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The Effect of Non-Newtonian Fluid Midsole Footwear on Lower Limb Biomechanics after 5 km of Running in High Temperature

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Abstract: This study's aim was to examine the effect of non-Newtonian fluid (NN) shoe and ethylene vinyl acetate (EVA) shoe on human lower limb biomechanics and muscle activation during running in hot temperatures. Thirty-five men utilizing a rearfoot strike ran 5 km at a self-selected tempo at an average summer temperature of 41.7 ± 1.0 °C and relative humidity of 80.7 ± 3.5%. The kinematics, kinetics, and muscle activation of the right leg were monitored from landing until the pedal was off the ground. A two-way repeated-measures ANOVA was conducted to investigate the main effects of the shoe condition, temperature, and interaction effect. Wearing NN at high temperature resulted in increased hip range of motion (ROM) (p = 0.001). The knee torque increased significantly when wearing EVA and NN shoes after the temperature increased (p = 0.006). When wearing EVA and NN, the ground reaction force (GRF) and loading rate (LR) increased significantly after the temperature increased (p = 0.001; p = 0.009). When wearing NN after running for 5 km at a high temperature, the displacement range of center of pressure (COP) was significantly reduced ($p < 0.001$), while the EVA was significantly increased ($p < 0.001$). Neither pair of shoes substantially altered muscle activity. After excluding the factor of fatigue, the increase in temperature not only changed the properties of the material inside the shoe, but also changed the parameters of the biomechanics of the human lower limbs. After the temperature increases, the shoes made of non-Newtonian fluid materials can quickly stabilize under the condition of increased shear stress and reduce the displacement of the human body. Thus, it indicated that non-Newtonian fluid shoes may lower the risk of injury when running in extremely hot conditions.

Keywords: non-Newtonian fluid; EVA; high temperature; footwear; biomechanics

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1. Introduction

Running is one of the most popular physical activities in the world, with many individuals choosing it as either a form of recreation [1] or to become professional athletes. Running-related injuries are often caused by overused or wrongly selected running shoes [2,3]; therefore, the use of the appropriate running footwear can help to minimize injury risk [4,5]. There are several literature reports investigating how shoe design can reduce injury risk or improve running performance [6–8]. Footwear material can influence shock absorption; therefore, it can be an important measure of the shoe in regard to running-related injury prevention [5]. Embedding materials with different mechanical properties (i.e., soft, medium, and hard EVA insoles) into the shoe sole can significantly decrease the peak vertical loading rate [9]. It is recommended that runners utilizing a rearfoot strike running style use heel-cushioned shoes [10]. This style can help to decrease the magnitude of the vertical ground reaction force, subsequently reducing the impact load on the lower leg joints and potentially minimizing the risk of injuries. The mechanical characteristics of running shoes are usually examined in cross-sectional or longitudinal study designs using brand new footwear [11]. However, it should be noted that the mechanical parameters of a running shoe can also be altered when used in extreme weather conditions [12]. Cook et al. [13] demonstrated that running shoes containing air wedges, fiberglass plates and molded and composite midsole materials can preserve approximately 67% of their original shock absorption capability after 160–240 km using continuous machine-simulated mileage testing. After 400–800 km, these shoes retained less than 60% of their initial shock absorption capacity. Another study has demonstrated that three different hardnesses of EVA running footwear only lose 7.3% of their shock absorption capability over 420 km of running [14]. Thus, we think that it is important to investigate how changes in shoe sole material can alter its cushioning and shock absorption capacity during prolonged running, especially in a high temperature environment.

EVA and polyurethane (PU) materials are often utilized for shock absorption in running footwear [15], though more novel midsole materials are being developed each year [16]. A new type of non-Newtonian fluid (NN) midsole foam containing hydrogenated styrene elastomer has been embedded into the midsole, and one benefit of the NN shoes is that they are extremely temperature sensitive [17]. M. Hojjat et al. found that the rheological characteristics of non-Newtonian fluids showed shear thinning behavior after temperature rise [18]. On the other hand, the viscosity of non-Newtonian nanofluids decreases most significantly when the temperature rises to 50 °C [19]. High temperatures have become ever-more usual because of global warming, and the average temperature in the world has continuously risen [20]. Extreme changes in weather conditions may also have influenced the mechanical properties of running footwear [21]. Several studies have shown that the temperature of the midsole rises by 15 to 20 min after the start of running, but then stabilizes because of the thermal equilibrium [21]; thus, the uneven foot temperature created by friction between the foot and the footwear progressively transfers to the midsole [22]. According to Pouya Barnoon et al., non-Newtonian fluids closer to the horizon have more substantial effects on heat transfer [23], indicating that heat transfer of non-Newtonian fluids is theoretically possible when the shoe is running on the ground. Despite the fact that ambient temperature is not transported linearly into the midsole, studies have demonstrated that footwear may be impacted by ambient temperature [1]. Mohammad et al. [12] assumed that friction and compression between the foot and the shoe, as well as foot temperature and ambient temperature, are the most influential factors in footwear temperature change. As the temperature of the foam increases, pliability, compression, and recovery rates also increase, and its cushioning performance may alter and influence the lower limb biomechanics of exercisers during running [24].

