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Leg stiffness during running in highly cushioned shoes with a carbon-fiber plate and traditional shoes

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ABSTRACT

Background: Nike ZoomX Vaporfly (NVF) improves running economy and performance. The biomechanical mechanisms of these shoes are not fully understood, although thicker midsoles and carbon fiber plates are considered to play an important role in the spring-like leg characteristics during running. Leg stiffness (k_{leg}) in the spring-mass model has been commonly used to investigate spring-like running mechanics during running.
Research question: Does k_{leg} during running differ between NVF and traditional (TRAD) shoes?
Methods: Eighteen male habitual forefoot and/or midfoot strike runners ran on a treadmill at 20 km/h with NVF and TRAD shoes, respectively. k_{leg}, vertical oscillation of the center of mass (ΔCoM), spatiotemporal parameters, and mechanical loading were determined.
Results: k_{leg} was 4.8% lower in the NVF shoe condition than in the TRAD condition, although no significant difference was observed. ΔCoM was not significantly different between shoe conditions. Spatiotemporal parameters and mechanical loading were also not significantly different between shoe conditions.
Significance: The NVF shoe is well known as improving the running economy and running performance for the cause by characteristics of better spring function. Contrary to expectation, k_{leg} and other parameters were not significantly different during running in the NVF compared to TRAD shoe at 20 km/h. These findings indicate that well-trained runners' spring-like running mechanics would not alter even if wearing the NVF shoes.

1. Introduction

Nike ZoomX Vaporfly (NVF) shoes are characterized by a full-length carbon-fiber plate embedded in a thicker midsole with highly compliant and resilient foam [1]. The advantage of NVF shoes for running is well known in that they improve running performance [2] by improving running economy [1,3,4]. In addition, characteristics of NVF shoes are presumed to assist the spring-like mechanism of the lower limb during running.

The mechanisms of improving running economy and/or running performance with NVF shoes have been investigated by many researchers [1–7]. Previous studies have shown that the differences in ground reaction force (GRF) and/or spatiotemporal parameters between NVF and traditional (TRAD) shoes were comparably small, and these were insufficient to explain the mechanism of improvement of running economy during running in NVF shoes [1,3,4]. Further, NVF shoes have been shown to enhance the mechanical advantages of the lower limb joint [6], such as reducing the energy loss at the metatarsophalangeal joint during the stance phase [8]. This mechanical advantage caused by increasing the longitudinal bending stiffness with embedded carbon-fiber plates [6,9–13] and could contribute toward the improvement in running economy [6]. However, it is suggested that increasing the longitudinal bending stiffness by the carbon-fiber plate is not the only factor that improves running economy [14]. Therefore, the biomechanical mechanisms by which NVF shoes improve running economy are not fully understood.

An elastic mechanism, in which elastic energy is stored and released in a series of elastic elements of the lower limb, is thought to work during running [15,16] and make the running more economical. Additionally, the sole of the shoe acts as a spring [1,17,18]. Better spring function of NVF shoes has been reported in previous studies [1,6]. Moreover, carbon-fiber plates also affect the spring-like behavior at the

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muscle-tendon unit level in the gastrocnemius muscle [13,19]. However, to our knowledge, the effect of NVF shoes on the spring-like mechanism of the lower limb during running has not been clarified yet. Understanding the alteration of spring-like leg mechanics during running in NVF shoes may lead to elucidation of biomechanical mechanisms involved in improving running economy.

A simple spring-mass model has been proposed to quantify the spring-like running mechanics in previous studies [20–22]. This model represents the single linear leg spring of the lower limb and is used to describe the spring-like compression loaded by the body mass and external force [21,22]. Leg stiffness (k_{leg}) calculated using this approach is a biomechanical parameter which has negative correlation with running economy across individuals [23–25]. It is reported that other factors (i.e., surface and/or midsole foam) also affect k_{leg} during running [26,27]. Kulumala et al. demonstrated that k_{leg} significantly increased and the vertical oscillation of the center of mass (ΔCoM) did not change during running in maximalist shoes compared to TRAD shoes [27]. These results suggest that adjustment of k_{leg} is key factor for keeping ΔCoM low [26,27]. Keeping ΔCoM low is also beneficial to prevent the decreasing of running economy [28,29]. Hence, it was speculated that an appropriate adjustment of k_{leg} for characteristics of midsole foam is one of the determining factors in running economy.

