improved incremental exercise performance and O_c in the absence of muscle damage and show, for the first time, that despite worsening of O_c consequent to muscle damage, improved O_c in HCS is maintained. **Key Words:** RUNNING ECONOMY, FOOTWEAR, MUSCLE HISTOLOGY, ENDURANCE PERFORMANCE, MUSCLE SORENESS, DOWNHILL RUNNING

Endurance running performance is dependent on a sustained high rate of, predominantly oxidative, metabolic energy transfer to support and propel forward the body's center of mass. The sustainable running speed for a given distance is determined by the interaction of several physiological factors, specifically the maximal rate of oxygen uptake ($\dot{V}O_{2max}$) and the fractional utilization of $\dot{V}O_{2max}$, which together determine the sustainable $\dot{V}O_2$, and the conversion of this $\dot{V}O_2$ into forward movement, which depends on the O_2 cost (O_c) of running (i.e., running economy) (1). The importance of running economy to long-distance running performance is well documented (2,3), and it has been shown to differentiate performance among individuals with similar $\dot{V}O_{2max}$ (4). Interventions that improve running economy are therefore of great importance to running performance.

During running, at each ground contact, the body is subjected to substantial vertical loading (approximately 2–3 times body weight; (5)), and a combination of eccentric and isometric contractions, and elastic energy storage in tendons are required to slow the downward acceleration during the initial phase of stance (loading phase). To cover the marathon distance (42.195 km), a runner with a stride length of 2.4 m will strike the ground a total of 35,163 times, resulting in the accumulation of considerable impact load and necessitating a high volume of eccentric and isometric muscle actions. This situation ultimately results in greater impairments to running performance relative to exercise with little or no impact, or fewer eccentric actions (6). Direct assessment of skeletal muscle ultrastructure has provided evidence of disruption to the normal myofibrillar banding pattern (7–10) after strenuous exercise

involving repeated eccentric muscle actions. Accordingly, long-distance running events, and plyometric and resistance training, which may be included in endurance training programs to improve running economy (11–13), are associated with substantial muscle soreness, inflammation and swelling, increased concentration of creatine kinase (CK) in the plasma, and the loss of muscle function and running economy, which persists for several days (14,15).

During downhill running, there is an increase in braking forces (16), which results in increased eccentric muscle actions and loading compared with level running, a combination that is known to result in significant muscle damage (6). Indeed, previous studies utilizing a downhill running protocol (−15% grade) have reported a group mean increase (~3.2% to 6.4%) in the O_c of running (17–19), an increase that is similar to that reported after a marathon (+7%) (15) and a competitive duathlon (+5%) (20). A downhill running intervention therefore provides the opportunity to elicit considerable muscle damage similar to that observed after major endurance competitions.

It has been shown that running shoes with highly compliant and resilient foam, increased longitudinal bending stiffness, and carbon fiber plates can improve running economy compared with other running shoes (21–24). However, these investigations were conducted with individuals who were well rested, with no muscle damage, and it is not clear whether these beneficial effects remain evident in the presence of substantial muscle damage, a phenomenon known to alter running economy (15,17–20).

Given the importance of running economy to long-distance running performance, an intervention that improves running economy in both the absence and presence of muscle damage would be of great practical benefit. Based on recent advances in shoe technology, specifically the integration of highly compliant and resilient materials into the sole of the shoe (e.g., [21–24]), further investigation into the potential for highly cushioned shoes to improve running economy in the presence of muscle damage is warranted. The purpose of the current study was therefore to test the hypotheses that, compared with a control running shoe (CON), a highly cushioned running shoe (HCS) would 1) improve incremental treadmill test performance and running economy (assessed both as O_c and energy cost (E_c)) during exercise in a "fresh" nondamaged state, and 2) attenuate the deterioration in running economy elicited by muscle damage consequent to a downhill run.

METHODS

This article reports the results of two experiments. The first experiment was conducted to investigate the effects of different types of footwear on time to the limit of tolerance (a proxy for running performance) and running economy during incremental treadmill exercise. The second experiment was conducted to investigate whether footwear influences running economy in the presence of muscle damage.

Participants

Experiments I and II were conducted on the same group of participants. Twenty-two males (mean ± SD: age, 23 ± 6 yr; height, 1.78 ± 0.05 m; body mass, 76.3 ± 7.5 kg) and 10 females (mean ± SD: age, 28 ± 9 yr; height, 1.67 ± 0.04 m; body mass, 63.3 ± 8.8 kg) volunteered and provided written informed consent to participate in these experiments, which had been approved by the University of Exeter Research Ethics Committee. This sample size was based on preliminary data, collected from 13 participants, which indicated a ~6.2% difference in the change in O_c between footwear conditions before compared to after downhill run (α =0.05, power = 0.95). Participants were recreationally active, performing a minimum of two running sessions per week for the previous 3 months, with a weekly mileage that ranged from approximately 10 to 50 miles. All participants reported to be in good health and to have not experienced any musculoskeletal injury in the 3 months before testing. Because of constraints in the footwear sizes available, all participants were required to be comfortable running in UK sizes 5.5 or 9.0 Nike running shoes. Participants were instructed to attend all testing sessions in a well-hydrated state, having completed no strenuous exercise within the previous 48 h, abstained from alcohol for a minimum of 24 h, and avoided food and caffeine for 3 h before each laboratory visit.

Experimental Design

Participants visited the laboratory on six occasions over a 4-wk period with each visit separated by a minimum of 24 h (Fig. 1). During the first visit, participants completed a treadmill familiarization run in both types of footwear. Treadmill familiarization involved participants practicing lowering themselves onto, and lifting themselves clear of, the moving treadmill belt, while wearing the facemask required for respiratory measurements, for a period of 10 min in each of the two shoes used in the study. Participants were also familiarized to the downhill treadmill protocol by running at −15% gradient for 5 min in each footwear condition. After familiarization to the treadmill and the two running shoes, participants were randomized in a counterbalanced design and subsequently completed incremental treadmill tests in both footwear conditions (experiment I: visits 2 and 3). After completion of the two incremental tests, participants were pair-matched, according to $\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1}) and speed at lactate threshold (sLT), and randomly allocated to either the CON ($n = 16$) or HCS ($n = 16$) group for experiment II (visits 4–6).

The vertical stiffness and resilience of the midsole of the two running shoes used in this study were determined using methods described previously (see Ref. [23] for details). The control (CON) shoe's underfoot system was 247 N·mm^{-1} in vertical stiffness and 69% resilient. The highly cushioned shoe (HCS) was more compliant and resilient than CON, having an underfoot system that was 123 N·mm^{-1} in vertical stiffness and 85% resilient. Note that HCS increased cushioning properties while being ~30–40 g lighter than CON (mass of UK size 9.0: 273 g CON vs 232 g HCS; mass of UK size 5.5: 218 g CON vs 187 g HCS).