The results of the simulation study using mechanical impacts appear to be more reliable than those of the real human test [1,25,26]. However, kinematics, kinetics, and muscular activity during progressive adaptation to a climatically changing environment might also be attributed to the temperature-induced alteration in footwear. Temperature-induced changes in the shoe's mechanical material are more evident in the literature [1,25,26]. But, these changes may result in altered kinematics, kinetic, and muscular activity during running. Menant et al. [27] have demonstrated that variations in the material of the midsole can impede the dynamic balance control system and softer materials can increase the center of mass and base of support (COM-BOS) offset, as well as the center of mass and center of pressure (COM-COP) difference. Most research compares shoes with EVA and PU cushions, but these materials are not commercially available [9,27,28]. Wunsch et al. [28] demonstrated that most runners are limited to purchasing molded running shoes. Only limited studies have investigated the effects of NN shoes on lower-limb movement, kinetic parameters, and muscle activity. Therefore, this study aimed to investigate how the temperature-induced changes in different cushion materials (EVA foam vs. NN) affect the kinematics, kinetics, and muscle activity of the lower leg after running for 5 km [29]. We expected that the temperature change would increase the kinematic and kinetics characteristics of the lower extremities, resulting in an increment in joint angles and joint moments in both shoes due to the material being subjected to high temperature changes. High temperatures would result in an increment in initial peak ground reaction forces and loading rates in NN shoes. Finally, the elevated temperature of the shoe material is likely to increase the path to the COP.

2. Materials and Methods

2.1. Participants

Priory sample size calculations (G*Power 3.1.7) revealed that a minimum sample size of 34 participants would be appropriate to detect significant differences between the EVA and NN groups (power: 0.8, effect size: 0.25, $\alpha = 0.05$, and $\beta = 0.2$).

Thirty-five healthy physically active male university students (23.2 ± 1.9 yrs., 1.8 ± 0.8 m, 76.2 ± 5.7 kg) were recruited for this experiment. All participants were habitual rearfoot strike runners and had a shoe size of 41 (EUR). The participants in this study engaged in regular exercise at least 3–5 times per week or had an average weekly running distance of at least 20 km. They had no history of lower extremity sports injuries within the past 6 months and were free of any musculoskeletal diseases [30]. Prior to the experiment, all participants gave written informed consent to take part in the study, which was performed in accordance with the Declaration of Helsinki and approved by the Ethical Institutional Review Board of Ningbo University (RAGH202303153005.2).

2.2. Experimental Shoes

The NN shoe was developed and manufactured by a Japanese manufacturer (Descente Ltd., Kabushiki-gaisha Desanto, Osaka, Japan). And, NN fluid was placed in the triangular region at the heel of the midsole (Figure 1). The same manufacturer also produced the EVA shoes that we used in this study (Figure 1). To aid the experimental comparison, all shoe components were designed and manufactured using the same method, except for the midsole material, which was different.