Herein, we aimed to clarify the differences in k_{leg} during running in the NVF and TRAD shoes. We hypothesized that a higher k_{leg} would be observed during running in NVF shoes to keep ΔCoM low.

2. Materials and methods

2.1. Participants

We measured the effect size from the result of k_{leg} of our pilot study. The number of participants of pilot study was determined to be 12 runners based on a previous study [27] closer to our experimental protocol. The necessary sample size was calculated using G*Power (version 3.1.9.6) based on the mean and standard deviation from the pilot study that at least 15 participants were required to achieve power 0.8 and alpha level 0.05.

We recruited 20 distance runners to account for possible attrition. Inclusion criteria consisted as below: 1) runners in a long-distance team of Juntendo University and a recent sub-16-min 5000-m or equivalent race performance; 2) runners who have participated in long-distance races wearing the NVF shoes. No female runners met these inclusion criteria around our research environment, and participants in this study included only male runners. The sex of participants was defined based on self-report. Consequently, 20 male distance runners (age 20.7 ± 0.9 years, height 1.70 ± 0.04 m, body mass 57.2 ± 4.9 kg, leg length 0.81 ± 0.03 m) participated in this study. Leg length was defined as the length between great trochanter and lateral malleolus. Participants' official season record of the athletic 5000-m track race was 13:51.2–15:53.2 (Table S1). Considering the effect of foot strike pattern on k_{leg} [30,31], 18 runners with habitual forefoot strike and/or midfoot strike (calculated using foot strike angle [32]) were included in the analysis. Participants had no history of running-related injury or pain in their lower limbs in the 12 months prior to participation. All participants provided written informed consent for study participation. This study was approved by the institutional ethics committee (approval code: JUGE2020–76) and was conducted in accordance with the Declaration of Helsinki.

2.2. Shoe condition

Two different types of running shoes were used in this study. One was a maximalist shoe, in which a carbon-fiber plate was embedded between the polyether block amide midsole (Nike ZoomX Vaporfly NEXT%: NVF, Nike, USA). This shoe had a 40-mm heel height, 30-mm forefoot height located at the metatarsophalangeal joint, 10-mm heel-toe drop, and 186-g mass (shoe size US 9.0). The other was a traditional (TRAD) shoe (MEDIFOAM Melos MF-003, Achilles, Japan) with ethylene-vinyl acetate (EVA) midsole embedded polyurethane (PU) foam. This shoe had a 30-mm heel height, 15-mm forefoot height located at the metatarsophalangeal joint, 15-mm heel-toe drop, and 200-g mass (shoe size US 9.0). The participants wore the most comfortable size of each shoe in the experimental trial.

2.3. Experimental protocol

After a warm-up period, participants ran on an instrumented split-belt treadmill (FTMH-1244, Tec Gihan Co., Ltd., Uji, Japan) in two shoe conditions. The first 15 km/h speed phase was used for participants to familiarize themselves with treadmill running with each running shoe. Subsequently, participants continued to run for one minute at 20 km/h. In both warm-up and running trials, a harness was placed on their trunk. The trial order was randomized across the participants.

2.4. Data collection

A total of 37 retro-reflective markers were secured to the whole body based on the Plug-in gait model [27] with additional markers on the right and left of the great trochanter. Three-dimensional coordinates of the retro-reflective markers were obtained using a 13-camera motion capture system (VICON Nexus 2.3, Oxford, UK) with a sampling frequency of 250 Hz.

The instrumented treadmill incorporated two split-force plates. The participants ran on only the left side of the split belt. The ground reaction force (GRF) was recorded at a sampling frequency of 1 kHz. The GRF data were synchronized with the coordinate data.

2.5. Data analysis

Kinematic and kinetic variables were calculated during one minute of steady state running at 20 km/h. All variables were averaged over 30 consecutive steps of participant's left leg.