All exercise tests were completed using the same motorized treadmill (Woodway ELG 55; Woodway Gmbh, Weil am
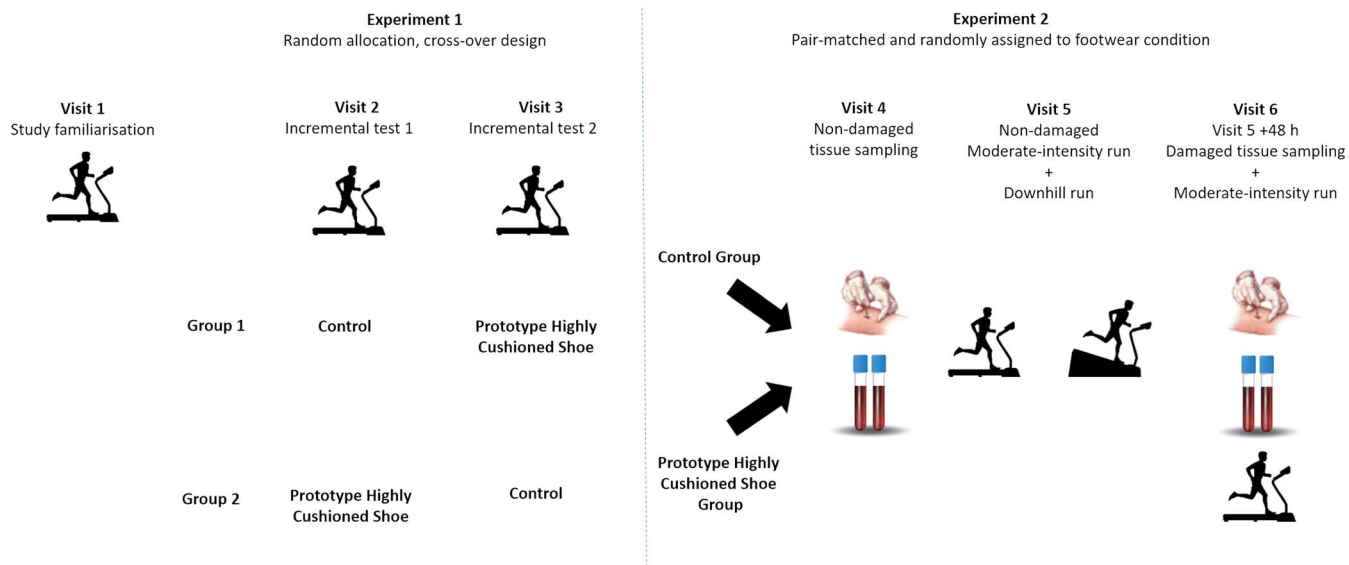
FIGURE 1—Schematic illustration of the study visits for experiments I and II.

Rhein, Germany) set at a 1% incline (25), with the exception of the downhill run, which was performed at −15%. Exercise tests were conducted in an air-conditioned laboratory with ambient temperature of 18°C–20°C and relative humidity of 45%–55%.

Experiment I: Effect of Footwear on Running Economy and Performance during Incremental Exercise

Experiment I consisted of two incremental exercise tests, one test performed in each footwear condition, for determination of running economy, sLT, speed at lactate turn-point ($sLTP$), speed at a fixed blood lactate concentration of 3 mM, $\dot{V}O_{2peak}$, the peak speed attained in the test, and time to the limit of tolerance (T_{lim}). The starting speed of the tests was estimated for each participant following consideration of training history, recent running performance, and (where they existed) the results of previous incremental tests. The tests comprised 3-min running stages, interspersed by 30-s rest periods, during which the participant straddled the moving treadmill belt while a fingertip capillary blood sample was collected for subsequent analysis of blood lactate concentration (YSI 2300; Yellow Springs Instruments, Yellow Springs, OH). At the completion of each 3-min stage, running speed was increased by 1 km·h^{-1}, and this process was repeated until the participant could not complete a stage or declined the opportunity to start a new stage. T_{lim} was recorded to the nearest second. Breath-by-breath pulmonary gas exchange data were collected continuously throughout the test. $\dot{V}O_{2peak}$ was determined as the highest 30-s rolling mean achieved during the test. The blood lactate concentration values were plotted against running speed and sLT and $sLTP$ were identified from visual determination of breakpoints in the lactate–speed relationship. The speed corresponding to the first breakpoint, where blood lactate concentration rises above the baseline value, was defined as the sLT and the speed corresponding

to the second disproportionate increase in the lactate–speed relationship, at approximately 3–5 mM, was defined as the $sLTP$. The sLT and $sLTP$ were estimated independently and agreed upon by two experienced assessors. The running speed corresponding to a fixed blood lactate concentration of 3 mM was also determined using linear regression of the speed and lactate values measured immediately above and below 3 mM.

Experiment II: Effect of Footwear on Running Economy after Muscle Damage

Participants visited the laboratory on three occasions (visits 4–6). On visit 4, they provided muscle tissue and venous blood samples representative of a control (i.e., nondamaged, well-rested) state. On visit 5, they completed a 10-min moderate intensity run at sLT, for the assessment of running economy. This was immediately followed by a 30-min downhill run (−15% grade) at 70% $\dot{V}O_{2peak}$; this was expected to result in appreciable muscle damage based on previous reports (17–19). On visit 6, 48 h after the downhill run (i.e., damaged state), the participants provided muscle tissue and venous blood samples and completed another 10-min moderate intensity run at sLT.

The starting speed for the downhill run was equivalent to $sLT + 2$ km·h^{-1}. Breath-by-breath pulmonary gas exchange data were monitored throughout the downhill run, and treadmill speed was adjusted every 5 min, if necessary, to maintain the predetermined 70% $\dot{V}O_{2peak}$ target for each participant.

Measurements

Perceived muscle soreness. Participants were asked to rate their perceived muscle soreness on a scale consisting of 0 to 6 points, where 0 represents "no soreness" and 6 is indicative of "intolerable soreness." They were also asked to indicate at what maximum intensity they believed themselves capable of running using a modified 10-point RPE scale, where 0 denotes "nothing" and 10 represents "maximal/

exhaustion." Participants were asked to provide their ratings on seven occasions: 1) at rest, immediately before the pre-downhill moderate-intensity run; 2) immediately after the downhill run; 3) at rest, 24 h after the downhill run; 4) at rest, 48 h after the downhill run and immediately before the 48-h post–moderate-intensity run; 5) immediately after the 48-h post–moderate-intensity run; 6) at rest, 72 h after the downhill run; and 7) at rest, 1 wk after the downhill run.

Venous blood analysis. Venous blood samples were drawn from an antecubital vein into 5-mL lithium-heparin tubes (Vacutainer; Becton-Dickinson, Franklin Lakes, NJ) and centrifuged at 4000 rpm and 4°C for 8 min. Plasma was extracted and immediately stored at −80°C for subsequent determination of total CK. Plasma CK was determined spectrophotometrically according to the International Federation of Clinical Chemistry–approved method by CK-N-acetylcysteine kinetic measurement (37°C) with commercial reagents (Roche Diagnostics, Meylan, France) for use on the Cobas 8000/c702 (Roche Diagnostics, Mannheim, Germany).

Pulmonary gas exchange. Breath-by-breath pulmonary gas exchange and ventilation were measured continuously during all treadmill tests. Participants wore a facemask and breathed through a turbine assembly (Triple V, Jaeger; Viasys Healthcare GmbH, Hoechberg, Germany). The inspired and expired gas volume and concentration signals were continuously sampled, the latter using paramagnetic (O_2) and infrared (CO_2) analyzers (Jaeger Oxycon Pro; Viasys Healthcare GmbH) via a capillary line connected to the face mask. The analyzers were calibrated before each test using a known gas mixture (15.12% O_2 and 5.07% CO_2) and ambient air. The turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph Inc., Shawnee, KS). The volume and concentration signals were time aligned, accounting for the transit delay in capillary gas and analyzer rise time relative to the volume signal. Breath-by-breath data were converted to second-by-second data using linear interpolation and $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$, and RER were assessed for each 30-s time period.