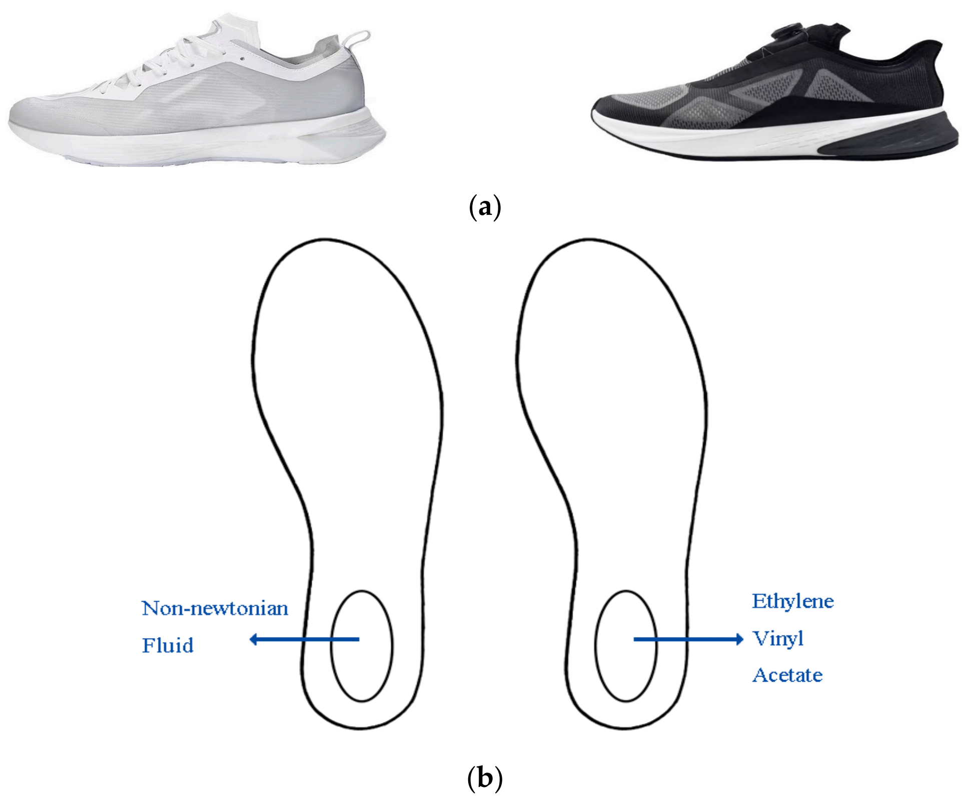

Figure 1. Experimental shoes were used by the participants. (**a**) The non-Newtonian fluid (NN) shoe is on the left-hand side and the ethylene vinyl acetate (EVA) shoe is on the right-hand side; (**b**) location of the cushion materials within the midsole.

2.3. Experimental Protocol

At the first visit to the laboratory, a maximal voluntary isometric contraction (MVIC) test was performed to obtain the peak electromyogram (EMG) amplitude of the rectus femoris (RF), medial gastrocnemius (MG), and soleus (SOL) muscles using a CON-TREX motorized dynamometer (CON-TREX MJ System, CMV, Dübendorf, Switzerland). For each joint, we used the setting recommended by the manufacturer [31].

After the MVIC tests, participants completed the running trial in the lab. Participants were randomly assigned into two groups based on whether they wore the NN or EVA shoe during the trails and when running for 5 km. The participants warmed up with a 5-minute exercise of running at a self-selected speed on a motorized treadmill [32]. Next, as a preparation for the experiment, 34 reflective markers were attached and secured with tape to the participants' bodies according to Opensim's Gait-2392 model (see supplementary file). We excluded the head marker after considering the model's impact on the lower limbs [33]. The marker trajectories were recorded with an eight-camera VICON motion capture system (Oxford Metrics Ltd., Oxford, UK), which had a sampling frequency of 200 Hz during the running trials. Vertical ground reaction force was collected at a sampling frequency of 1000 Hz with a force plate (AMTI, Watertown, MA, USA) embedded in the floor of the lab, which was approximately located in the middle of the range of the track that could be captured using the cameras. In addition, EMG activity of the RF, GM, and SOL were recorded at 1000 Hz using a wireless Delsys EMG device (Delsys, Boston, MA, USA) [34]. All data collection was performed simultaneously. Participants were asked to run across a 20-meter runway at their self-selected running speed, which was measured using time gates placed 2 m before and after the force plate. A total of 6–8 trials were carried out by each participant, but only three trials that were the closest to the self-selected speed (established in the familiarization session) were included in the analysis.

After the running trial, participants ran 5 km on a 400-meter track outdoors. Brower timing gates were installed at the outdoor track to monitor each participant's average running speed to ensure a relatively consistent running speed. To ensure that the markers and EMG sensors' locations remained the same place, the 5-kilometer running trial was executed with the markers and sensors remaining on their body. After the 5-kilometer running trial, a surface thermocouple portable thermometer (WRNM-01) was used to measure the shoe-sole temperature at the heel triangle of the shoe (Figure 1). Next, the running trial in the lab was repeated using the above-described conditions.

2.4. Data Analysis

The marker trajectories were smoothed with a 12-Hz low-pass Butterworth filter, and ground reaction force data were filtered at 60 Hz [28]. A custom-written MATLAB (MathWorks, Natick, MA, USA) script was used to convert the filtered marker trajectory and ground reaction force data into an OpenSim-suitable format. A static calibration trial was performed before the running trial in order to optimize individual segment dimensions. The angular displacement of the joints was calculated for each stride using inverse kinematics and inverse dynamics algorithm tools in OpenSim (SimTK v. 4.0.1) were then used to calculate joint moments [35]. Joint flexion is expressed through negative values, while joint extension is expressed through positive values. Kinematic and kinetic datasets were time normalized for the stance phase (0–100%) in order to use time-series comparison. Kinetic variables were normalized to body weight, and COP was adjusted based on leg length to reduce height's influence [33]. To match dynamic results with applied forces, OpenSim's Residual Reduction Algorithm (RRA) was used to conduct residual reduction on the model. RRA modifies the model's center of mass by estimating and applying external forces and moments operating on or around each pelvic axis [36].

The raw EMG signals were filtered in the frequency range of 10–500 Hz using a bandpass fourth-order Butterworth filter [37]. The filtered EMG amplitudes were smoothed with a root mean square (RMS) with a window size of 50 ms. Next, the EMG signal was normalized to the peak MVIC amplitude, and the dataset was then time normalized (0–100%) to the stance phase of the running trials.

2.5. Statistical Analysis

All measured parameters were reported as means and standard deviations. Prior to statistical analysis, the homogeneity and normality of the measured and calculated dataset were checked via the Shapiro–Wilk and Leven's tests. A two-way repeated-measures ANOVA was conducted to investigate the main effects of the shoe condition, the temperature, and their interaction on kinematics, kinetics, and muscle activation degree. The alpha level was set at 5%. In case of any significant interaction, a Bonferroni post hoc test was performed. Statistical calculations using discrete variables were executed using SPSS 22.0 (IBM, Armonk, NY, USA).

