Running into fatigue: The effects of footwear on kinematics, kinetics, and energetics

Maximilian Sanno[1,2], Gaspar Epro[3], Gert-Peter Brüggemann[1], and Steffen Willwacher[1,4]

[1] Institute of Biomechanics and Orthopedics, German Sport University Cologne, Germany
[2] German Research Center of Elite Sport, German Sport University Cologne, Germany
[3] Sport and Exercise Science Research Center, School of Applied Sciences, London South Bank University, United Kingdom
[4] Department of Mechanical and Process Engineering, Offenburg University of Applied Sciences, Germany

Address for correspondence:
Maximilian Sanno
Institute of Biomechanics and Orthopedics
German Sport University Cologne
Am Sportpark Müngersdorf 6
50933 Cologne, Germany
Tel.: +49-221-49827630
Fax: +49-221-4971598
Email: max.sanno@web.de

ABSTRACT

Purpose: Recent studies identified a redistribution of positive mechanical work from distal to proximal joints during prolonged runs, which might partly explain the reduced running economy observed with running-induced fatigue. Higher mechanical demand of plantar flexor muscle-tendon-units, e.g., through minimal footwear, can lead to an earlier onset of fatigue, which might affect the redistribution of lower extremity joint work during prolonged runs. Therefore, the purpose of this study was to examine the effects of a racing-flat and cushioned running shoe on the joint-specific contributions to lower extremity joint work during a prolonged fatiguing run.

Methods: On different days, eighteen runners performed two 10-km runs with near-maximal effort in a racing-flat and a cushioned shoe on an instrumented treadmill synchronized with a motion-capture-system. Joint kinetics and kinematics were calculated at 13 pre-determined distances throughout the run. The effects of shoes, distance, and their interaction were analyzed using a two-factor repeated-measures ANOVA.

Results: For both shoes, we found a redistribution of positive joint work from ankle (-6%) to knee (+3%) and hip (+3%) throughout the entire run. Negative ankle joint work was higher ($p<0.01$) with the racing-flat compared to the cushioned shoe. Initial differences in foot-strike patterns between shoes disappeared after 2 km of running distance.

Conclusion: Irrespective of the shoe design, alterations in the running mechanics occurred in the first 2 km of the run, which might be attributed to the existence of a habituation rather than fatigue effect. While we did not find a difference between shoes in the fatigue-related redistribution of joint work from distal to more proximal joints, more systematical studies are needed to explore the effects of specific footwear design features.

Key Words: SHOE, ANKLE, JOINT TORQUE, RUNNING ENHANCEMENT, RUNNING ECONOMY, RUNNING MECHANICS, HEELSTRIKE PATTERN

INTRODUCTION

Running economy is an essential predictor of distance running performance and is defined by the metabolic cost for a given submaximal running velocity (1). Running economy declines with running-induced fatigue, which is, among other factors, related to changes in running mechanics (2–5). In a recent publication, we demonstrated that energy generation shifts partly from distal to proximal joints during a near-maximal effort 10-km run, which likely has a detrimental effect on running economy because more proximal joints are less equipped for efficient energy generation (6).

Previous studies suggest that changes in running mechanics are not always in a linear relationship with running distance and sometimes exhibit a higher rate of change in the beginning compared to later stages of an exhausting run (7,8). In our previous work (6), we also observed a nonlinear response to the running distance, e.g., in the positive work of the ankle, knee, and hip joints as well as the flexion angle and torque of the knee. However, we did not analyze these qualitatively observed nonlinearities in detail.

We speculate that at least two processes influence the changes in running mechanics with running distance: habituation and fatigue. Habituation might occur in the early stages of a run to harmonize the current state of a runner’s neuromuscular system with the running environment, e.g., footwear or surface, and the requirements of the run (running distance and velocity). On the other hand, fatigue is defined as the exercise-induced reduction in the ability to generate muscle force or power due to changes in the neural drive or exhaustion of contractile function (9) and might, therefore, affect running mechanics during later stages of prolonged runs. However, studies addressing running mechanics, especially joint kinetics, throughout fatiguing runs are rare (10), and therefore, knowledge about the potential influence of habituation and fatigue is limited.

Next to habituation and fatigue, footwear can also affect the running kinematics and kinetics within the lower extremities (8,11–16). When assessed in an unfatigued state, running with minimal footwear (very flexible, reduced cushioning, drop height, and mass compared to cushioned running shoes) places a higher mechanical demand (higher joint torques, negative power, and work) on the plantar flexor muscle-tendon-units in comparison to wearing more cushioned shoes (13,15,17–19). However, whether this higher mechanical demand on ankle plantar flexors in an unfatigued state amplifies the previously reported fatigue induced redistribution of joint work from the ankle towards more proximal joints throughout a fatiguing run (6) is currently not known.

Running shoes are predominantly characterized by their mass, built-in cushioning materials, longitudinal bending stiffness as well as motion control technologies incorporated underneath the medial longitudinal arch (20–22). These design features not only affect running kinematics and kinetics but also running economy (22–24). A recent study demonstrated that a prototype shoe incorporating a highly compliant and resilient midsole material with a full-length carbon-fiber plate was able to improve running economy on average by 4% (25). This improvement appears to be partly due to superior energy storage within the midsole foam material and reduced ankle plantarflexion torque (26). In case this lower mechanical plantarflexion demand in the unfatigued state (26) would affect the fatigue-induced redistribution of joint work, an additional pathway for the improvement of running economy with cushioned running shoes may be conceivable.

Therefore, the purpose of this study was to investigate the difference between a typical racing flat shoe and a typical cushioned running shoe with regards to joint-specific contributions to lower extremity joint work during a fatiguing 10-km run with a near-maximal effort in rearfoot runners. We hypothesized that using a racing flat shoe in comparison to a cushioned shoe leads to a more pronounced and earlier fatigue-related redistribution of positive work from distal to proximal joints during a fatiguing near-maximal effort run. This hypothesis was motivated by the findings that wearing racing flat shoes requires a higher mechanical demand at the ankle compared to cushioned shoes (13,15,19,26). Furthermore, we hypothesized that separating a fatiguing near-maximal effort run into a habituation and fatigue phase will reveal markedly larger changes in biomechanical parameters in the initial habituation compared to the fatigue phase of running. The findings of the present study will improve the understanding of habituation- and fatigue-related alterations in running mechanics and their interaction with footwear design in prolonged fatiguing runs.