Running economy. The gross oxygen cost (O_c; mL·kg^{-1}·km^{-1}) was calculated for all speeds ≤ sLTP, and the energy cost (E_c; kcal·kg^{-1}·km^{-1}) of running was calculated for all speeds ≤ sLTP with RER <1.00. For the incremental tests, a valid running economy measurement had to be achieved at the same running speeds in both footwear conditions within-participant to be included in the analysis. The mean running economy for each individual for each footwear condition was then determined and used for further analysis. The O_c of running was derived from the final 60-s mean $\dot{V}O_2$ measured during each stage of the incremental test, and the mean $\dot{V}O_2$ measured over the final 5 min of the moderate-intensity runs. The attainment of $\dot{V}O_2$ steady state was defined as an increase of <50 mL during the final 60 s and/or an increase of <25 mL during the final 30 s of each 3-min stage for the incremental test and was confirmed in all cases. The same criteria were applied during the final 5 min of the 10-min moderate-intensity runs. The E_c of running was determined for the incremental tests (experiment I) and the moderate-intensity runs (experiment II)

using $\dot{V}O_2$ and $\dot{V}CO_2$ data measured during the same time periods used to determine O_c. For E_c, the relative contributions of fat and carbohydrate metabolism (g·min^{-1}) were calculated using updated nonprotein respiratory quotient equations (26), and the energy derived from fat and carbohydrate at rest and during exercise was calculated by multiplying the amount of substrate oxidized by its energy equivalent (27). It is not possible to calculate E_c when RER exceeds 1.00, but O_c was recorded with the proviso that $\dot{V}O_2$ was clearly in steady state according to the criteria stated previously.

Muscle biopsy. Muscle tissue samples were obtained at rest through an incision (~0.6 cm) made to the skin above the medial aspect of the *vastus lateralis* muscle under local anesthesia (~3 mL of 20 mg·L^{-1} lidocaine without adrenaline) using the percutaneous needle biopsy technique under suction (28). Biopsy samples were immediately placed in a 0.1 M phosphate buffer solution, dissected free from fat and connective tissue, subdivided, fixed in 2% glutaraldehyde and 2% paraformaldehyde solution in 0.1 M sodium cacodylate buffer (pH 7.2), and stored at 4°C until further processing.

Muscle tissue analysis. The muscle tissue sample was washed in buffer (3 × 5 min), and small fragments of tissue were postfixed in 1% osmium tetroxide (reduced with 1.5% wt/vol potassium ferrocyanide) in cacodylate buffer for 1 h. Samples were subsequently washed (3 × 5 min) in deionized water and stained *en bloc* in 1% uranyl acetate for 1 h, then washed (3 × 5 min) again in deionized water, and dehydrated in a graded ethanol series (30%, 50%, 70%, 80%, 90%, and 95% for 10 min, each followed by 2 × 100% for 20 min) before being embedded in Spurr resin (Taab Laboratories, Aldermaston, United Kingdom). The muscle tissue fibers were aligned in the embedding molds to permit longitudinal sectioning along the fibers. Ultrathin sections of 60 nm were collected on pioloform-coated 100-mesh copper EM grids (Agar Scientific, Standsted, United Kingdom) and contrasted with Reynold's lead citrate. The sections were imaged using a transmission electron microscope (JEM-1400, JEOL, Peabody, MA) operated at 120 kV, and images were taken with a digital camera (ES 1000 W CCD; Gatan, Abingdon, United Kingdom).

Prepared sections were sampled and subsequently assessed for indices of muscle damage, with the research technician blind to both the sample treatment group (i.e., footwear condition) and time point (i.e., before or 48 h after downhill run). Sarcomeres were sampled systematically by taking 10–13 micrographs at a magnification of 20,000×. Subsequently, each image was assessed for disruption to sarcomere banding patterns and classified according to Z-disk damage, as follows: 0, no damage; 1, wavy appearance; 2, mild streaming; and 3, disintegration (29). The percentage of images corresponding with each rating was subsequently determined for each individual at each time point. To assess sarcomere and A-band lengths, each image was overlaid with a randomly placed square grid lattice (grid spacing, 3.1623 μm) and measurements were performed at each vertical intersection with the center of Z lines and the edge of the A-bands, respectively, and this resulted in 59 ± 9 fibers (range, 44–82) from each sample.

Statistical Analysis

For experiment I, paired-samples t-tests were used to evaluate differences in running economy (O_c and E_c), $\dot{V}O_{2peak}$, peak running speed, sLT, sLTP, running speed at 3 mM blood lactate, and T_{lim} between footwear conditions during the incremental treadmill tests, and to test for any order effect. Pearson's product–moment correlation coefficients were used to assess relationships between 1) differences in running economy between shoes and incremental test performance (T_{lim}), and 2) differences in running economy between shoes and body mass.

For experiment II, independent-samples t-tests were used to evaluate between-group differences in running economy (O_c and E_c), %$\dot{V}O_{2peak}$ sustained, and mean running speed during the downhill run. A two-way repeated-measures ANOVA was used to assess differences in running economy between the moderate-intensity runs (i.e., before and 48 h after downhill run) due to footwear. Further two-way repeated-measures ANOVA (condition–time) was used to assess the influence of footwear on subjective ratings of exertion, muscle soreness, changes in sarcomere and A-band lengths, and blood biochemistry (i.e., plasma CK) measurements. Separate mixed-model ANOVAs were performed according to Z-disk damage classification.

Statistical analyses were run using Statistical Package for the Social Sciences version 26. Statistical significance was set as $P < 0.05$. Significant interactions and main effects were examined using Bonferroni *post hoc* tests. Data are presented as mean ± SD.

RESULTS

Experiment I: Effect of Footwear on Running Economy and Performance during Incremental Exercise

The mean starting speed for the incremental tests was 8.0 ± 1.0 km·h^{-1}. No significant test order effect was observed for any measures (all $P > 0.05$). When focusing on footwear conditions, a significant difference was observed for T_{lim} ($P < 0.01$), with participants running 5.7% ± 5.8% longer in the HCS (29:16 ± 6:45 min:ss) compared with CON (27:48 ± 6:43 min:ss), despite no difference in $\dot{V}O_{2peak}$ (CON: 3.52 ± 0.76 vs HCS: 3.48 ± 0.74 L·min^{-1}). Peak running speed attained was significantly ($P < 0.001$) greater in HCS (16.5 ± 2.1 km·h^{-1}) compared with CON (16.1 ± 2.1 km·h^{-1}; Fig. 2). There was no significant difference in sLT (CON: 10.3 ± 1.8 vs HCS: 10.4 ± 1.9 km·h^{-1}) or sLTP (CON: 12.8 ± 2.0 vs HCS: 12.8 ± 2.1 km·h^{-1}) between conditions (all $P > 0.05$). However, there was a significant increase in the running speed corresponding to a fixed blood [lactate] of 3 mM ($P < 0.05$), with individuals able to run at a higher speed in the HCS (13.0 ± 2.3 km·h^{-1}) compared with CON (12.6 ± 2.1 km·h^{-1}; Fig. 2).