Comparison of time-series datasets was calculated using Statistical Parameter Mapping (SPM, www.spm1d.org (accessed on 1 November 2022)). Using a time-normalized stride, a two-way repeated-measures ANOVA was performed. The SPM (1) test statistics were computed to examine the shoe–temperature interaction. In every SPM analysis, the test statistic SPM (1) was computed first, followed by the critical threshold F. Based on Random Field Theory, α% of random curves were expected to exceed the critical threshold. The difference was regarded as statistically significant once the test statistic's trajectory surpassed the crucial threshold. A Bonferroni correction test was applied to determine the location of the difference if an interaction occurred. α level was set at 5%. A detailed description of the SPM method is provided in several other studies [38,39].

3. Results

3.1. Effects of the Shoe Conditions

Wearing NN increased the range of motion (ROM) of the hip joint by 57–68% ($p = 0.001$) of the stance phase after running for 5 km, as shown in Table 1. There was no significant effect on the ankle and knee joints' ranges of motion.

Table 1. Sagittal joint ROM for the hip, knee, and ankle joints.

Joint (x°)	Variables	EVA (Pre)	EVA (Post)	NN (Pre)	NN (Post)	Main Effect Shoe	Main Effect Temp	Interaction Effect
Hip	ROM	34.0 ± 1.7	34.2 ± 3.8	34.2 ± 3.3	37.8 ± 3.4	**F = 69.708; *p* = 0.001**	F = 1.785; *p* = 0.252	F = 1.640; *p* = 0.270
Knee	ROM	25.7 ± 2.9	27.2 ± 2.6	25.6 ± 2.4	24.9 ± 2.0	F = 1.237; *p* = 0.328	F = 0.137; *p* = 0.730	F = 0.600; *p* = 0.482
Ankle	ROM	25.8 ± 3.3	28.1 ± 4.9	24.7 ± 1.7	28.9 ± 1.7	F = 0.013; *p* = 0.916	F = 14.307; *p* = 0.019	F = 0.657; *p* = 0.463

Note: Statistical significance was set at $p < 0.05$. The significant differences in interaction effect are based on the results of Bonferroni post hoc tests (α = 0.008). The bold figure represents significant differences.

The first peak ground reaction force and instantaneous loading rate increased significantly after 5 km of running at high temperatures ($p = 0.001$; $p = 0.009$) in both shoe conditions. In the EVA group, there was no significant effect of the main effect of temperature on muscle activation on the RF, MG, and SOL muscles' average EMG activity, as shown in Figures 2 and 3.

Wearing NN increased the torque in the sagittal plane of the knee by 21–23% ($p = 0.001$) and 37–45% ($p < 0.001$) of the stance phase after running for 5 km, as shown in Table 2. There was no significant effect on the peak sagittal torque of the hip and ankle joints.

Table 2. Sagittal joint torque peak values for the hip, knee, and ankle joints.

Joint Torque (N·m·kg^{-1})	EVA (Pre)	EVA (Post)	NN (Pre)	NN (Post)	Main Effect Shoe	Main Effect Temp	Interaction Effect
Hip-flexion torque	1.0 ± 0.1	1.0 ± 0.1	0.8 ± 0.02	1.2 ± 0.1	F = 0.173; *p* = 0.718	F = 7.867; *p* = 0.107	F = 21.078; *p* = 0.044
Knee-flexion torque	0.7 ± 0.1	0.8 ± 0.1	0.7 ± 0.03	0.9 ± 0.1	**F = 47.701; *p* = 0.002**	**F = 31.750; *p* = 0.006**	F = 0.205; *p* = 0.674
Ankle-dorsiflexion torque	2.4 ± 0.1	2.4 ± 0.04	2.5 ± 0.1	2.4 ± 0.2	F = 0.424; *p* = 0.550	F = 3.642; *p* = 0.129	F = 2.178; *p* = 0.214

Note: Statistical significance was set at $p < 0.05$. The significant differences in interaction effect are based on the results of Bonferroni post hoc tests (α = 0.008). The bold figures represent significant differences.