METHODS

Participants

We recruited a total of eighteen male competitive (n = 6) and recreational (n = 12) long-distance runners (age 24.4 ± 3.7 years; body height 1.83 ± 0.06 m; body mass 77.1 ± 8.3 kg) with a season-best time between 34:00 min and 54:30 min in a 10-km run. These eighteen runners were a subset of the participants of a previous study (6) and were selected because they showed a habitual rearfoot strike landing pattern during shod running. We focused the analysis on rearfoot runners since we expected that cushioning systems would have the strongest effect in this type of footfall pattern. All participants stated that they had experience in the use of racing flats and cushioned shoes as well as running on a treadmill. Further, they were free of any musculoskeletal injuries or impairments for at least the prior twelve months. Each participant signed informed written consent before participation. The University Ethics Committee had approved the study protocol (No. 102/2017), and the protocol met all requirements for human experimentation following the Declaration of Helsinki.

Experimental protocol

In a cross-sectional study design, all participants performed two separate 10-km treadmill runs with near-maximal effort (105% of their season-best time throughout the 10-km distance with an average running velocity of 3.6 ± 1.1 $m \cdot s^{-1}$) as described in our previous study (6) with at least seven recovery days between the runs. Participants used a different shoe type for each run in a randomized order. Seven days before the first run, participants performed a run with a self-determined running velocity and duration to familiarize themselves with both shoes and the treadmill. Before each run, the participants executed a warm-up run in the test shoe at a self-determined running velocity with a duration of at least 5 minutes. The participants were continuously encouraged and kept informed of the covered distance during both runs.

Footwear properties

All participants wore two shoe types (Fig. 1, I). The first shoe condition ($shoe_{Racing}$) was a typical racing flat shoe (Adizero Pro 4, Adidas AG, Herzogenaurach, Germany) with a shoe mass of 0.170 kg (size: US 10). The other shoe condition ($shoe_{Cushion}$) was a typical cushioned running shoe without any additional support elements underneath the medial longitudinal arch of the foot (Glycerin 10, Brooks Sports Inc., Seattle, Washington, USA) with a shoe mass of 0.348 kg (size: US 10) (Fig. 1, I).

Both shoes underwent the ‘Minimal Shoe Index’ test (20), which indicates the minimalism of a running shoe. The ‘Minimalist Shoe Index’ describes shoes on a scale ranging from 1 (no minimalism at all) to 100 (perfectly minimal footwear). We found a score of 60 for $shoe_{Racing}$, and 18 for $shoe_{Cushion}$ (see Appendix, Supplemental Table 1, ‘Minimal Shoe Index’ test).

***** Insert Fig. 1 about here *****

We performed two mechanical tests to evaluate the midsole material properties of the shoes in an unused state (Fig. 1, II and III).

In order to test longitudinal bending stiffness, each shoe was fixed on a rearfoot shoe last which we had mounted on a moving apparatus (low-friction ball bearing sled) in a material testing machine (Z020; Zwick GmbH & Co.KG, Ulm, Germany) to allow for a natural bending behavior (Fig. 1, II). The longitudinal bending stiffness we tested is related to the bending behavior of the forefoot and midfoot part of the shoe. The material testing machine executed 20 cycles with a vertical displacement of 50 mm and a vertical velocity of 15 $mm \cdot s^{-1}$. Longitudinal bending stiffness was calculated by dividing vertical force by vertical displacement. Maximal bending stiffness and vertical force results were averaged over 20 cycles (Fig. 1, II).

To quantify cushioning properties of the midsole material, we mounted a rigid rearfoot-form in a material testing machine (Z020; Zwick GmbH & Co.KG, Ulm, Germany) and compressed the midsole in a vertical direction with 2000 N (Fig. 1, III). This load is similar to the average maximal vertical ground-reaction force (GRF) during stance phases in this study. We calculated the mechanical energy stored and returned for both shoe conditions at a constant compression velocity of 16 $mm \cdot s^{-1}$ (Fig. 1, III). The mechanical test revealed a significant difference between the shoe conditions in the deformation ($shoe_{Racing}$ 10.1 mm vs. $shoe_{Cushion}$ 13.6 mm) as well as the resilience values (energy return in $shoe_{Racing}$ 63.9% vs. $shoe_{Cushion}$ 73.1%) (Fig. 1, III), which are comparable to similar shoes reported in the literature (25).

Running kinematics and kinetics

We captured joint kinematics with a 13 infrared camera motion capture system (250 Hz, MX-F40; Vicon Motion Systems, Oxford, UK) and collected GRF data with four three-dimensional force transducers (1000 Hz, MC3A-3-500-4876; AMTI Inc., Watertown, USA) embedded in a single-belt treadmill (Treadmetrix, Park City, USA) synchronized with the motion capture system. We attached the markers of the foot over the anatomical landmarks on the upper of the shoe. All marker trajectories and GRF data were filtered with a recursive 4th order Butterworth low-pass filter (cutoff frequency: 20 Hz) (27). As described in our previous study (6), a three-dimensional inverse dynamics model of the total body was used to calculate the kinematic and kinetic parameters of the lower extremity (28). The upright standing position determined the neutral position of all joints (0° joint angles). We expressed joint torques in the anatomical coordinate system of the proximal segment. Throughout the entire stance phase, the negative and positive work at the ankle, knee, and hip joint were calculated by numerical integration of the power-time curve. Positive work was determined by summing all positive integrals and negative work by summing all negative integrals (29).

All spatiotemporal, joint kinematic, and joint kinetic parameters were determined during the stance phase of the right leg and averaged over 20 stance phases at each of the 13 distances (0 km, 0.2 km, 0.5 km, 1 km, and following each kilometer to 10 km). Firstly, we calculated ankle dorsiflexion and knee joint flexion angles at foot touch-down (TD) as well as ankle plantarflexion at toe-off (TO). In addition, to assess the footfall pattern of the runners, we determined the angle between the foot and the treadmill surface at TD (foot-$\mathrm{TS}_{\mathrm{TD}}$). Furthermore, we determined maximal joint angles and calculated maximal external joint torques of ankle dorsiflexion, knee and hip flexion. We normalized maximal external joint torques as well as negative and positive work at the ankle, knee, and hip joint to body mass. Subsequently, the relative joint-specific contributions to the total lower-extremity joint work were calculated. All analyses were performed for the sagittal plane, separately for each individual joint, as described in our previous studies (6,28).

At the end of the run, we determined the maximal heart rate (M51; Polar Electro, Kempele, Finland), and the rating of perceived exertion using the Borg 6 – 20 scale (30).

Statistical analysis

We used a two-factor repeated-measure analysis of variance (ANOVA) to detect possible main and interaction effects with two within-subjects factors (shoe condition and running distance). We calculated partial eta squared (η_p^2) as normalized effect size measure, which explains the proportion of the total variance related to main and interaction effects (shoe condition and running distance). The suggested norms from Cohen (31) were used for η_p^2 with 0.01 representing small, 0.06 medium, and 0.14 large effect.