Valid running economy measurements were obtained at 6 ± 2 running speeds for O_c ($n = 32$) and 4 ± 2 running speeds for E_c ($n = 22$). The O_c of running was significantly lower in the HCS (O_c, 204 ± 15 mL·kg^{-1}·km^{-1}) compared with CON (O_c, 210 ± 16 mL·kg^{-1}·km^{-1}; $P < 0.001$; Fig. 2), with the magnitude of the difference ranging from -7.0% to $+11.2\%$ (Fig. 3). The footwear-specific improvements in O_c were significantly correlated with changes in E_c ($r = 0.87$, $P < 0.001$; $n = 22$), but the difference in E_c between HCS (1.04 ± 0.07 kcal·kg^{-1}·km^{-1}) and CON (1.07 ± 0.09 kcal·kg^{-1}·km^{-1}) was not significant ($P = 0.07$). The improvement in incremental test performance was not significantly correlated with the change in running economy between footwear conditions when expressed either in absolute units (O_c, $r = -0.25$, $P = 0.16$; E_c, $r = 0.04$, $P = 0.99$) or as a percent change (O_c, $r = 0.31$, $P = 0.09$; E_c, $r = 0.04$, $P = 0.86$). No significant relationship was observed between body mass and the absolute ($r = -0.20$, $P = 0.27$; E_c, $r = -0.13$, $P = 0.55$) or percent ($r = 0.22$, $P = 0.22$; E_c, $r = 0.14$, $P = 0.54$) change in running economy between footwear conditions.

Experiment II: Effect of Footwear on Running Economy after Muscle Damage

There were no significant differences in physical characteristics or physiological/fitness indices between the two groups of participants who were pair-matched to take part in this experiment (Table 1).

Downhill run. Participants ran at 13.6 ± 1.9 km·h^{-1} during the downhill run, and this required 65% ± 5% of their incremental test $\dot{V}O_{2peak}$ between 5 and 30 min. No significant differences were observed in the mean running speed ($P = 0.92$) or the percentage $\dot{V}O_{2peak}$ sustained ($P = 0.49$) between footwear conditions.

Muscle histology. It was not possible to assess Z-disk disruption for one participant in the HCS group in the nondamaged state due to poor quality TEM images. In this case, the group mean score was applied. Accordingly, a total of 680 TEM images (pre: $n = 330$; post: $n = 350$) from 61 muscle tissue samples were evaluated blindly by three assessors. There was high interrater agreement for Z-disk damage ($r = 0.91$).

As expected, in the nondamaged state, there was no footwear-specific difference in the classification of muscle damage ($P > 0.05$; Fig. 4). When considered across the entire cohort, 80% ± 21% of the TEM images had no indication of muscle damage, 16% ± 14% presented with a wavy Z-disk, 3% ± 12% had mild disruption, and 1% ± 3% were classed as disintegrated. In the damaged state, there were fewer TEM images that presented with no indication of muscle damage (46% ± 31%; $P < 0.001$), and there was a significant increase ($P < 0.001$) in the number of images presenting with a wavy Z-disk (41% ± 26%), relative to the nondamaged state. No significant differences were observed in the number of images with mild disruption (9% ± 18%; $P = 0.07$) or with disintegrated (4.0% ± 12%; $P = 0.48$) Z-disks between damaged and nondamaged states. Footwear had no significant effect on the extent of muscle damage observed after the downhill run (all $P > 0.05$). Sarcomere length was significantly ($P = 0.02$) different across the cohort between the nondamaged (2003 ± 25 nm) and damaged (2095 ± 41 nm) conditions, but there was no footwear-specific difference in this change
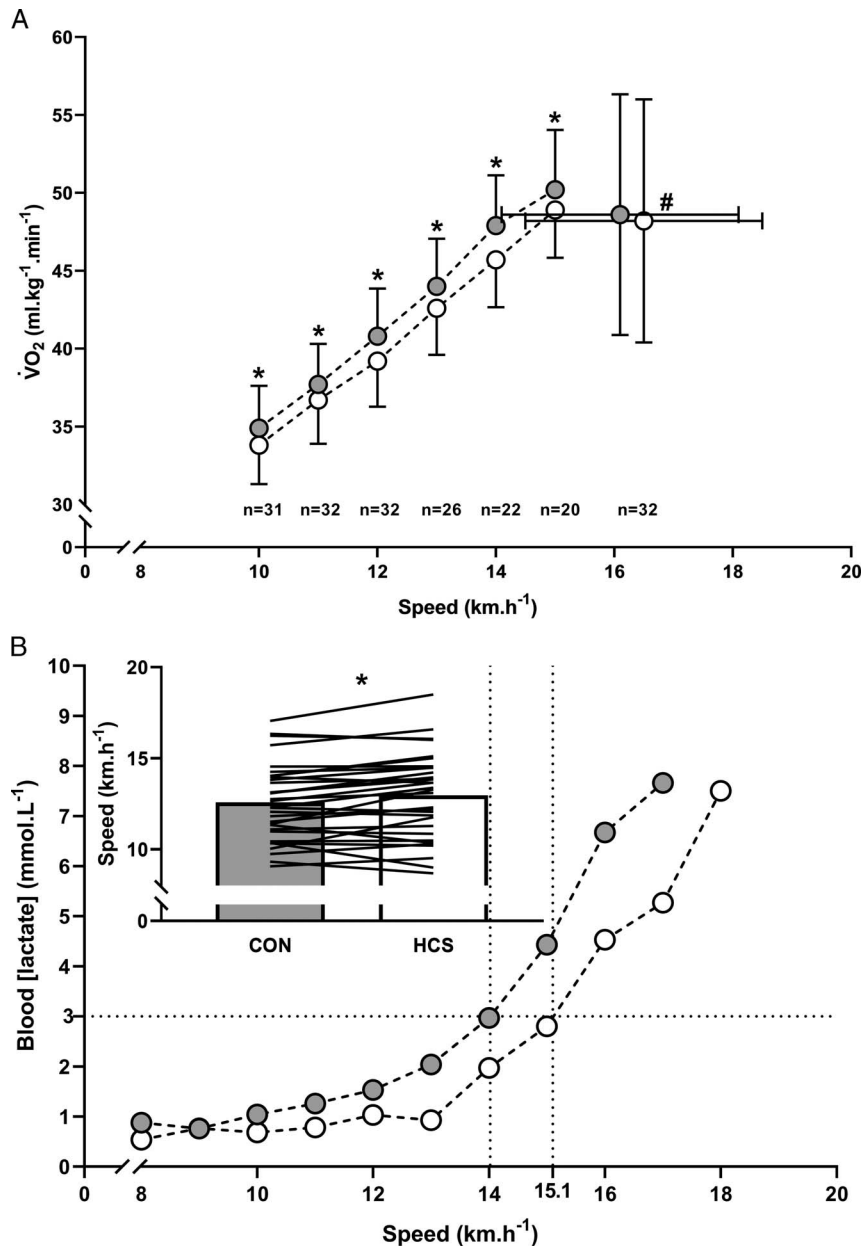
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FIGURE 2—Effect of footwear (CON, *gray*; HCS, *white*) on the O_c of running (A) and blood [lactate] (B) during the incremental treadmill test. For panel A, the group mean running economy is provided for each speed where a valid measurement had been attained in both footwear conditions within-participant ($n \geq 20$), with the sample size at each speed indicated. In panel B, the blood [lactate]–speed relationship is provided for a representative participant and the group mean speed at 3 mM blood [lactate] is also illustrated in the inset figure. The dotted lines in panel B indicate the speed corresponding to a blood [lactate] of 3 mM for CON and HCS. *Statistically significant between-condition difference ($P < 0.05$). #Statistically significant between condition difference in peak running speed ($P < 0.05$).