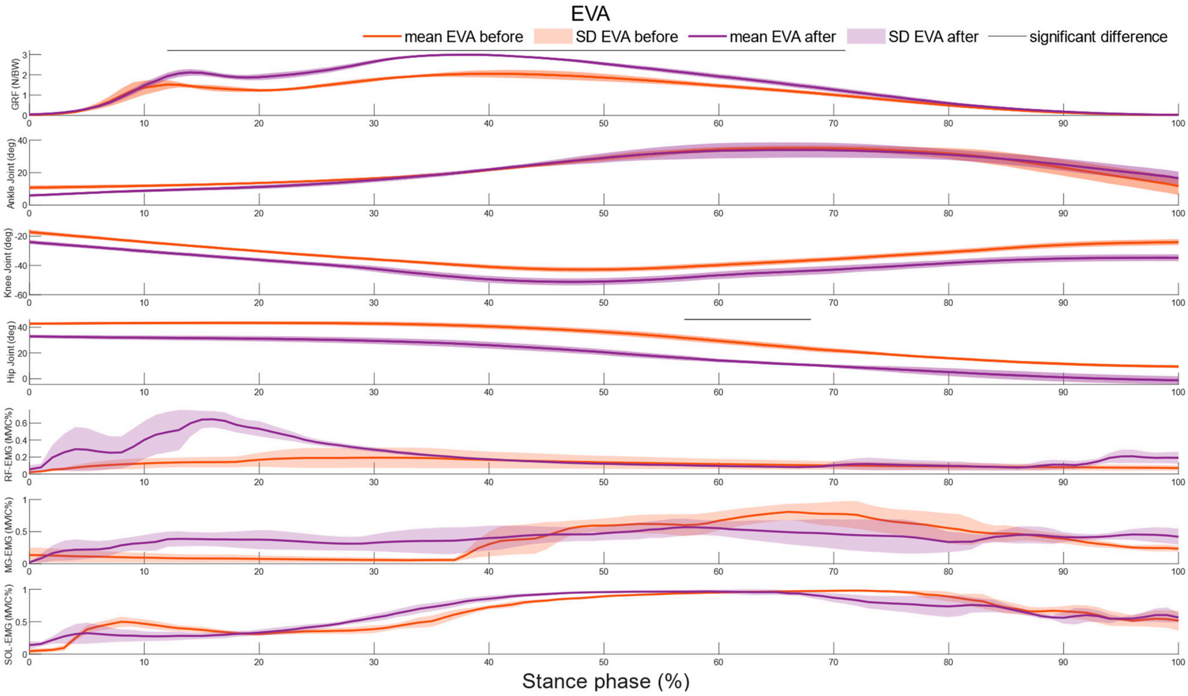

Figure 2. Comparison between EVA's GRF and sagittal plane joint angles for hip, knee, and ankle joints and muscle activity.

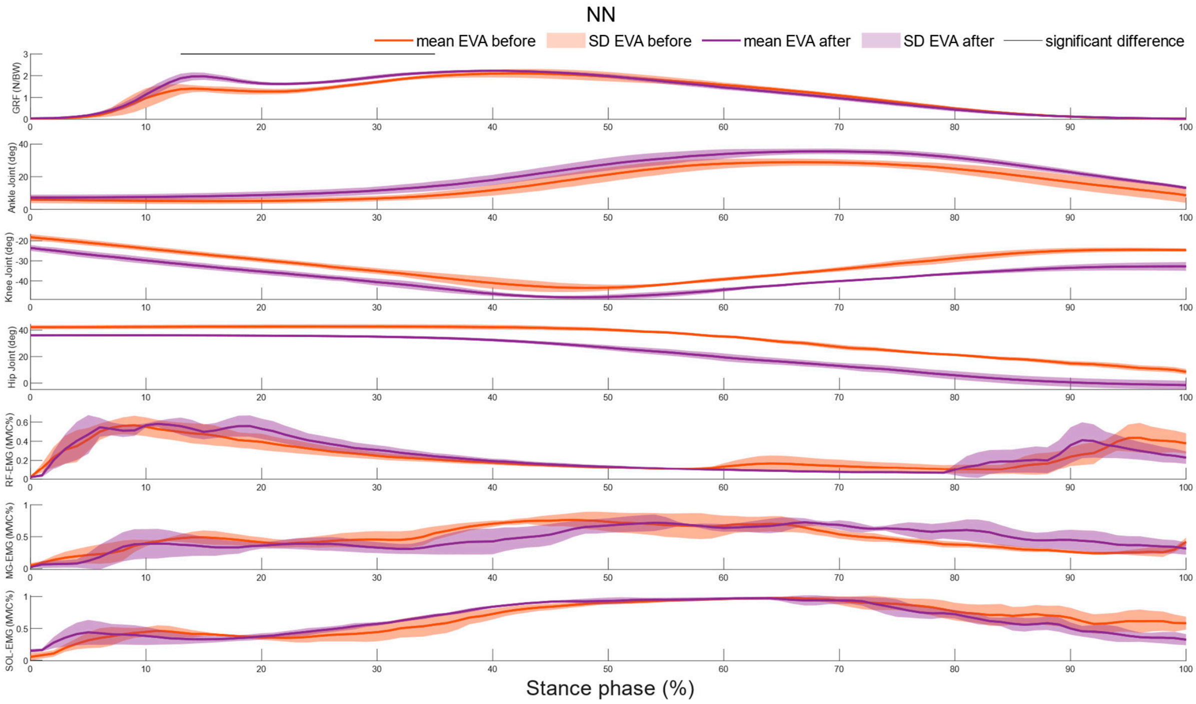

Figure 3. Comparison between NN's GRF and sagittal plane joint angles for hip, knee, and ankle joints and muscle activity.