In the case of a shoe condition main effect, we applied pairwise post-hoc comparisons using Fisher's least significant difference correction between the shoe conditions at each of the 13 distances. With respect to two intervals, we performed post-hoc tests for each parameter, regardless of whether we found a running distance main effect. We selected a first distance interval (0 – 2 km) in an attempt to capture habituation (HAB) effects based on qualitative observations in our previous study (6) and earlier findings (7,8). We considered the second distance interval (2 – 10 km) in an attempt to capture fatigue (FAT) processes.

To assess the validity of our assumption that the changes observed with running distance are related to habituation and fatigue processes, we fit different types of models to the results observed over running distance. We used three different models: A simple linear model (all data: 0 – 10 km), a quadratic model (all data: 0 – 10 km), and a bi-linear model (two-components: 0 – 2 km, and 2 – 10 km). We then calculated the sum of squared errors for each model as a measure of model fit.

All statistical analyses were performed using SPSS Statistics 23 (IBM Corp., Armonk, NY, USA) with the level of significance set at $\alpha = 0.05$. We present all results in the text and figures as group means and standard deviations.

RESULTS

Heart rate and rating of perceived exertion

At the end of the run, we found no significant shoe main effect for heart rate (shoe$_{\text{Racing}}$: 176 ± 15 BPM; shoe$_{\text{Cushion}}$: 179 ± 15 BPM) and rating of perceived exertion (16.9 ± 1.3; 16.9 ± 1.7), respectively.

Spatiotemporal parameters

No significant shoe by distance interaction effects were found for spatiotemporal parameters (Table 1). A significant shoe main effect was found for step frequency (Table 1), where step frequency was on average higher for shoe$_{\text{Racing}}$ (2.75 ± 0.16 Hz) compared to shoe$_{\text{Cushion}}$ (2.72 ± 0.15 Hz), and for flight time (Table 1), which was on average shorter for shoe$_{\text{Racing}}$ (0.126 ± 0.025 s) compared to shoe$_{\text{Cushion}}$ (0.129 ± 0.024 s). A significant distance main effect was found for contact time, step length, and step frequency (Table 1). Contact time and step length increased with running distance while step frequency decreased irrespective of the shoe condition (see Appendix, Supplemental Table 2, Spatiotemporal parameters; Supplemental Fig. 1 and 2, Fitting methods).

***** Insert Table 1 about here *****

Joint work

No significant shoe by distance interaction effects or shoe main effects for any joint work parameter other than for the negative work at the ankle were observed (Table 1), which was on average 0.043 $J \cdot kg^{-1}$ (corresponds to approx. 7%) higher with shoe$_{\text{Racing}}$ throughout the entire run than with shoe$_{\text{Cushion}}$ (see Appendix, Supplemental Fig. 3, Joint work). Even though no significant shoe main effect for the negative knee joint work was found (Table 1), it was noticeable that the difference between both shoes throughout the entire run (negative knee joint work was on average 0.038 J·kg^{-1} smaller for shoe$_{\text{Racing}}$ compared to shoe$_{\text{Cushion}}$) was similar to the difference in the negative work at the ankle joint (see Appendix, Supplemental Fig. 3, Joint work). Accordingly, we found a difference in relative contributions of the ankle and knee joint to the total negative lower-extremity joint work between the shoe conditions (Fig. 2; see Appendix, Supplemental Table 3, Relative joint work).

***** Insert Fig. 2 about here *****

Concerning the running distance, significant main effects were found for the positive work at the ankle, knee, and hip joint, as well as for the negative work at the ankle joint (Table 1). Irrespective of the shoe condition, we found that the positive work at the ankle joint decreased significantly ($P < 0.001$) as well as the knee and hip joint increased significantly (knee: $P < 0.001$; hip: $0.012 < P < 0.025$) from the beginning (mean value of both shoe conditions for the ankle: 0.68 ± 0.12 J·kg^{-1}; knee: 0.36 ± 0.09 J·kg^{-1}; hip: 0.26 ± 0.13 J·kg^{-1}) to the end of the run (ankle: 0.61 ± 0.14 J·kg^{-1}; knee: 0.41 ± 0.10 J·kg^{-1}; hip: 0.30 ± 0.16 J·kg^{-1}). Detailed values for each shoe condition can be found in the Appendix (Supplemental Fig. 3, Joint work). Accordingly, independent of the shoe condition, we found a redistribution of relative positive work from distal to proximal joints from the beginning (ankle 53.0%, knee 28.1%, hip 19.0%) to the end of the run (46.9%, 31.2%, 21.9%). For more specific values please see Fig. 2 and the Appendix (Supplemental Table 3, Relative joint work).

During the HAB phase, negative work at the ankle increased significantly ($P = 0.031$) for shoe$_{\text{Cushion}}$ (Table 1; Fig. 3). For shoe$_{\text{Racing}}$, negative work at the knee and hip joint increased significantly ($P < 0.05$) during the HAB phase (Table 1; Fig. 3). Positive work at the ankle decreased significantly ($P < 0.01$) in the HAB and FAT phase, independent of the shoe condition (Table 1; Fig. 3). The positive work at the knee and hip joint showed significant ($P < 0.05$) increases only for the HAB phase irrespective of the shoe condition (Table 1; Fig. 3).

***** Insert Fig. 3 about here *****

Footwear differences at the beginning of the run

We identified several kinematic and kinetic differences between the shoe conditions at the beginning of the run, indicating a more plantarflexed foot strike pattern for $\text{shoe}_{\text{Racing}}$ and a higher mechanical demand placed on plantar flexor muscle-tendon-units.

Specifically, at the 0-km distance we found a significantly ($P = 0.012$) higher negative work at the ankle with $\text{shoe}_{\text{Racing}}$ compared to $\text{shoe}_{\text{Cushion}}$ (see Appendix, Supplemental Table 4, Pairwise comparisons between shoes; Supplemental Fig. 3, Joint work). The maximal ankle dorsiflexion torque was higher for $\text{shoe}_{\text{Racing}}$ compared to $\text{shoe}_{\text{Cushion}}$, but this difference was not significant ($P = 0.163$) at the 0-km distance, but then significant ($P = 0.034$) at 0.2 km (Fig. 4). At the 0-km distance, the foot-TS_{TD} ($P = 0.010$), ankle dorsiflexion angle at TD ($P < 0.001$) (Fig. 5), and maximal ankle dorsiflexion angle ($P = 0.008$) with $\text{shoe}_{\text{Racing}}$ was decreased significantly compared to $\text{shoe}_{\text{Cushion}}$ (see Appendix, Supplemental Fig. 4, Maximal joint angle). However, at the 0-km distance, the ankle plantarflexion angle at TO with $\text{shoe}_{\text{Racing}}$ was increased significantly ($P = 0.002$) compared to $\text{shoe}_{\text{Cushion}}$ (Fig. 5).