($P = 0.78$). No differences were observed in the length of the A-band after the downhill run ($P = 0.44$), and there was no group-specific effect between the pre- and 48-h post-downhill runs ($P = 0.64$).

Creatine kinase. Resting plasma CK values in the non-damaged state were not significantly different ($P = 0.67$) between HCS (290 ± 384 U·L^{-1}) and CON (345 ± 324 U·L^{-1}). Plasma CK was significantly elevated ($P < 0.01$) in the HCS (870 ± 597 U·L^{-1}) and CON (474 ± 282 U·L^{-1}) 48-h post-downhill run, but there was no footwear-specific difference in this change ($P = 0.07$).

Subjective ratings. Ratings of perceived muscle soreness were significantly altered during the study period ($P < 0.01$). Participants experienced peak soreness 48 h after the downhill run, with soreness returning to baseline after 7 d, with no footwear-specific differences in the severity or time course of the response (all $P > 0.05$). The maximum intensity that participants perceived they would be able to run was also altered in the damaged state, mirroring the response profile for perceived muscle soreness. No footwear-specific differences were observed for estimated running intensity ($P = 0.74$), with both groups indicating that they could run
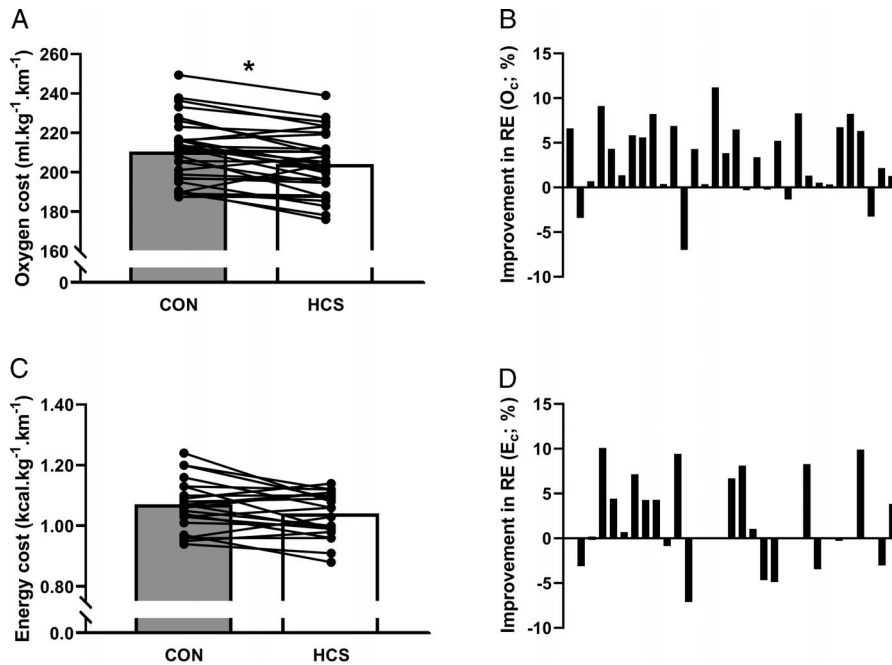
FIGURE 3—Effect of footwear (CON, *gray*; HCS, *white*) on running economy during the incremental treadmill test. The mean O_c (A) and E_c (B) across all speeds are shown for the group and each individual for all speeds where a valid running economy had been attained in both footwear conditions within-participant. The within-participant change in running economy is displayed for O_c (C) and E_c (D). *$P < 0.05$.

at a similar intensity at the pre- and 48-h post-downhill run time points ($P = 0.36$).

Moderate-intensity runs. The moderate-intensity runs were performed at sLT, which occurred at 10.4 ± 1.8 $km \cdot h^{-1}$ or $75\% \pm 7\%$ $\dot{V}O_{2peak}$. Despite being performed at a relatively low intensity, an RER >1.00 precluded the assessment of E_c in nine participants during the pre-downhill run. The group mean RER was 0.96 ± 0.03 ($n = 23$). Because of a significant ($P = 0.03$) increase in RER for the 48-h post-downhill run condition (group mean RER, 0.98 ± 0.04), the pre- to 48-h post-downhill run E_c comparison was limited to 16 participants (CON, $n = 8$; HCS, $n = 8$). For these 16 participants, the pre- and 48-h post-downhill run RER values were 0.95 ± 0.04 and 0.95 ± 0.03, respectively.

The O_c during the pre-downhill moderate-intensity run was not significantly different ($P = 0.14$) between the CON (211 ± 17 $mL \cdot kg^{-1} \cdot km^{-1}$) and HCS ($O_c$, 202 ± 16 $mL \cdot kg^{-1} \cdot km^{-1}$) groups. Similarly, no statistical difference ($P = 0.42$) was observed for E_c between CON (1.04 ± 0.08 $kcal \cdot kg^{-1} \cdot km^{-1}$) and HCS ($1.01 \pm 0.06$ $kcal \cdot kg^{-1} \cdot km^{-1}$). The O_c was significantly ($P < 0.001$) different across the cohort for the moderate-intensity run performed before (206 ± 17 $mL \cdot kg^{-1} \cdot km^{-1}$) and 48 h after the downhill run (216 ± 15 $mL \cdot kg^{-1} \cdot km^{-1}$), but the change in O_c was not different ($P = 0.73$) between CON ($+11 \pm 10$ $mL \cdot kg^{-1} \cdot km^{-1}$) and HCS ($+9 \pm 10$ $mL \cdot kg^{-1} \cdot km^{-1}$). However, O_c was significantly ($P = 0.048$) lower in HCS (O_c, 211 ± 11 $mL \cdot kg^{-1} \cdot km^{-1}$) compared with CON ($O_c$, 221 ± 17 $mL \cdot kg^{-1} \cdot km^{-1}$) during the moderate-intensity run 48 h after the downhill run (Fig. 5A). There was no significant difference in E_c between the pre- and 48-h post-downhill runs ($P = 0.17$), nor was there a difference in E_c between the CON

and HCS groups at 48 h after the downhill run ($P = 0.51$; Fig. 5B).

DISCUSSION

We examined the effects of an HCS compared with a control running shoe on 1) incremental running performance and running economy (as O_c and E_c) and 2) running economy after a downhill run used to elicit muscle damage. It should be noted that experiment I used a crossover design such that participants completed an incremental treadmill test in both the HCS and the CON shoes on separate days. In contrast, because

TABLE 1. Group mean physical and physiological characteristics for the two groups of participants in experiment II.

|	CON ($n = 16$)	HCS ($n = 16$)
Physical characteristics		
Age (yr)	24 ± 7	24 ± 7
Height (m)	1.73 ± 0.08	1.76 ± 0.06
Mass (kg)	70.9 ± 11.7	73.5 ± 7.9
Sex (M/F)	9/7	13/3
Physiological descriptors, experiment 1		
CON		
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	48.1 ± 7.2	49.2 ± 8.4
sLT ($km \cdot h^{-1}$)	10.3 ± 1.6	10.4 ± 2.0
$sLTP$ ($km \cdot h^{-1}$)	12.8 ± 1.6	12.9 ± 2.3
Speed at 3 mM	12.4 ± 1.9	12.8 ± 2.3
O_c ($mL \cdot kg^{-1} \cdot km^{-1}$)	209 ± 14	212 ± 18
E_c ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.06 ± 0.07	1.08 ± 0.10
HCS		
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	47.4 ± 6.7	48.9 ± 8.9
sLT ($km \cdot h^{-1}$)	10.4 ± 1.6	10.5 ± 2.2
$sLTP$ ($km \cdot h^{-1}$)	12.8 ± 1.7	12.9 ± 2.4
Speed at 3 mM	12.8 ± 1.9	13.1 ± 2.7
O_c ($mL \cdot kg^{-1} \cdot km^{-1}$)	205 ± 11	203 ± 19
E_c ($kcal \cdot kg^{-1} \cdot km^{-1}$)	1.05 ± 0.06	1.04 ± 0.10