The envelope area of COP increased significantly after a 5-kilometer run in EVA and decreased significantly after the same run in NN (F = 47.456; $p < 0.001$), as shown in Figure 4. There was no significant effect on the range of displacement and total displacement of COP.

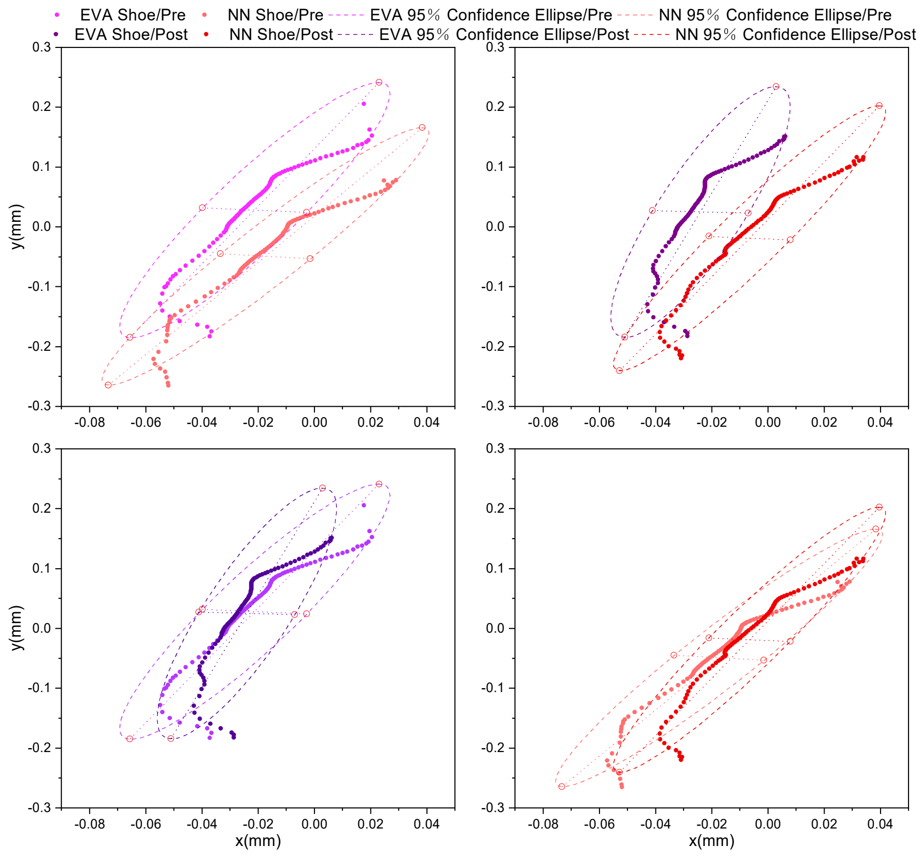

Figure 4. Depiction of the COP trajectory, as well as the results of the x-axis offset range, y-axis offset range, and envelope area. The upper left and upper right boxes represent the COP variations for different midsole materials at the same temperature. The bottom left and bottom right are the COP variations for the same shoe tool at different temperatures.

3.2. Effects of the Temperature

The midsole temperatures of NN shoes increased by an average of 343% (54.84 °C from 22.53 ± 0.43 °C) after the 5-kilometer running trial, while EVA midsole temperature was elevated by 327% (50.87 °C from 22.46 ± 0.52 °C), on average.

There was no significant effect on ankle, knee, and hip joint ranges of motion values. The knee moment in the sagittal plane was significantly higher at 88–100% of the stance phase ($p = 0.001$) after a 5-kilometer run in rising temperatures in either NN or EVA shoes. There was no significant effect of the main effect of temperature on hip and ankle torques.

In both shoe conditions, the range of COP displacement significantly increased after a temperature rise ($p < 0.001$). The COP envelope area of EVA increased significantly after a temperature rise over 5 km, while that of NN decreased significantly ($p < 0.001$). In terms of total displacement, the main effect of temperature had no significant effect on either shoe after 5 km of running.

4. Discussion

The aim of this study was to investigate the effect of high temperatures on differently cushioned shoes. We explored how changes in shoe material could alter the kinematics, kinetic, and muscle activity characteristics of the lower leg after prolonged running at high temperatures. We can confirm that there is not much difference between these two shoes, after 5 km of running, NN fluid shoes will be more suitable for extreme weather changes.

Our results demonstrated that the RF, MG, and SOL EMG activity after the 5-kilometer trial running were not influenced by the shoe midsole material or the temperature effect (Figure 5). This finding allows us to rule out the fatigue that causes the joints' changes.