External joint torques

We could neither identify a shoe by distance interaction effect nor a significant shoe main effect for any joint torque parameters, but significant running distance main effects for all joint torques were found (Table 1).

Maximal ankle dorsiflexion torque decreased significantly ($P < 0.05$) over the entire run for both shoe conditions (Fig. 4), although it should be noted that $P = 0.05$ for the FAT phase using shoe$_{\text{Cushion}}$ (Table 1) and so this difference was not strictly significant. For both shoe conditions, a significant ($P < 0.01$) increase in maximal knee flexion torque (Fig. 4) was detected only during the HAB phase (Table 1).

***** Insert Fig. 4 about here *****

Joint angles

We found significant shoe by distance interaction effects for parameters describing the foot strike pattern of runners, more precisely foot-TS$_{\text{TD}}$ and ankle dorsiflexion angle at TD Table 1).

A closer look at the post-hoc comparisons revealed that the interaction effects for foot-TS$_{\text{TD}}$ and ankle dorsiflexion angle at TD were caused by a significant difference between the shoe conditions that was only present during the HAB phase and disappeared during the FAT phase (Fig. 5). In addition, we found only for shoe$_{\text{Racing}}$ that the ankle dorsiflexion angle at TD decreased significantly ($P < 0.05$) during the FAT phase (Fig. 5). We found a higher ankle dorsiflexion angle at TD (Fig. 5), and a higher maximal ankle dorsiflexion angle (see Appendix, Supplemental Fig. 4, Maximal joint angle) throughout the entire run, when using shoe$_{\text{Cushion}}$ in comparison to shoe$_{\text{Racing}}$ (Fig. 5).

***** Insert Fig. 5 about here *****

The shoe by distance interaction effect for the ankle plantarflexion angle at TO (Table 1) was represented by a decrease in the ankle plantarflexion angle in the FAT phase only with

$\text{shoe}_{\text{Racing}}$ (Fig. 5). There was a significant shoe main effect for the maximal ankle dorsiflexion angle (Table 1). We found a decreased ankle plantarflexion angle at TO throughout the entire run, when using $\text{shoe}_{\text{Cushion}}$ in comparison to $\text{shoe}_{\text{Racing}}$ (Fig. 5). A running distance main effect for the maximal knee joint flexion angle and the knee joint flexion angle at TD was identified (Table 1) indicating a more flexed knee joint configuration with increasing running distance.

Fitting models of changes in running mechanics

While assessing the nonlinear nature of changes in running mechanics throughout the 10-km runs, we found for all joint work parameters that fitting a bi-linear model resulted in the smallest sum of squared errors compared to a linear or quadratic model. This finding was independent of the shoe condition analyzed (see Appendix, Supplemental Table 5, Sum of squared errors; Supplemental Fig. 5 and 6, Fitting methods). Similarly, we found for all joint torque parameters and joint angle parameters (except for maximal ankle dorsiflexion when using $\text{shoe}_{\text{Racing}}$, and maximal hip flexion torque using $\text{shoe}_{\text{Racing}}$ and $\text{shoe}_{\text{Cushion}}$) that fitting a bi-linear model resulted in a smaller sum of squared errors compared to fitting a linear or quadratic model, independent of the shoe condition (see Appendix, Supplemental Table 5, Sum of squared errors; Supplemental Fig. 7 – 10, Fitting methods).

DISCUSSION

The primary purpose of this study was to investigate the difference between a typical racing flat shoe and a typical cushioned running shoe with regards to joint-specific contributions to lower extremity joint work during a fatiguing 10-km run with a near-maximal effort in rearfoot runners. We hypothesized that using a racing flat shoe in comparison to a cushioned shoe leads to a more pronounced and earlier fatigue-related redistribution of positive work from distal to proximal joints during a fatiguing near-maximal effort run.

The joint work magnitudes in the current study were comparable to previous studies analyzing running at similar velocities (11,19,32,33). Differences in the magnitude of lower extremity joint work might be explained by different experimental setups (overground vs. treadmill), skill levels of runners, or analysis details such as the segmentation of the foot (11,13,19,26,32,33), which can affect power calculations at more proximal joints (34).

While we identified significant effects of running distance for both absolute and relative positive work parameters indicating a redistribution of positive work from distal to proximal joints for both shoe conditions, we did not find a shoe by distance interaction effect for any joint work-related parameter. Consequently, our central hypothesis that using a racing flat shoe in comparison to a cushioned shoe leads to a more pronounced and earlier fatigue-related redistribution of positive work from distal to proximal joints during a fatiguing near-maximal effort run could not be accepted.

This result was not expected because, in accordance with the literature (13,15,19), we also found a higher mechanical demand at the ankle (+3% dorsiflexion torque; +8% negative work) for shoe$_{\mathrm{Racing}}$ compared to shoe$_{\mathrm{Cushion}}$ at the beginning of the run. However, this increased demand for shoe$_{\mathrm{Racing}}$ disappeared over the course of the run, which might partly explain the lack of difference in the redistribution of joint work between the shoe conditions (Fig. 2).

Next to the higher energy absorption capacity in the rear part of the midsole, shoe$_{\mathrm{Cushion}}$ was characterized by a threefold higher longitudinal bending stiffness (Fig. 1). Previous studies analyzing shorter running distances found an association between the longitudinal bending stiffness of footwear and the length of the lever arm of the GRF at the ankle (28). However, in this study (28), not all runners made use of this longer lever arm and increased internal ankle plantarflexion torques. Instead, some runners prolonged the push-off period and thereby avoided the generation of increased muscle forces (28). This subject specific response might partly explain the inconsistent evidence provided by other studies reporting the response in ankle joint torques to increased bending stiffness levels of footwear in the literature (11,32). An increase in GRF lever arm at the ankle along with higher energy absorption capacity of $\text{shoe}_{\text{Cushion}}$ and the associated adaptations in foot strike behavior could influence fatigue-related reduction in ankle joint torque. Therefore, the increased bending stiffness of $\text{shoe}_{\text{Cushion}}$ might also partly explain the lack of difference in the redistribution of joint work between the shoe conditions (Fig. 2).