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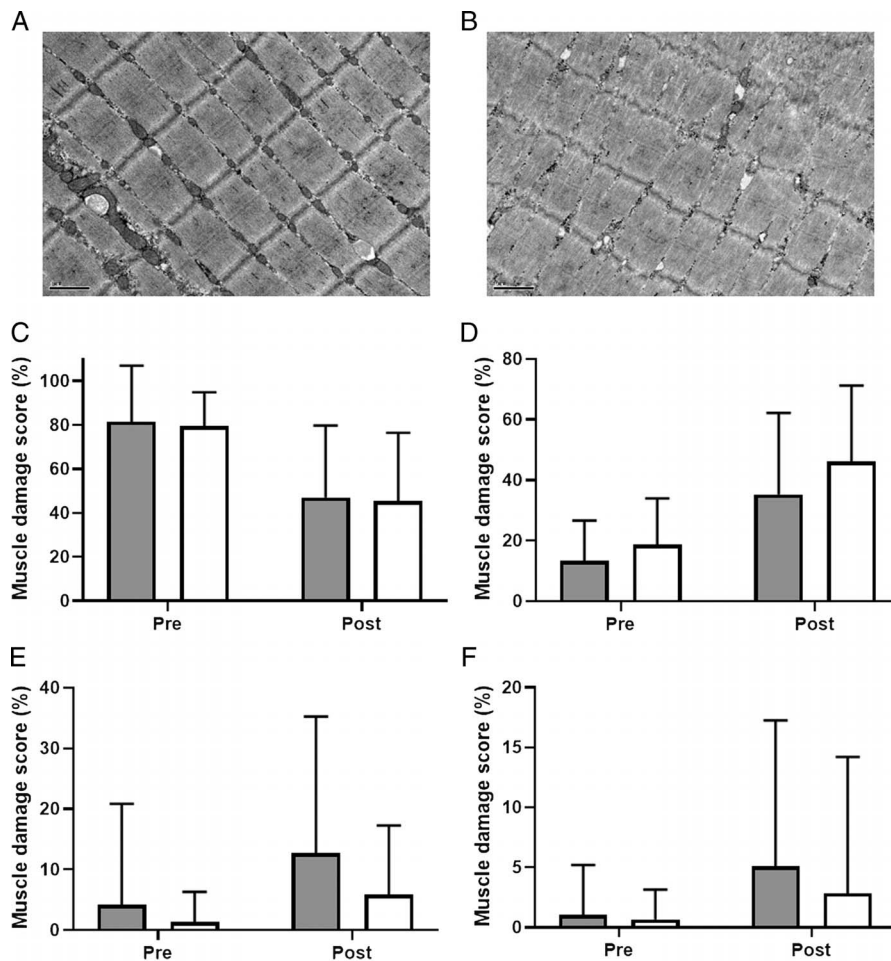
FIGURE 4—Representative electron micrographs of longitudinal skeletal muscle sections pre- (A) and 48 h post- (B) downhill running in the CON condition, and the group mean (±SD) TEM ratings of muscle damage (C–F) for CON (*gray columns*) and HCS (*white columns*). Each TEM image was scored according to the absence (C) or presence (D) of wavy Z-disk, mild Z-disk streaming (E), or disintegration of the Z-disk (F), and the percentage of images corresponding to each rating was subsequently determined for each participant. *Main effect for time, $P < 0.05$.

of the "repeated bout" effect on indices of muscle damage (30), experiment II used a parallel groups design in which participants were pair-matched to either an HCS or a CON shoe group and then undertook a single trial assessment of running economy both before and after a downhill run designed to elicit substantial muscle damage. The principal novel findings were that, compared with CON, HCS improved incremental treadmill test performance (~5.7%) and reduced O_c (~3.2%), and 48 h after a 30-min downhill run at −15% grade, which elicited muscle damage, O_c was lower (by ~4.7%) in HCS compared with CON. This study indicates HCS improved incremental treadmill test performance and enhanced O_c, but not E_c, both in the absence and presence of muscle damage.

Experiment I: Effect of footwear on running economy and performance during incremental exercise. We tested the hypothesis that an HCS would enhance incremental exercise performance and improve running economy (i.e., lower the O_c of running) in a "fresh," nondamaged, state relative to CON. In support of this hypothesis, we found that HCS improved incremental test performance (T_{lim} was increased by ~5.7%) and enhanced O_c (which was reduced by

~3.2%) across a range of submaximal speeds (Fig. 2A). Importantly, the improvement in O_c we measured in HCS compared with CON was greater than the test–retest variability for O_c assessment in our laboratory (2.8% ± 2.2%). Our economy findings are consistent with previous investigations on footwear made with compliant and resilient midsoles (31,32) and a prototype of the Nike Zoom Vaporfly 4% (21–24), but here we build on previous findings to show that incremental exercise performance is also enhanced by HCS compared with CON. The first study to evaluate the Vaporfly prototype reported a 4% mean improvement in metabolic power relative to two other established marathon racing flats/shoes (Nike Zoom Streak 6 and Adidas Adizero Adios Boost 2). Similar to the findings of the present study, this effect was independent of running speed (23). These findings were further corroborated by Hunter et al. (24) and Barnes and Kilding (21). Hunter and colleagues (24) reported that O_c was, on average, ~2% and ~3% lower in the Vaporfly 4% relative to the Streak 6 and Boost 2 marathon shoes, respectively. Similarly, Barnes and Kilding (21) reported that the Vaporfly 4% improved running economy by ~3% relative to track spikes (Nike Zoom Matumbo 3)

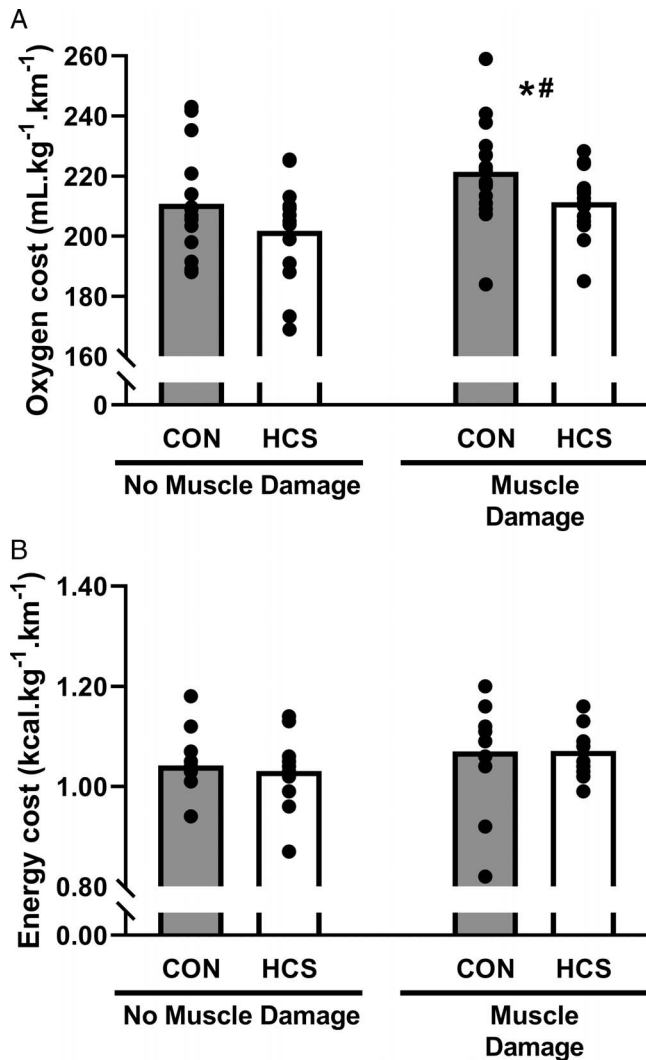APPLIED SCIENCES

FIGURE 5—O_c (A) and energy cost (B) of running at sLT (10.4 ± 1.8 km·h^{-1}) before and 48 h after the downhill run for CON and HCS. *Within-group effect for time, $P < 0.05$. #Between-group effect, $P < 0.05$.