Regarding kinematics data, raw data of the position coordinates of the markers were smoothed using a fourth-order low-pass Butterworth filter. The optimal cut-off frequency for each marker was identified using residual analysis [33]. The cut-off frequencies ranged from 13 to 23 Hz. Furthermore, each smoothed coordinate was used to determine the center of mass (CoM) of the whole body in the Plug-in gait full-body model. The vertical oscillation of the CoM (ΔCoM) was calculated as the difference between the maximum and minimum values of the CoM during a gait cycle. Leg spring was defined as a distance vector between the point of the hip and the ankle marker to exclude the effect of shoe midsole deformation on leg compression [27]. Leg compression was defined as the length change of the leg spring during the stance phase, and it was normalized to the leg length.

Regarding kinetics data, raw data of the GRF were smoothed using a fourth-order low-pass Butterworth filter with a cut-off frequency of 40 Hz [34]. The timing of the initial foot contact and toe-off was identified using vertical GRF to calculate the spatiotemporal parameters. The threshold for foot contact was set at 50 N to help determine the stance and flight phases of each gait cycle. The GRF acting through the leg spring (GRF_{leg}) was determined as the vector of the GRF projected to the leg spring axis (Fig. 1) using the following equation [31]:

$$GRF_{leg} = GRF \cdot \cos\theta_d \tag{1}$$

$$\theta_d = \theta_{GRF} - \theta_0 \tag{2}$$

where θ_d is the difference angle between θ_{GRF} and θ_0, θ_{GRF} is the angle of the resultant GRF, and θ_0 is the approach angle to the leg spring axis. GRF_{leg} was normalized to the body mass.

We calculated the leg stiffness (k_{leg}) using the above variables. k_{leg} was calculated as the ratio of the peak GRF_{leg} (kN) to the maximal leg

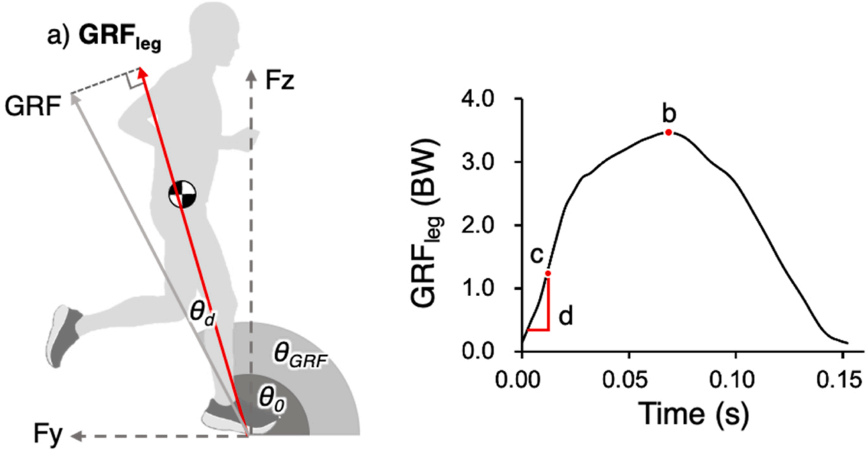

Fig. 1. Ground reaction force and mechanical loading during running. (a) The ground reaction force applied to the lower limb (GRF_{leg}) and (b) peak GRF_{leg} during the stance phase were calculated according to Gill et al. [28]. (c) Impact force and (d) loading rate during the stance phase were calculated according to Lieberman et al. [35].

compression (m) [27]:

$$k_{leg} = \text{Peak } GRF_{leg} \cdot \text{Maximal leg compression}^{-1} \tag{3}$$

Moreover, we calculated the spatiotemporal parameters and mechanical loading. Contact time was defined as the time duration from the initial foot contact to toe-off, and flight time was defined as the time duration from toe-off of one foot to the initial foot contact of the opposite foot. Step frequency (SF) was calculated as the reciprocal of the step time, which is the sum of the contact time and flight time. Step length (SL) was calculated from the ratio of the treadmill belt speed to the SF. The impact force and loading rate during the stance phase were calculated following the method by Lieberman et al. [35] to evaluate the mechanical loading for the forefoot strike (Fig. 1): Impact force was defined as the magnitude of GRF_{leg} at 6.2% during the stance phase. Loading rate was calculated as the time-derivation between 200 N to impact force of vertical GRF.