The second hypothesis of this study was that separating a fatiguing near-maximal effort 10-km run into a habituation (HAB) and fatiguing (FAT) phase will reveal markedly larger changes in biomechanical parameters in the initial HAB phase of running. Although the participants executed a warm-up run with self-determined velocity and duration before the actual run, we observed a nonlinear behavior of several biomechanical variables over the running distance. Such nonlinear behavior of biomechanical variables seems to be more pronounced in recreational runners (6). To assess the validity of our assumption that the changes observed with running distance are related to habituation and fatigue processes, we fit different types of models to the results observed over running distance. We found that fitting a bi-linear (two-components: 0 – 2 km, and 2 – 10 km) model or a quadratic model provided a better fit to the data over running distance for most biomechanical variables compared to using a simple linear model, independent of the used shoe condition. Specifically, we found significant changes for more than half ($\text{shoe}_{\text{Racing}}$: n = 14; $\text{shoe}_{\text{Cushion}}$: n = 12) of the 20 analyzed parameters during the HAB phase (Table 1). In particular, we observed that positive work at all lower extremity joints (see Appendix, Supplemental Fig. 3, Joint work), maximal ankle dorsiflexion and knee joint flexion torques (Fig. 4) as well as maximal knee joint flexion angles (see Appendix, Supplemental Fig. 4, Maximal joint angle) changed more substantially during the HAB phase, independent of the shoe condition (Table 1). While further research is needed to address this issue more specifically, we believe that these findings provide evidence in support of our second hypothesis that changes in running mechanics in an intense, prolonged run underlie HAB and FAT processes. It is noteworthy that when using shoe$_{\text{Cushion}}$, the ankle angle at TD became less dorsiflexed ($P < 0.001$) (Fig. 5) and the negative work at the ankle increased ($P = 0.031$) (Fig. 3) at a near-linear rate during the HAB phase compared to shoe$_{\text{Racing}}$ (see Appendix, Supplemental Fig. 5 and 10, Fitting methods). Such decreases in the ankle dorsiflexion angle at TD were also found in other studies (8,35) during the first 5 minutes of a 30 minutes run (corresponding approximately to the 1-km distance in our study) and this was independent of the shoe midsole thickness. The more pronounced ankle dorsiflexion angle at TD with shoe$_{\text{Cushion}}$ at the beginning of the run might be related to differences in rearfoot construction (12), midsole thickness, and heel-toe drop height (8,13,14,22). While using a more dorsiflexed ankle angle at TD might allow for a greater energy absorption by the foam materials of shoe$_{\text{Cushion}}$, it might have led to a greater demand for the dorsiflexors of the ankle joint (i.e. mainly m. tibialis anterior) due a greater leverage of the GRF (12,36,37). It is possible that the neuromuscular system tries to establish a balance between passive impact absorption and mechanical demand of the dorsiflexors of the ankle joint during the HAB phase during prolonged runs when wearing cushioned footwear. This hypothesis is in line with previous research showing a decrease in ankle dorsiflexion angle at TD during prolonged runs (10) or when performing a localized dorsiflexors fatigue protocol (38). This mechanism might have been accentuated in this study given the relatively short familiarization time that each participant had with the new shoe conditions, even though they were generally experienced with running with racing flat and cushioned shoes.

The difference in foot strike and ankle dorsiflexion angle at TD between the shoe conditions did not persist throughout the entire run, as the more pronounced rearfoot strike pattern when using shoe$_{\text{Cushion}}$ decreased continuously during and disappeared at the end of the HAB phase. This finding challenges the assumptions from previous reports analyzing short bouts of running with previous short habituation to the shoe condition (12–15,32) that foot strike behaviors between more minimalist and more cushioned shoes persist during prolonged running. Since increased heel height can change the working conditions of ankle plantar flexor muscle-tendon-units (12), it might be possible that runners adjusted their foot strike behavior during the HAB phase in order to optimize the economy of power generation.

Further, habituation effects, regarding foot strike behavior, may be due to long-term habituation effects, for example, habituation to barefoot running may take 8 weeks or longer (39). It is further conceivable that the participants may have been insufficiently accustomed to running on a treadmill (40), or that the materials of the midsole of shoe$_{\text{Cushion}}$ changed their properties throughout the HAB phase due to the repeated cyclic loading. Further, interactions with changes in running mechanics outside the sagittal plane need to be considered (41). In order to better understand the habituation of the neuromuscular system to different kinds of shoes or other external constraints, future studies should consider and control in detail the short-term (warm-up phase before a test run) and longer-term habituation. These studies should also address changes within the biomechanical properties of biological tissues involved in generating propulsion and support. These changes might include, e.g., alterations in tendons and ligaments stiffness or modifications in the contractile elements within muscle-tendon-units. In this context, recent work has identified that the fluid content of ankle plantar flexor muscles undergoes a rapid initial increase followed by a decrease at slower rate during 75 minutes of running (42). Changes in muscle fluid content have been related to the active and passive force generation potentials of muscles (43,44) and should therefore be considered when investigating changes in joint mechanics during prolonged, intense activities.

In contrast to the HAB phase, few (shoe$_{\text{Racing}}$: n = 6; shoe$_{\text{Cushion}}$: n = 2) of the 20 analyzed parameters changed significantly ($P < 0.05$) during the FAT phase (Table 1). During the FAT phase, the foot-TS$_{\text{TD}}$ and ankle dorsiflexion angle at TD were not different between the shoe conditions (Fig. 5). Furthermore, in the FAT phase, maximal ankle dorsiflexion torques were not different between shoes (Fig. 4). Therefore, we assume that the mechanical demand of plantar flexor muscle-tendon-units was slightly higher in shoe$_{\text{Racing}}$ only during the HAB phase and similar during the FAT phase, which might partly explain the comparable decline of positive work at the ankle during this phase. In particular, positive work at the ankle decreased at a near-linear rate during the FAT phase (see Appendix, Supplemental Fig. 6, Fitting methods), independent of shoe condition (Table 1). However, it is noticeable that the decrease in positive work at the ankle during the FAT phase was higher for shoe$_{\text{Racing}}$ compared to shoe$_{\text{Cushion}}$ (Fig. 3). This finding is similar to the delayed decrease in positive work at the ankle recently described by Cigoja at el. (45) for shoes with higher longitudinal bending stiffness. Since shoe$_{\text{Cushion}}$ had a higher bending stiffness than shoe$_{\text{Racing}}$, we speculate that the difference in bending stiffness might have played a role in this distance specific difference between the shoe conditions.

While this study provides a clear indication that changes in running biomechanics over prolonged fatiguing runs are not necessarily a linear function of running distance, there is more research needed to understand the mechanisms underlying this phenomenon. Based on the current findings, we can only speculate that the changes during the HAB phase might be due to a harmonization of the runners' neuromuscular system with the running environment, e.g., footwear and surface, and the requirements of the task, e.g., running distance and velocity. In contrast, the more linear changes during the FAT phase could be related to fatigue effects of the involved muscle-tendon-units.