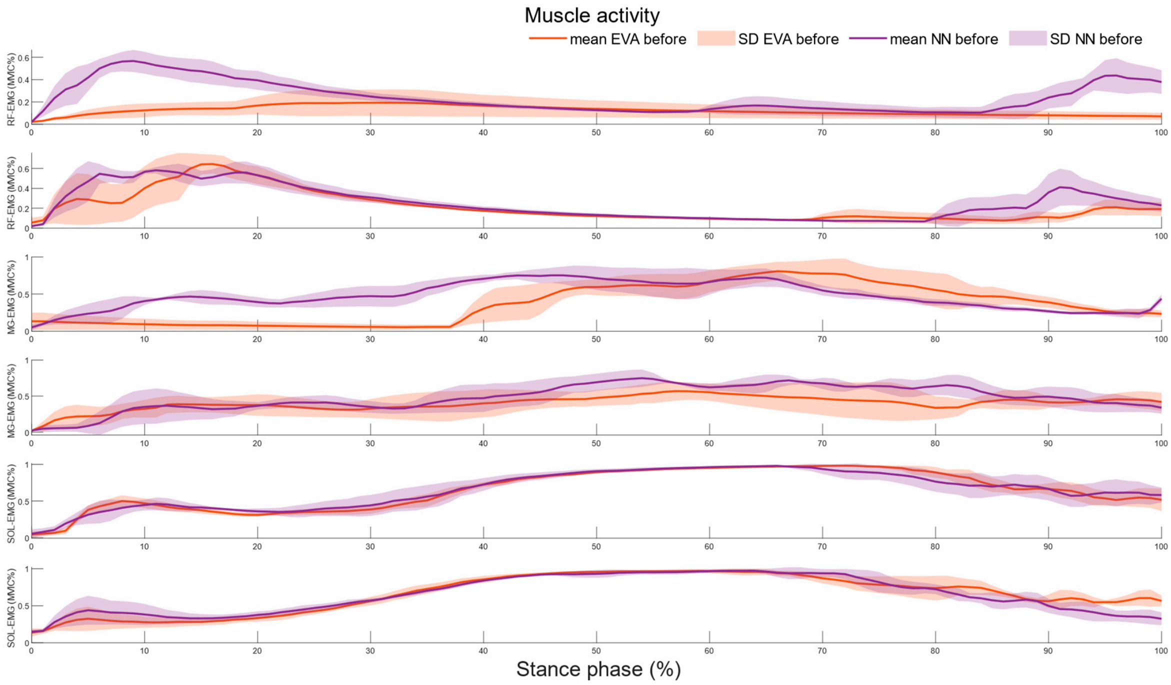

Figure 5. Comparison between before and after a 5-kilometer running trial in both shoes' muscle activity.

It is logical to think that as the temperature rises, the change in the material causes a change in the first peak of the ground reaction force. A study by Dixon et al. [10] demonstrated that EVA footwear had no effect on lower-limb joint displacement, regardless of midsole stiffness, though the softer midsole substantially decreased the peak vertical loading rate (131.28 to 138.40 and 139.54 BW/s). This observation is reflected in our results— namely, we found that after the 5-kilometer running trial, the initial peak and loading rate were both higher, likely due to the temperature-induced changes in the midsole in both shoes. Scott et al. [40] found that if the heel protector does not adequately reduce the impact load of running, the injury risk may increase. Consistent with previous reports, the results of our study indicate that high temperatures in the midsole of EVA and NN shoes lead to an increased peak GRF and elevated loading rates. These findings indicated that runners might be subjected to a higher injury risk when running in extremely high temperatures, possibly because the shoe materials' integrity becomes less stable. It has been shown that when footwear midsole EVA foam reaches a temperature of 70 °C, the material begins to dissolve [12]. The midsole temperature of each shoe worn by the participants exceeded 70 °C; thus, the cushioning capability of the EVA shoes is degrading. High temperatures cause EVA shoes to lose strength [41]. The applied force will increase and reduce the cushioning capacity. Previous reports have demonstrated that padded footwear effectively decreases the loading rate [42,43]. This cushioning material can maintain its material properties under high temperatures and reduce the risk of injury. We demonstrated a significant increase in the rate of first peak GRF after the shoes were exposed to prolonged running in a high-temperature condition. This result confirms our initial assumption that the excessive softening of footwear after exposure to high temperatures results in a loss of elastic support during heel landings. After the 5-kilometer running trial, the temperature of the midsole increased similarly in both shoes. The EVA shoes showed a substantially larger displacement range and envelope area than NN shoes, while NN has a significantly smaller envelope area. This outcome is likely attributed to the temperature increase, which differently affected the two shoes. Based on the differences in the GRF characteristics, we can see that NN shoes seem to be more consistent with the trial before the 5-kilometer run and have smaller changes in COP. Thus, we can assume that the cushion material was less affected by the temperature than the EVA shoe. This outcome can be the specific result of the NN material. We thought that there would be some deformation of non-Newtonian fluids at some higher temperature, resulting in less viscosity and greater tension [44], thereby producing faster wrapping on the heel.