The continuous data of the leg compression and GRF_{leg} were normalized to 101 data points per stance phase with cubic spline interpolation.

Table 1
Mean ± SD values of the discrete parameters.

Parameters		NVF	TRAD	*p*	*d*
Leg stiffness	(kN/m)	26.61 ± 2.34	27.96 ± 2.63	0.12	0.68
ΔCoM	(mm)	81.63 ± 6.62	81.21 ± 6.06	*0.85*	0.15
Maximal leg compression	(mm)	69.51 ± 6.08	67.49 ± 5.98	0.66	0.70
Peak GRF_{leg}	(N)	1806.2 ± 190.6	1850.1 ± 150.5	0.47	0.34
	(BW)	3.22 ± 0.24	3.30 ± 0.18	0.27	0.36
Impact force	(BW)	0.71 ± 0.21	0.81 ± 0.24	0.20	0.66
Loading rate	(BW/s)	62.42 ± 22.03	72.41 ± 23.45	0.21	0.54
Contact time	(s)	0.15 ± 0.01	0.15 ± 0.01	0.85	0.29
Flight time	(s)	0.15 ± 0.01	0.16 ± 0.06	0.17	0.06
Step frequency	(step/s)	3.21 ± 0.08	3.24 ± 0.09	0.29	0.26
Step length	(m)	1.74 ± 0.05	1.72 ± 0.05	0.33	0.23

2.6. Statistical analysis

The normality of the data was confirmed using the Shapiro-Wilk test. A paired t-test was used to determine differences in the mean discrete parameters between shoe conditions using a statistical software (R, Vienna, Austria). Differences in continuous parameters between shoe conditions were examined using one-dimensional statistical parametric mapping (SPM) with the open source spm1d (https://spm1d.org/) in MATLAB 2019b (MATLAB, MathWorks, Natick, USA). The level of significance was set at $\alpha = 0.05$. Cohen's d effect sizes were calculated using G*Power.

3. Results

Concerning discrete parameters, k_{leg} in the NVF shoe condition was 4.8% lower than that in the TRAD shoe condition, although no significant difference was observed. Indeed, there were no significant differences in the discrete parameters between shoe conditions (Table 1). In the NVF shoe condition, SF was 0.9% (0.05 ± 0.05 steps/s) lower, and SL was 0.7% (1.24 ± 3.02 cm) greater than in the TRAD shoe condition, although no significant difference was observed in both SF and SL. Impact force and loading rate were reduced in NVF shoes by 12.4% and 13.8% on average, respectively, although no significant differences were observed. The average impact force and loading rate were reduced by 12.4% and 13.8%, respectively, in the NVF shoes compared to the TRAD shoes, although no significant differences were observed.

In contrast, GRF_{leg} was significantly different between shoe conditions in the first half of the stance phase with respect to continuous parameters. GRF_{leg} from 1% to 7% of the stance phase was significantly lower, although GRF_{leg} from 22% to 26% of the stance phase was significantly higher in the NVF shoe condition than in the TRAD shoe condition (Fig. 2. a). A significant difference in leg compression among shoe conditions was observed at the initial foot contact, mid-stance, and toe-off phases (Fig. 2. b). Leg compression was significantly lower in the initial foot contact phase (1–16% of the stance phase), whereas significantly higher values were observed in the midstance (48–68% of the stance phase) and toe-off (93–100% of the stance phase) phases in the NVF shoe condition than in the TRAD shoe condition.

4. Discussions

The purpose of this study was to clarify the differences in k_{leg} during running between the NVF and TRAD shoes. Based on the previous findings on the effect of maximalist shoes on k_{leg} [27], we hypothesized that k_{leg} would be increased during running in NVF shoes compared to that with TRAD shoes. This adjustment of k_{leg} was thought to be an important spring-like mechanism for keeping ΔCoM low during running in shoes made of highly compliant materials [26,27]. However, k_{leg} was 4.8% lower on average in NVF shoes, although there are no significant differences between shoe conditions. Moreover, ΔCoM was similar in