correlated with the improvement in O_c. The absence of a significant correlation might be explained, in part, by reduced sensitivity of performance measurement when utilizing a discontinuous "step-based" incremental test compared with a continuous "ramp" test. However, the dissociation between improvements in exercise performance and improvements in O_c might also suggest that HCS benefits running performance through mechanisms that are independent of effects on running economy. There was no significant difference in sLT or $sLTP$ between the HCS and CON conditions, but this might again be related to limited sensitivity of the multistage test protocol (i.e., LT and LTP can only be selected at discrete speeds). However, there was a clear rightward shift in the blood [lactate]–running speed relationship with HCS compared with CON (Fig. 2B), such that when the speeds corresponding to fixed blood lactate concentrations, such as 3 mM, were interpolated, they were significantly higher in HCS than in CON. The right-shifted lactate–speed relationship paralleled the right-shifted $\dot{V}O_2$–speed relationship and would be expected to result in enhanced endurance running performance (33).

We observed substantial interindividual differences in the improvement in O_c afforded by the HCS shoe, which ranged from -7.0% to $+11.2\%$, but with 26 out of 32 (81%) participants experiencing improved O_c with HCS (Fig. 3B). The variability of this response could not be explained by sex, differences in body mass, or $\dot{V}O_{2peak}$ and would also have been influenced by potential measurement error and day-to-day variability in O_c. Thus, our results suggest that the potential benefits of differences in shoe properties may not be "global" but rather may be specific to individual participants or specific circumstances.

Experiment II: Effect of footwear on running economy after muscle damage. Downhill running is associated with considerable eccentric muscle actions and loading, a combination that is known to result in significant muscle damage (6). The purpose of this experiment was to determine whether the decrement in running economy that typically accompanies muscle damage may be influenced by running shoes with differing cushioning properties. We utilized a range of assessment techniques to appraise the extent of muscle damage after a bout of downhill treadmill running including direct (i.e., Z-disk disruption/damage via muscle biopsy), indirect (i.e., plasma CK; perceived muscle soreness), and functional (i.e., running economy) assessments of muscle damage and performance. Using transmission electron microscopy, we detected significant, albeit relatively minor, structural changes to the Z-disk and lengths of the sarcomere and A-band after the downhill run (Fig. 4). We also observed a mild twofold increase in plasma CK relative to baseline, and participants reported substantial muscle soreness. Because of its high task specificity, our primary functional measure to assess the extent of muscle damage was running economy. Consistent with the other markers of muscle damage, we observed a significant increase in O_c (but not E_c) when running at a comfortable speed (sLT) after the downhill run compared with before the downhill run (Fig. 5).

and by 4% relative to the Adidas Adizero Adios 3 marathon racing shoes. Most recently, Hebert-Losier et al. (22) found that the Vaporfly 4% improved running economy by 4.3%–4.4% at a range of running speeds and reported that the mean running speed during a 3-km TT was increased by ~0.4 km·h^{-1} relative to participants' habitual running shoes.

Although O_c was significantly lower in HCS compared with CON, there was no significant difference in E_c between footwear conditions ($P = 0.07$) despite the magnitude of effect being similar for O_c and E_c and there being a significant correlation between the change in O_c and the change in E_c with HCS compared with CON. This difference is likely a function of the greater number of valid data sets available for O_c compared with E_c. E_c cannot be calculated when RER >1.00, whereas we accepted O_c provided that $\dot{V}O_2$ met our stringent criteria for being steady state (see "Experimental considerations").

Surprisingly, the improvement in incremental treadmill test performance with HCS in the present study was not significantly

Before performing the downhill treadmill run, participants completed a 10-min run at sLT for the assessment of running economy in the nondamaged state. This run was followed immediately by a downhill running protocol. Then, 48 h later, the participants completed another 10-min run at sLT. In contrast to the findings of experiment I, and despite a similar magnitude of difference between footwear conditions (~4%), we observed no significant difference in O_c pre-downhill run between HCS and CON in this parallel groups design, presumably as a consequence of heterogeneity and the smaller sample size in experiment II (see "Experimental considerations"). Furthermore, we observed no footwear-specific difference in the extent of increase in O_c after the downhill treadmill run. However, in support of our second hypothesis, we found that the O_c of running at sLT 48 h after the downhill run was significantly lower in the HCS group (−4.6%) compared with the CON group.

Consistent with our intent to evoke muscle damage capable of altering running economy, the extent to which O_c was increased (+5.2%) 48 h after the downhill treadmill run was similar to other studies that utilized a downhill running protocol to induce muscle damage (+3.2%, [17]; +6.4%, [18]; +5% [19]). Moreover, the increase in O_c was similar to that reported after a marathon (+7%, [15]) and a competitive duathlon (+5%, [20]). These changes may be attributed, at least partly, to an increased metabolic demand arising from damaged fibers (34,35), which, during exercise, continue to consume O_2 but contribute to a much lesser extent to force generation (15). Indeed, greater muscle fiber excitation and thus increased potential for fiber activation (36) are typically observed during submaximal isometric muscle actions after damaging exercise (37,38). Muscle damage may also alter muscle fiber recruitment patterns and thus may help to explain the changes in running kinematics that have been observed after exercise-induced muscle damage (17,39).

In evaluating the effects of muscle damage and footwear on the energy cost of running (E_c), we observed a significant increase in RER 48 h after the downhill run in both footwear conditions, indicative of increased carbohydrate metabolism. Although this may be partly the consequence of an increased relative exercise intensity due to the elevated O_c, this change in substrate utilization may also be due to the presence of inflammatory cells that stimulate glucose oxidation and also reduce the maximal work capacity of the muscle(s) (40). Because of the increase in RER during the moderate-intensity run 48 h after downhill exercise, it was not possible to assess E_c in 16 participants. Based on substrate-dependent differences in the amount of ATP produced per molecule of O_2 consumed, increased carbohydrate utilization would be expected to decrease O_c, assuming that the underlying energetic demands remain unchanged (41). However, in spite of a muscle damage-related increase in RER during the moderate-intensity run, O_c was greater, indicating that other factors connected with muscle damage more than offset the effect of a relatively minor change in substrate utilization on O_c. Muscle damage clearly represents a scenario in which changes in RER can influence the relationship between O_c and E_c.