LIMITATIONS

This study has several limitations. First, the mechanical test to analyze cushioning properties of shoe midsoles was technically limited in the compression velocity of 16 mm·s^{-1}

due to the limits of our material testing machine (Fig. 1, III). Typical compression velocities are approximately threefold higher during running and could be simulated with other material testing machines (25). The mechanical test was also limited to a one-dimensional actuation of force and allowed a general characterization of midsole mechanical energy storage and return capabilities only in the rearfoot region of the shoe and not over the entire midsole as performed in a previous study (25). Second, we investigated only one type of typical racing flat and cushioned shoe. Third, we attached the reflective markers of the foot to the corresponding position on the shoe, which might not exactly represent the movement of the foot inside the shoe, which may have affected our results. Fourth, we chose an explorative approach by using Fisher's least significant difference correction between the shoe conditions at each of the 13 distances, which has increased the statistical power to identify smaller differences between footwear conditions, but at the same time has increased the risk for a type 1 error. Fifth, the running economy was not directly quantified. Finally, the isometric or isokinetic force capacities of the leg extensors before and after the prolonged fatiguing run were not determined, therefore we can only speculate about potential fatigue effects in these muscle groups.

CONCLUSION

Our findings demonstrate that a typical racing flat shoe (with less cushioning material and lower longitudinal bending stiffness) and a typical cushioned running shoe do not differ in the fatigue-related redistribution of positive work from distal to proximal joints, despite small differences in the timing of the redistribution between shoes.

Furthermore, irrespective of the analyzed shoe, the majority of the kinetic and kinematic alterations in the running mechanics occurred in the first 2 km of the 10 km fatiguing run, which might be attributed to the existence of a habituation rather than a fatigue effect, indicating a nonlinear response to the running distance. Despite the observed changes in the habituation phase, positive work and maximal ankle dorsiflexion torque decreased continuously between 2 and 10 km of the run, leading to the previously described redistribution of positive work from distal to proximal joints. Overall, these findings improve the knowledge on the role of footwear for fatigue-related alterations in running mechanics during prolonged fatiguing runs.

ACKNOWLEDGMENTS

The authors thank all participants for their physical efforts. We further thank Hans-Martin Küsel-Feldker for his engineering help and Sandra Friedemann, Marc-David Melchert, David Joachimmeyer, Tim Plöger, and Philipp Schäfers for their assistance during the data acquisition and post-processing phase of the study as well as Sandra Grothe for her graphic realization of figure 1.

CONFLICTS OF INTEREST

The manufacturers of shoe$_{\text{Racing}}$ (Adidas AG; Herzogenaurach, Germany) and shoe$_{\text{Cushion}}$ (Brooks Sports Inc., Seattle, Washington, USA) were not involved in the study design or the collection, analysis, or interpretation of data. Authors S.W. and G.P.B. received funding from Brooks Running Inc., Seattle, WA, to perform work not related to this study. There are no other conflicts of interest to declare. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of this study do not constitute an endorsement by the American College of Sports Medicine.

References

1. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Med. 2004;34(7):465–85. doi:10.2165/00007256-200434070-00005 Cited in: PubMed; PMID 15233599.
2. Kyröläinen H, Pullinen T, Candau R, Avela J, Huttunen P, Komi PV. Effects of marathon running on running economy and kinematics. Eur J Appl Physiol. 2000;82(4):297–304. doi:10.1007/s004210000219 Cited in: PubMed; PMID 10958372.
3. Rabita G, Slawinski J, Girard O, Bignet F, Hausswirth C. Spring-mass behavior during exhaustive run at constant velocity in elite triathletes. Med Sci Sports Exerc. 2011;43(4):685–92. doi:10.1249/MSS.0b013e3181fb3793 Cited in: PubMed; PMID 20881886.
4. Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. Med Sci Sports Exerc. 2002;34(8):1324–31. doi:10.1097/00005768-200208000-00014 Cited in: PubMed; PMID 12165688.
5. Derrick TR, Dereu D, McLean SP. Impacts and kinematic adjustments during an exhaustive run. Med Sci Sports Exerc. 2002;34(6):998–1002. doi:10.1097/00005768-200206000-00015 Cited in: PubMed; PMID 12048328.
6. Sanno M, Willwacher S, Epro G, Brüggemann G-P. Positive work contribution shifts from distal to proximal joints during a prolonged run. Med Sci Sports Exerc. 2018;50(12):2507–17. doi:10.1249/MSS.0000000000001707 Cited in: PubMed; PMID 30169401.
7. Brüggemann G-P. Influence of fatigue on lower extermity function. In: Abrantes J, editor. 14. International Symposium on Biomechanics in Sports. Funchal Madeira - Portugal; 1996.

8. TenBroek TM, Rodrigues PA, Frederick EC, Hamill J. Midsole thickness affects running patterns in habitual rearfoot strikers during a sustained run. J Appl Biomech. 2014;30(4):521–8. doi:10.1123/jab.2012-0224 Cited in: PubMed; PMID 24615336.

9. Enoka RM, Duchateau J. Muscle fatigue: what, why and how it influences muscle function. J Physiol. 2008;586(1):11–23. doi:10.1113/jphysiol.2007.139477 Cited in: PubMed; PMID 17702815.

10. Weir G, Jewell C, Wyatt H, Trudeau MB, Rohr E, Brüggemann G-P, Hamill J. The influence of prolonged running and footwear on lower extremity biomechanics. Footwear Science. 2018;5(2):1–11. doi:10.1080/19424280.2018.1539127

11. Roy J-PR, Stefanyshyn DJ. Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. Med Sci Sports Exerc. 2006;38(3):562–9. doi:10.1249/01.mss.0000193562.22001.e8 Cited in: PubMed; PMID 16540846.

12. Willwacher S, Potthast W, Konrad M, Brüggemann G-P. Effect of Heel Construction on Muscular Control Potential of the Ankle Joint in Running. J Appl Biomech. 2013;29(6):740–8. doi:10.1123/jab.29.6.740

13. Fuller JT, Buckley JD, Tsiros MD, Brown NAT, Thewlis D. Redistribution of Mechanical Work at the Knee and Ankle Joints During Fast Running in Minimalist Shoes. J Athl Train. 2016;51(10):806–12. doi:10.4085/1062-6050-51.12.05 Cited in: PubMed; PMID 27834504.

14. Squadrone R, Rodano R, Hamill J, Preatoni E. Acute effect of different minimalist shoes on foot strike pattern and kinematics in rearfoot strikers during running. J Sports Sci. 2015;33(11):1196–204. doi:10.1080/02640414.2014.989534 Cited in: PubMed; PMID 25529114.

