



**HAL**  
open science

# The stiff plate location into the shoe influences the running biomechanics

Nicolas Flores, Guillaume Rao, Eric Berton, Nicolas Delattre

► **To cite this version:**

Nicolas Flores, Guillaume Rao, Eric Berton, Nicolas Delattre. The stiff plate location into the shoe influences the running biomechanics. Sports Biomechanics, 2019, pp.1-16. 10.1080/14763141.2019.1607541 . hal-02185104

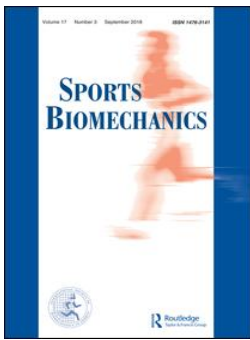
**HAL Id: hal-02185104**

**<https://amu.hal.science/hal-02185104v1>**

Submitted on 16 Jul 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## The stiff plate location into the shoe influences the running biomechanics

Nicolas Flores, Guillaume Rao, Eric Berton & Nicolas Delattre

To cite this article: Nicolas Flores, Guillaume Rao, Eric Berton & Nicolas Delattre (2019): The stiff plate location into the shoe influences the running biomechanics, Sports Biomechanics, DOI: [10.1080/14763141.2019.1607541](https://doi.org/10.1080/14763141.2019.1607541)

To link to this article: <https://doi.org/10.1080/14763141.2019.1607541>



Published online: 17 May 2019.



Submit your article to this journal [↗](#)



View Crossmark data [↗](#)

---



# The stiff plate location into the shoe influences the running biomechanics

Nicolas Flores<sup>a,b</sup>, Guillaume Rao<sup>b</sup>, Eric Berton<sup>b</sup> and Nicolas Delattre<sup>a</sup>

<sup>a</sup>Movement Sciences Department, Decathlon SportsLab, Villeneuve Ascq, France; <sup>b</sup>Sport Sciences Department, Aix Marseille University, The National Center for Scientific Research, Institute of Movement Sciences, Marseille, France

## ABSTRACT

The changes in running biomechanics induced by an increased longitudinal bending stiffness (stiff plates added into the shoes) have been well investigated, but little is known concerning the effects of the stiff plate location into the shoe on running biomechanics. Fourteen male recreational runners ran at two participant-specific running speeds ( $3.28 \pm 0.28$  m/s and  $4.01 \pm 0.27$  m/s) with two shoe conditions where a stiff plate was added either in high (under the insole) or low location (between the midsole and outsole). Ground reaction forces, lower limb joint angles, net joint torques and work, as well as alignment between the resultant ground reaction force and the leg were analysed. Among the running speeds performed by the runners, the high location significantly decreased propulsive ground reaction forces, increased metatarsophalangeal joint dorsiflexion and ankle plantarflexion, induced an increased alignment between the resultant ground reaction force and the runner's leg, thus decreasing all the lower limb joint torques and the positive work at the knee joint compared to the low location. The results suggested that the high stiff plate location into the shoe should be considered for running performance perspectives, but care should be taken to not alter the perceived comfort and/or increase injury risks.

## ARTICLE HISTORY

Received 26 November 2018  
Accepted 9 April 2019

## KEYWORDS

Footwear; shoe design; longitudinal bending stiffness; running speed; lower limb joint

## Introduction

The longitudinal bending stiffness (LBS) is a shoe feature that has raised interest in the shoe design for 20 years due to its influence on several tasks' performance. It has been reported that increasing LBS resulted in increased maximum jump height (Stefanyshyn & Nigg, 2000b), decreased sprinting time (Stefanyshyn & Fusco, 2004), and decreased oxygen uptake during running (Roy & Stefanyshyn, 2006). The reduced oxygen uptake during running can likely be due to the biomechanical changes induced by an increased LBS such as a decreased metatarsophalangeal (MTP) dorsiflexion (Madden, Sakaguchi, Tomaras, Wannop, & Stefanyshyn, 2016; Oh & Park, 2017; Willwacher, König, Potthast, & Brüggemann, 2013), decreased propulsive ground reaction forces (GRF) (Flores, Delattre, Berton, & Rao, 2017; Morio & Flores, 2017; Oh & Park, 2017), a shifted point of application of the GRF anteriorly under the shoe (Oh & Park, 2017; Willwacher et al., 2013), and an increased lever arm of the resultant

GRF relative to all the lower limb joints in the sagittal plane (Willwacher, König, Braunstein, Goldmann, & Brüggemann, 2014). Taken together, these kinematic and kinetic modifications may have changed the orientation of the lower limb kinematic chain and/or the resultant GRF in the sagittal plane, thus potentially influencing the alignment between the resultant GRF and the runners' leg (Alexander, 1991; Biewener, Farley, Roberts, & Temaner, 2004; Carrier, Heglund, & Earls, 1994; van Ingen Schenau, Boots, de Groot, Snackers, & van Woensel, 1992). As an altered alignment was previously shown to influence the metabolic cost of running (Moore, Jones, & Dixon, 2016), the kinematic and kinetic modifications induced by the LBS may have influenced the metabolic cost of running.