The footwear may be responsible for the changes in the ROM after 5 km of running in the heat. The results showed a significantly increased ROM in the hip joint when wearing NN shoes. The greater ROM of the hip joint might be a result of the heat. It induced changes in the NN shoes as a softened stance occurred on a less stable surface. At the same time, an increase in the hip torque of NN shoes was applied to accommodate the greater changes in joint mobility. The increased temperature is more likely to result in decreased viscosity and increased shear stress in NN materials [44,45]. Higher shear stresses permit the NN to have a shear-thickening effect [46], and some material hardening takes place, which makes the shoe more rigid and sustains the cushioning capacity of the shoe [47]. This result is supported by the vertical GRF dataset, which shows a similar pattern. But, the hip has adjusted to the softening of the shoe. This observation may have an impact on the hip-joint motion changes. We observed greater knee flexion in NN shoe compared to EVA before and after the 5-kilometer running trial. This outcome is similar to the findings of Clarke et al., who reported increased knee flexion when running in a shoe with a harder sole than in a shoe with a softer sole [48]. We can assume that the hip's ROM might be affected by these changes.

In terms of joint torque, temperature increases resulted in a larger knee-flexion torque in both shoe types after 5 km of running outdoors. This outcome may increase quadricep femoris muscle activity, patellar tendon strain, and patellofemoral joint stress to cooperate with the joints' changes [49]. Knee extension was higher during mid-stance in NN footwear than in EVA footwear, and we believe that the shear stress increase may have contributed to the increased knee extension moment [50].

There are some methodological limitations to this study that must be addressed. The greatest influencing factor in this study is the level of fatigue experienced by the participants. Our goal was to simulate real-like conditions; hence, we selected the 5-kilometer outdoor run as the task for participants to perform. Running in extreme weather conditions poses a greater risk to the human body, and it makes physical activity more demanding. Thus, we cannot overlook the fact that fatigue may have a higher impact on the observed changes than the changes occurring in the shoe's midsole material. The sample was homogenous, as the fitness level of the participants was similar. Thus, we can assume they were equally subjected to fatigue. In this case, fatigue would affect the observed variables in the same manner. Therefore, we think that the obtained changes are more likely attributed to the temperature-induced changes in the shoe midsole material than fatigue. However, we cannot support this idea with numerical results. Therefore, the possible effects of fatigue must be considered when interpreting the results of this study. The EMG activity pattern of the leg muscles is shown to be region specific to various tasks, which can be detected using HD-EMG [51]. In this study, we used bipolar surface EMG to record the amplitude changes in the observed muscles. It was not able to obtain a signal from a larger area of the muscles, which limited the accurate representation of the muscle activity. The mechanical properties (i.e., bending stiffness, cushion capability) of the shoes were not directly measured. We only used the temperature as a measure combined with GRF and COP results to make assumptions about the changes in shoe material. And, it must be considered that measuring kinetic and kinematic data outdoors was not possible. The surface in the lab and the track where the 5-kilometer run was performed did not have the same material and temperature. The outdoor 400-meter track had a standard Rekortan surface material, which was exposed to extreme heat, while the lab surface was inside the lab building and had a more rigid surface at room temperature. However, the before and after running trials were performed under the same conditions. The lab trial may not adequately mimic the outdoor foot–shoe–ground contact interaction.

Despite advancements in running shoe design technology, there has been no substantial reduction in the percentage of injuries incurred by distance runners [52]. High temperatures can cause shoe soles to soften and modify the contact surface. Similarly, high temperatures can alter the running surface [53]. High temperatures lead to alterations in inter-articular kinematics and modify the activation of particular specific muscles, as supported by the results of this study. Due to the features of NN, we considered the adaptive contact conditions for footwear. Although the midsole is partly unique to this material, the prescription of the shoe is, ultimately, determined by the runner's individual demands.

5. Conclusions

This study shows that the insertion of NN materials into the midsole may affect the angular changes in the hip joint, as well as the extension moment of the knee joint, during running. Changes in ground reaction force and COP trajectories may influence the adaptation of runners' lower-limb joints to environmental temperature changes' affects on footwear by modulating torque and joint range of motion. However, the characteristics of NN will enable runners to adjust to running at high temperatures more quickly. To some extent, this outcome helps to stabilize the unstable plane brought on by material softening. Thus, our study suggests that non-Newtonian fluid shoes can adapt to environmental changes during harsh climatic conditions, thereby helping runners to adapt more quickly to initial running conditions, preventing running-related injuries.

Supplementary Materials: The following supporting information can be downloaded via the following link: https://www.mdpi.com/article/10.3390/app13148024/s1, Figure S1: Marker location based on the Opensim gait model 2392. A total of 34 markers were attached to the bodies of the participants at the given anatomical positions.

Author Contributions: Conceptualization, J.Y. and E.S.; methodology, J.Y. and J.L.; software, L.G.; validation, B.K., J.L. and Y.G.; formal analysis, J.Y.; investigation, J.Y.; resources, L.G.; data curation, L.G.; writing—original draft preparation, J.Y.; writing—review and editing, B.K.; visualization, J.Y.; supervision, Y.G.; project administration, B.K. and J.L.; funding acquisition, Y.G. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Ningbo University (RAGH202303153005.2).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patient(s) to publish this paper.

Data Availability Statement: The data are unavailable due to privacy or ethical restrictions.

Conflicts of Interest: The authors declare no conflict of interest.

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