15. Goss DL, Lewek M, Yu B, Ware WB, Teyhen DS, Gross MT. Lower Extremity Biomechanics and Self-Reported Foot-Strike Patterns Among Runners in Traditional

and Minimalist Shoes. J Athl Train. 2015. doi:10.4085/1062-6050-49.6.06 Cited in: PubMed; PMID 25695854.

16. Frederick EC. Kinematically mediated effects of sport shoe design: A review. J Sports Sci. 1986;4(3):169–84. doi:10.1080/02640418608732116 Cited in: PubMed; PMID 3586110.

17. Sinclair J, Richards J, Shore H. Effects of minimalist and maximalist footwear on Achilles tendon load in recreational runners. J Comp Exer Physiol. 2015;11(4):239–44. doi:10.3920/CEP150024

18. Paquette MR, Zhang S, Baumgartner LD. Acute effects of barefoot, minimal shoes and running shoes on lower limb mechanics in rear and forefoot strike runners. Footwear Science. 2013;5(1):9–18. doi:10.1080/19424280.2012.692724

19. Firminger CR, Edwards WB. The influence of minimalist footwear and stride length reduction on lower-extremity running mechanics and cumulative loading. J Sci Med Sport. 2016;19(12):975–9. doi:10.1016/j.jsams.2016.03.003 Cited in: PubMed; PMID 27107980.

20. Esculier J-F, Dubois B, Dionne CE, Leblond J, Roy J-S. A consensus definition and rating scale for minimalist shoes. J Foot Ankle Res. 2015;842. doi:10.1186/s13047-015-0094-5 Cited in: PubMed; PMID 26300981.

21. Reinschmidt C, Nigg BM. Current issues in the design of running and court shoes. Sportverletz Sportschaden. 2000;14(3):71–81. Cited in: PubMed; PMID 11081243.

22. Hoitz F, Mohr M, Asmussen M, Lam W-K, Nigg S, Nigg B. The effects of systematically altered footwear features on biomechanics, injury, performance, and preference in runners of different skill level: a systematic review. Footwear Science. 2020;1–23. doi:10.1080/19424280.2020.1773936

23. Willwacher S. Running Shoes: Injury Protection and Performance Enhancement. In: Handbook of Human Motion. Cham: Springer International Publishing; 2018. p. 1613–28. (vol. 432).

24. Fuller JT, Bellenger CR, Thewlis D, Tsiros MD, Buckley JD. The effect of footwear on running performance and running economy in distance runners. Sports Med. 2015;45(3):411–22. doi:10.1007/s40279-014-0283-6 Cited in: PubMed; PMID 25404508.

25. Hoogkamer W, Kipp S, Frank JH, Farina EM, Luo G, Kram R. A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. Sports Med. 2018;48(4). doi:10.1007/s40279-017-0811-2 Cited in: PubMed; PMID 29143929.

26. Hoogkamer W, Kipp S, Kram R. The Biomechanics of Competitive Male Runners in Three Marathon Racing Shoes: A Randomized Crossover Study. Sports Med. 2019;(49):133–43. doi:10.1007/s40279-018-1024-z Cited in: PubMed; PMID 30460454.

27. Mai P, Willwacher S. Effects of low-pass filter combinations on lower extremity joint moments in distance running. J Biomech. 2019;95109311. doi:10.1016/j.jbiomech.2019.08.005 Cited in: PubMed; PMID 31451201.

28. Willwacher S, Kurz M, Menne C, Schrödter E, Brüggemann G-P. Biomechanical response to altered footwear longitudinal bending stiffness in the early acceleration phase of sprinting. Footwear Science. 2016;8(2):99–108. doi:10.1080/19424280.2016.1144653

29. Stefanyshyn DJ, Nigg BM, Stefanyshyn DJ, Nigg BM. Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. J Biomech. 1997;30(11-12):1081–5. doi:10.1016/s0021-9290(97)00081-x Cited in: PubMed; PMID 9456374.

30. Borg G. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982;14(5):377–81.

31. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, New Jersey: Lawrence Erlbaum Associates Inc; 1988. p. 40, 286–7.

32. Cigoja S, Firminger CR, Asmussen MJ, Fletcher JR, Edwards WB, Nigg BM. Does increased midsole bending stiffness of sport shoes redistribute lower limb joint work during running? J Sci Med Sport. 2019;22(11):1272–7. doi:10.1016/j.jsams.2019.06.015 Cited in: PubMed; PMID 31272917.

33. Schache AG, Blanch PD, Dorn TW, Brown NAT, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. Med Sci Sports Exerc. 2011;43(7):1260–71. doi:10.1249/MSS.0b013e3182084929 Cited in: PubMed; PMID 21131859.

34. Zelik KE, Honert EC. Ankle and foot power in gait analysis: Implications for science, technology and clinical assessment. J Biomech. 2018;751–12. doi:10.1016/j.jbiomech.2018.04.017 Cited in: PubMed; PMID 29724536.

35. TenBroek TM, Rodrigues P, Frederick EC, Hamill J. Effects of unknown footwear midsole thickness on running kinematics within the initial six minutes of running. Footwear Science. 2013;5(1):27–37. doi:10.1080/19424280.2012.744360

36. Willwacher S, Regniet L, Fischer KM, Oberländer KD, Brüggemann G-P. The effect of shoes, surface conditions and sex on leg geometry at touchdown in habitually shod runners. Footwear Science. 2014;6(3):129–38. doi:10.1080/19424280.2014.896952

37. Willwacher S, Fischer KM, Rohr E, Trudeau MB, Hamill J, Brüggemann G-P. Surface Stiffness and Footwear Affect the Loading Stimulus for Lower Extremity Muscles When Running. J Strength Cond Res. 2020. doi:10.1519/JSC.0000000000003410 Cited in: PubMed; PMID 32028460.

38. Christina KA, White SC, Gilchrist LA. Effect of localized muscle fatigue on vertical ground reaction forces and ankle joint motion during running. Hum Mov Sci. 2001;20(3):257–76. Cited in: PubMed; PMID 11517672.

39. Hollander K, Liebl D, Meining S, Mattes K, Willwacher S, Zech A. Adaptation of Running Biomechanics to Repeated Barefoot Running: A Randomized Controlled Study. Am J Sports Med. 2019;47(8):1975–83. doi:10.1177/0363546519849920 Cited in: PubMed; PMID 31166116.

40. Nigg BM, De Boer, R W, Fisher V. A kinematic comparison of overground and treadmill running. Med Sci Sports Exerc. 1995;27(1):98–105. Cited in: PubMed; PMID 7898346.