There was no footwear-specific difference in the extent of muscle damage evident 48 h after the downhill run in any of our measurements (see "Experimental considerations"). It should be recognized that the extreme decline (−15%) used in the downhill running protocol is in contrast to conditions typically experienced during training and competition, and likely results in differences in the etiology of muscle damage, with more significant mechanical disruption and less metabolic disturbance experienced during extreme downhill running compared with regular training and competition (42). Although the extreme downhill protocol provided the opportunity to induce substantial muscle damage in a time-efficient and well-controlled manner, it likely negated our ability to differentiate the effect of footwear on muscle damage, *per se*, or to investigate possible differences in running economy *during* the damaging exercise. As a result, generalization of the results beyond the present conditions is limited. Although some preliminary evidence exists in other cushioned footwear (43), further detailed investigation is required to determine whether HCS may be effective in reducing muscle damage during conditions that are more typical of field-based exercise (i.e., athletes experiencing a high daily and weekly training load), during which an improved running economy is also likely to be evident.

Implications for performance. The results of the present study have several potentially important implications for athlete performance and training. With regard to performance, the running speed that can be maintained during the marathon can be estimated according to the sustainable $\dot{V}O_2$ (which, for this example, is assumed to equate to the mean $\dot{V}O_2$ at sLT) and running economy, determined as O_c (i.e., sustainable marathon running speed ($km·h^{-1}$) = $\dot{V}O_2$ at sLT ($mL·kg^{-1}·min^{-1}$) × 60/O_c ($mL·kg^{-1}·km^{-1}$); [1]). Accordingly, the observed 3.2% improvement in O_c in HCS compared with CON in the nondamaged state can be estimated to enhance marathon running speed by ~0.35 $km·h^{-1}$ (3.6%), and thus improve marathon running times by approximately 9 min for individuals with physiological characteristics similar to the participants in the current study ([1]; but see also Ref. [44] for important caveats). Given that the typical variation in marathon performance is ~2.6% (45) and is lower still in elite athletes (e.g., the performances of the Men's Marathon World Record holder varied by 0.95% for the 2018 and 2019 London Marathon races), it is clear that HCS may provide considerable benefit to distance running performance.

Our findings also demonstrate, for the first time, that HCS may improve running economy compared with CON when skeletal muscles have been damaged by eccentric exercise (i.e., downhill running). It may be speculated that this reduction in the metabolic demand of running in both the nondamaged and damaged states may provide a useful means for coaches and athletes to manipulate training programs to improve performance. For example, in reducing the metabolic cost of running, thus reducing the physiological and perceptual strain of running at a given speed, HCS may permit a greater volume of training to be accomplished; conversely, for the same physiological and perceptual demand, athletes

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may train at a higher intensity (43). Similarly, HCS may have the potential to accelerate an athlete's return to high-intensity training after competition or an intense period of training. The potential role of footwear to manipulate training load and physiological and performance adaptations is a ripe area for future research.

We observed no sex-specific differences between footwear conditions in experiment I or experiment II. Specifically, incremental exercise performance and O_c were enhanced to a similar extent for both males and females in the nondamaged state (experiment I), and a similar difference in O_c was noted in both sexes in the HCS group compared with CON in experiment II. These results suggest that, although HCS is variable across individuals, it may have similar efficacy for males and females.

Experimental considerations. We found that O_c (but not E_c) was significantly improved during incremental exercise in the HCS shoe relative to CON in experiment I, but not in the nondamaged state during experiment II despite a similar effect size (~3%–4%). This discrepancy may be due to lower statistical power in experiment II, which used a parallel-groups design, relative to experiment I, which used a within-subject, repeated-measures design. Based on the effect size observed in experiment II (Cohen's $d = 0.55$), 108 participants would be required to achieve 80% statistical power. It is therefore important to consider the findings of experiment II within the context of experiment I and other studies (e.g., [21–24,31,32]) that have consistently shown that running shoes with a highly compliant and resilient foam sole improve running economy. We also note that despite having a similar direction and magnitude of change to O_c, differences in E_c did not attain statistical significance in the present study. Again, this seems to be a function of statistical power, with fewer data being available for E_c compared with O_c because of the effects of muscle damage on RER and the inability to calculate E_c in such circumstances. We included O_c in the analyses at running speeds up to and including $sLTP$ even if RER exceeded 1.0—but only when $\dot{V}O_2$ met our stringent criteria for being accepted as steady state. During exercise, hyperventilation due to anxiety, pain, or mouthpiece discomfort can elevate RER despite $\dot{V}O_2$ being stable and there being negligible nonoxidative contribution to total energy turnover.

The O_c of running is predictably impaired with increased shoe mass, with a 100-g increase in mass resulting in a ~1% increase in O_c (46). In the current study, the CON shoe was approximately 30–40g heavier than HCS, depending on shoe size. This difference in shoe mass would be expected to lower O_c in HCS by ~0.35% relative to CON, which represents approximately 10% of the difference observed. Although it was not possible to mask the appearance or differences in "feel" between the running shoes, it was emphasized to each participant that it was not known whether the HCS would be detrimental or beneficial, or have no effect on running performance or the physiological responses to exercise. For experiment I, participants were randomly allocated to footwear condition to minimize any condition-order bias. No significant test order effect was observed for any physiological or performance-based measures.

It was not possible to assess plasma CK or to collect muscle tissue for determination of muscle ultrastructure at more frequent time points during the study. Given the high interindividual variability in the time course of plasma CK appearance and disappearance in the bloodstream after muscle-damaging exercise (47), we were unable to determine and thus compare peak responses between individuals. It should also be noted that the muscle biopsy procedure might itself increase plasma CK levels (48). These factors limited our ability to examine closely the possible effects of HCS in attenuating the extent of muscle damage incurred by the downhill running intervention.

We assessed running economy before and 48 h after muscle damaging exercise at a relatively slow and comfortable running speed, equivalent to each participant's predamage sLT. It has been previously shown that highly glycolytic, type II muscle fibers are more susceptible to eccentric exercise-induced muscle damage compared with more oxidative, type I muscle fibers (8). Our assessment of muscle damage did not account for possible differences in the extent of damage between type I and type II fibers, and it is possible that we would have observed even greater decrements in running economy after muscle damage at faster running speeds that require the recruitment of more type II muscle fibers. It should be noted that muscle tissue was collected from only the *musculus vastus lateralis*, and it is possible that other muscles, including the *soleus, gastrocnemius*, and *gluteus maximus*, may have experienced different degrees of muscle damage consequent to the downhill running intervention and/or been differentially influenced by footwear.

Our study included an acute insult designed to induce quite substantial muscle damage. The extent and etiology of this muscle damage likely differ from that typically experienced in regular training and competition. Nevertheless, the protocol provided an appropriate means to examine whether possible running economy improvements with HCS might be maintained in the face of substantial muscle tissue disruption. A preliminary report (43) and anecdotal evidence from athletes suggest that an alternate HCS can reduce training-related muscle soreness and enable the absorption of higher training loads. Further studies are required to determine whether HCS in general may ameliorate the fatigue or muscle damage that results from single high-intensity or long-duration training sessions, high weekly training loads, and competition.

CONCLUSIONS

In the absence of muscle damage, compared with CON, HCS significantly enhanced time to the limit of tolerance and the peak speed attained during an incremental treadmill test and reduced O_c across a range of speeds. The O_c was also significantly lower in HCS compared with CON, 48 h after downhill exercise, that is, in the presence of significant muscle damage. The findings of the present study therefore indicate that HCS may improve maximal incremental running performance and positively influence O_c both in the absence and presence of muscle damage induced by a single downhill run.

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