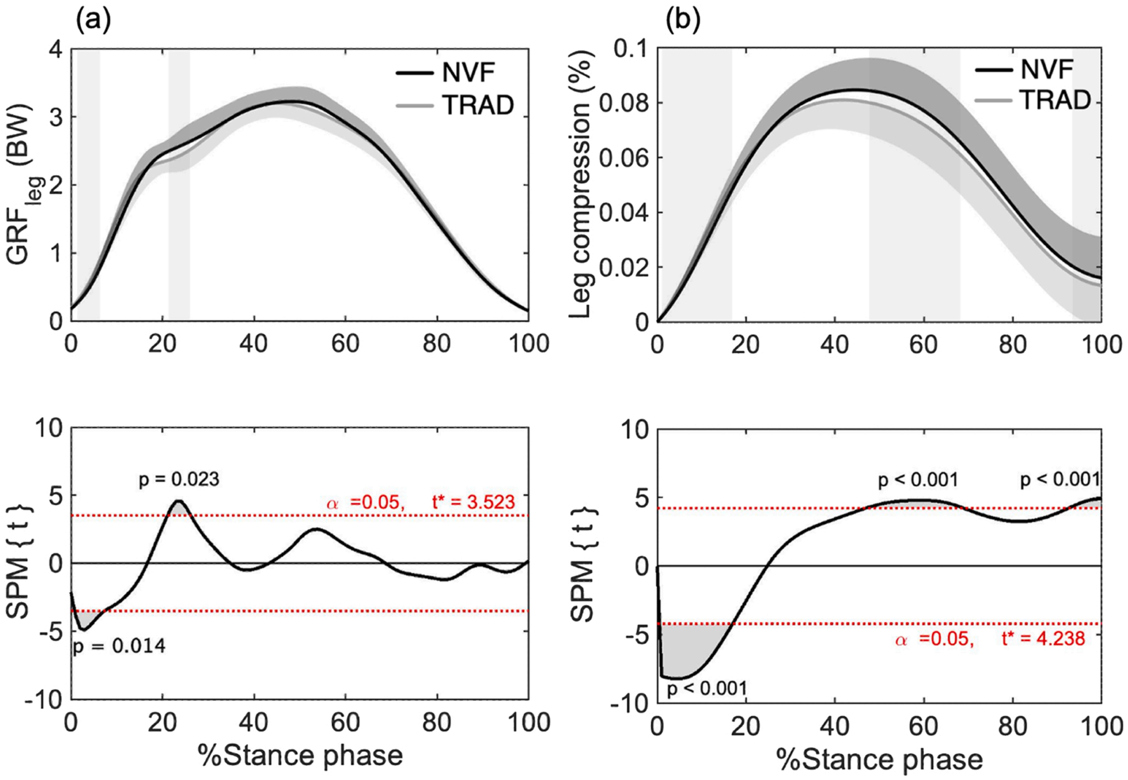

Fig. 2. Mean ± SD curves for continuous parameters. (a) GRF$_{leg}$ and (b) leg compression (top figures) and one-dimensional statistical parametric mapping (SPM) results (bottom figures). In the bottom figures, the horizontal dashed lines indicate the critical t * based on $\alpha = 0.05$, and supra-threshold clusters result in $p < 0.05$. The vertical shaded regions in the top figures correspond to the region of supra-threshold clusters and represent a significant difference ($p < 0.05$) between shoe conditions.

NVF shoes compared to TRAD (Table 1). Therefore, our hypothesis was rejected.

A previous study indicated that soft and thick midsoles decrease proprioceptive feedback from the foot [36]. It was thought that an increase in k_{leg} could improve the decreasing proprioceptive feedback that occurred in the compliant conditions although we did not measure the proprioceptive feedback directly. Indeed, a previous study has observed a greater k_{leg} in maximalist shoe than the traditional shoe condition [27]. Moreover, another study has observed an increase in maximal leg compression and a decrease in k_{leg} when shifting from a complaint to a stiffer surface [26]. However, opposite results were observed in this study when changing the shoe condition from the TRAD shoe to the NVF shoe. Specifically, the difference in maximal leg compression between shoe conditions was 3.0% on average, although the difference was not significant (Table 1). In addition, the continuous parameter of leg compression from 48.0% to 68.0% of the stance phase was significantly higher in the NVF shoe condition than in the TRAD condition (Fig. 2). Thus, the leg compression and k_{leg} alterations during running in NVF shoes are similar to those during running on a stiffer surface [26]. Moreover, Kerdock et al. indicated that the elastic energy return from the surface assists the runner's leg spring [26]. The characteristics of NVF shoe is well known as having approximately two times greater compliance and energy return than the traditional racing shoes [1]. It was suggested that the higher energy return of NVF shoe might assists the runner's leg spring. Further research into the interaction between different midsole characteristics is needed to better understand their effect on k_{leg}.