41. Willwacher S, Sanno M, Brüggemann G-P. Fatigue matters: An intense 10 km run alters frontal and transverse plane joint kinematics in competitive and recreational adult runners. Gait Posture. 2020;76277–83. doi:10.1016/j.gaitpost.2019.11.016 Cited in: PubMed; PMID 31884254.

42. Willwacher S, Sleboda DA, Mählich D, Brüggemann G-P, Roberts TJ, Bratke G. The time course of calf muscle fluid volume during prolonged running. Physiol Rep. 2020;8(9):e14414. doi:10.14814/phy2.14414 Cited in: PubMed; PMID 32378332.

43. Sleboda DA, Roberts TJ. Incompressible fluid plays a mechanical role in the development of passive muscle tension. Biol Lett. 2017;13(1). doi:10.1098/rsbl.2016.0630 Cited in: PubMed; PMID 28123108.

44. Sleboda DA, Roberts TJ. Internal fluid pressure influences muscle contractile force. Proc Natl Acad Sci U S A. 2020;117(3):1772–8. doi:10.1073/pnas.1914433117 Cited in: PubMed; PMID 31879350.

45. Cigoja S, Fletcher JR, Nigg BM. Can increased midsole bending stiffness of sport shoes delay the onset of lower limb joint work redistribution during a prolonged run?

Conference: International Society of Biomechanics in Sports 2020, At Liverpool, United Kingdom. 2020.

FIGURE AND TABLE LEGENDS

FIG. 1: Footwear conditions (I): ‘Adizero Pro 4‘ (Shoe$_{\text{Racing}}$) and ‚Glycerin 10’ (Shoe$_{\text{Cushion}}$). Schematic illustration of the testing method (II) to quantify longitudinal bending properties of the running shoes. The shoes were mounted in a material testing machine (Z020; Zwick GmbH & Co.KG, Ulm, Germany) on a rearfoot shoe last, which was fixed on a moving apparatus (low-friction ball bearing sledge) to give the freedom to bend where its sole construction allows it to. The illustration presents the unloaded situation (gray) and the maximal bending situation (white) due to the vertical displacement (50 mm) of the load cell as well as the corresponding vertical force at maximal vertical displacement (Force$_{\text{MVD}}$) to bend the forefoot and midfoot part of the shoe as well as the bending stiffness for both analyzed shoes. Schematic illustration of the simple mechanical test (III) which was performed in a material testing machine (Z020; Zwick GmbH & Co.KG, Ulm, Germany) to evaluate midsole material properties (energy storage and return) by compressing the rearfoot midsole in vertical direction with 2000 N at a constant compression velocity of 16 mm·s^{-1}.

TABLE 1: Main effects of a two-factor repeated-measures ANOVA (*P*-values) with two within-subjects factors (shoe condition and running distance) as well as the interaction effect between both factors for spatiotemporal parameters, maximal (max) joint angles, joint angles at foot touch-down (TD) and toe-off (TO), angle between the foot and the treadmill surface at touch-down (foot-TS$_{\text{TD}}$), maximal external joint torques, and positive (pos) and negative (neg) joint work. The partial eta squared (η_p^2) values are presented as normalized effect sizes. The last two columns show the pairwise comparisons (*P*-values) of 0 km and 2 km as well as 2 km and 10 km of 10-km treadmill run with near-maximal effort for the shoes, ‘Adizero Pro 4‘ (Racing) and ‘Glycerin 10’ (Cushion). All significant differences ($P < 0.05$) are represented by bold printed *P*-values.

FIG. 2: Relative negative and positive work (mean ± standard deviation) at the ankle (triangle), knee (circle), and hip (square) joint in both shoe conditions (left: shoe$_{\text{Racing}}$; right: shoe$_{\text{Cushion}}$) throughout the 10-km treadmill run with near-maximal effort. The first distance interval (0 – 2 km) was selected to assess potential habituation effects (grey area) and the second distance interval (2 – 10 km) to demonstrate fatiguing processes. Significant differences between 0 km and 2 km as well as 2 km and 10 km are represented by *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$, respectively.

FIG. 3: Mean changes in negative and positive joint work during the habituation phase (HAB; corresponds to the distance of 0 – 2 km) and the fatigue phase (FAT; corresponds to the distance of 2 – 10 km) for shoe$_{\text{Racing}}$ and shoe$_{\text{Cushion}}$. All significant changes are represented by *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$, respectively.

FIG. 4: Maximum external torques (mean ± standard deviation) at the ankle, knee, and hip joint throughout the 10-km treadmill run with near-maximal effort in both shoe conditions (■ shoe$_{\text{Racing}}$: racing flat shoe; ○ shoe$_{\text{Cushion}}$: cushioned running shoe). The first distance interval (0 – 2 km) was selected to assess potential habituation effects (grey area) and the second distance interval (2 – 10 km) to demonstrate fatiguing processes. Significant differences between 0 km and 2 km as well as 2 km and 10 km are represented by *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$ for shoe$_{\text{Racing}}$ as well as ^$P < 0.05$, and ^^$P < 0.01$ for shoe$_{\text{Cushion}}$, respectively. A significant ($P < 0.05$) shoe difference for the maximum external torque of ankle was found for the 0.2-km distance and is represented by *S*. Further results of pairwise comparisons between shoes can be found in the Appendix (Supplemental Table 4, Pairwise comparisons between shoes).

FIG. 5: Selected kinematic parameters (mean ± standard deviation) for both shoe conditions (■ $\text{shoe}_{\text{Racing}}$: racing flat shoe; ○ $\text{shoe}_{\text{Cushion}}$: cushioned running shoe) throughout the 10-km treadmill run with near-maximal effort. Top left: the angle between the foot and the treadmill surface at touch-down ($\text{foot-TS}_{\text{TD}}$). Top right: ankle dorsiflexion angle at touch-down (angle_{TD}). Bottom left: ankle plantarflexion angle at toe-off (angle_{TO}). Bottom right: knee joint flexion angle at touch-down (knee_{TD}). The first distance interval (0 – 2 km) was selected to assess potential habituation effects (grey area) and the second distance interval (2 – 10 km) to demonstrate fatiguing processes. Significant differences between 0 km and 2 km as well as 2 km and 10 km are represented by $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ for $\text{shoe}_{\text{Racing}}$ as well as $^{\wedge\wedge\wedge}P < 0.001$ for $\text{shoe}_{\text{Cushion}}$, respectively. Significant ($P < 0.05$) shoe differences are represented by *S*. Further results of pairwise comparisons between shoes can be found in the Appendix (Supplemental Table 4, Pairwise comparisons between shoes).

SUPPLEMENTAL DIGITAL CONTENT

SANNO_2020_SDC_Running_into_fatigue_and_footwear.pdf