Furthermore, we focused on the possibility of NVF shoes improving the biomechanical parameters associated with higher running performance. Specifically, a 0.9% (0.05 ± 0.05 steps/s) decrease in SF and 0.7% (1.24 ± 3.02 cm) increase in SL on average in NVF shoes compared to that with TRAD shoes were indicated (Table 1). Previous studies also reported a slightly increasing SL in the NVF series shoe compared to traditional racing shoes [1,3,4,6]. Those two previous studies reported significant differences in SL [4] or SF [6] between NVF series shoes and traditional racing shoes. The slightly higher SL in NVF shoes was similar to previous studies. For distance runners, a 0.7% increase in SL may improve the running performance.

In addition, it was observed that GRF$_{leg}$ was significantly decreased immediately after the initial foot contact (1.0–16.0% during stance phase; Fig. 2, A), and both the impact force and loading rate were reduced in NVF shoes by 12.4% and 13.8% on average, respectively, although no significant differences were observed. (Table 1). In distance running, repetitive mechanical loading acting on the lower leg leads to cumulative physical trauma and the risk of running-related injury. In general, it is thought that the midsole foam helps reduce the mechanical loading applied from the ground, even though the impact force and loading rate were reported to increase during running in simple maximalist shoes in previous studies [27,37,38]. An increase in mechanical loading has been shown to be associated with an increase in k_{leg} [27,39]. Hence, we speculated that the decrease in mechanical loading might be because of a decrease in k_{leg}. It should be noted that all the participants in this study were habitual forefoot and/or midfoot strike runners, whereas the participants in previous studies were habitual rearfoot strike runners [27,37,38]. However, these results suggest that the NVF shoe might reduce the risk of impact-related running injury compared to the TRAD shoe and/or a simple maximalist shoe.

There are several limitations with the present study. First, the experiment was conducted using an instrumented treadmill. Although the biomechanical parameters in treadmill running were similar to overground running, it must be considered that there are several differences, such as lower limb joint kinematics and contact time [40]. Second, the participants in this study were only male runners. Hence, it was possible that the present results are limited to male runners.

Furthermore, it was unknown that the present results generalized for a female population. Further studies should be focused on sex differences. Finally, there are two possible problems as below. 1) we could not consider the differences in shoe midsole materials. Moreover, 2) The differences in running economy between NVF shoes and TRAD shoes was not clear. However, the ZoomX midsole of NVF shoes has approximately two times higher compliance and energy return compared to EVA and PU foam [1]. Therefore, we assumed that the differences in mechanical property between NVF shoes and TRAD shoes was similar to previous studies. Moreover, running in NVF shoes was well known for the lower running economy compared to traditional racing shoes [1,3,4,6]. We assumed that similar result of differences in running economy was also observed between NVF shoes and TRAD shoes. Further studies should be conducted to overcome these limitations. Additionally, it should be considered that it may be difficult to alter the part of the shoe because of the possible risk of damage to other parts [14].

5. Conclusion

The main results of this study were shown that the k_{leg} was not significantly different when running in the NVF shoe compared to TRAD shoe at 20 km/h. Furthermore, the other biomechanical parameters, such as ΔCoM, SL, SF, and mechanical loading were not significantly different between shoe conditions. These findings indicate that well-trained runners' spring-like running mechanics would not alter even if wearing the NVF shoes. Further investigation is needed to understand the biomechanical benefits of NVF shoes to improve the running economy and/or running performance.

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Conflicts of interest

All authors declare that there are no known conflicts of interest related to this project that may have influenced this manuscript.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2022.03.021.

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