The increased shoe LBS has usually been achieved by adding stiff plates into the shoes. In most studies, the stiff plates were located under the insoles of shoes (Flores et al., 2017; Morio & Flores, 2017; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Stefanyshyn & Fusco, 2004; Willwacher et al., 2014, 2013), while other studies inserted the stiff plate in the exact middle of the shoe midsole thickness (Stefanyshyn & Nigg, 2000b), or between the midsole and the outsole of shoes (Madden et al., 2016; Tinoco, Bourgit, & Morin, 2010). The different stiff plate locations into the shoe thus make the plate more or less distant from the foot (Figure 1). This induces different lever arms to the MTP joint centre of rotation that may influence the forefoot bending and affect all the lower limb kinematic and kinetic behaviour.



**Figure 1.** Picture of the shoe prototype used during the experiment (top), and locations of the stiff plate into the shoe (High and Low) with their respective distance ( $d_{\text{High}}$  and  $d_{\text{Low}}$ ) from the metatarsophalangeal joint center of rotation (MTP) (down). Subtracting  $d_{\text{High}}$  from  $d_{\text{Low}}$  equaled the forefoot midsole thickness (12 mm).

From a mechanical point of view, bending an object causes tensile stresses and lengthening on one side, compressive stresses and shortening on the other, and no tensile or compressive stresses on the neutral axis of the cross-section (Piana, Petrogalli, Paderno, & Carlsson, 2018; Turner & Burr, 1993). A similar stress distribution may occur in the midsole during the forefoot bending in running. Thus, a stiff plate located high, in the middle, or low into the shoe may interact differently with the compression and/or traction behaviour of the midsole materials. The stiff plate location is thus expected to influence the bending mechanical properties of the shoe during the forefoot bending, and this may alter running biomechanics.

The bending mechanical properties of the shoe forefoot may also be influenced by the magnitude and the rate of the applied load (Oleson, Adler, & Goldsmith, 2005; Stefanyshyn & Wannop, 2016). The running speed may act as a factor inducing more GRF (Hamill, Bates, Knutzen, & Sawhill, 1983; Novacheck, 1998) and potentially more MTP joint angle and angular velocity during the forefoot bending (Stefanyshyn & Wannop, 2016). The running speed may thus interact with the stiff plate location into the shoe and potentiate its effects on the running biomechanics.

The purpose of this study was to investigate the effects of the stiff plate location into the shoes, first mechanically on the longitudinal bending stiffness, and then on the biomechanical features previously reported to be influenced by the shoe longitudinal bending stiffness while running at two different speeds. It was hypothesised that a high location would decrease the shoe LBS assuming that the stiff plate would hinder less the compressive stresses than the tensile stresses in the midsole. This mechanical change expected with the high location would induce different effects on the biomechanical features previously reported to be influenced by the shoe LBS such as: greater MTP dorsiflexion and lower MTP joint net torque that would consequently modify the ground reaction forces and/or the lower limb joint biomechanics resulting in an altered alignment between the resultant GRF and the runners' leg compared to the low location. These biomechanical responses were mainly expected at the slower running speed because the greater loadings induced by faster running speed would induce a relatively lower influence of the stiff plate location. The study's purposes may be relevant for industrial applications of footwear manufacturers in view of the improvement of running performance.

## Methods

### *Participants*

Fourteen male regular runners ( $23 \pm 4$  years,  $174.3 \pm 5.0$  cm,  $68.1 \pm 6.3$  kg, 42 EU size), stating running at least one training session per week, volunteered to participate in the experiment. All participants gave their written informed consent to all the procedures performed during the experiment that were approved by the Aix-Marseille university ethics committee. To be included in this study, the participants should state being free from cardiopulmonary disorders and free from major injury sustained in the lower limbs requiring at least three weeks of recovery during the last year.

## **Shoe conditions**

Two shoe prototype conditions were used in this study. Five pairs per shoe condition were used to avoid any effect of material fatigue. The shoe conditions were identical in terms of appearance, geometry (12 mm and 20 mm thickness in the midsole forefoot and rearfoot, respectively), and midsole material (polyurethane foam in hardness 60 asker C; energy loss:  $31.7 \pm 1.0\%$ ; stiffness in compression:  $73.2 \pm 3.3$  N/mm; measured with an impact drop test at the shoe rearfoot (American Society for Testing and Materials, 2013)).

Stiff carbon plates (thickness: 0.9 mm; mass: 19 g; bending stiffness: 0.12 Nm/deg) were cut according to the insole shape and inserted in the shoes at two different locations (Figure 1). In the ‘high location’ condition, the carbon plate was added under the insoles to be near the foot. In the ‘low location’ condition, the carbon plates were inserted between the midsole and the outsole of the shoes to be far from the foot. The average mass of shoe prototypes was  $403.2 \pm 3.1$  g (shoe + stiff plate).

A mechanical bending test (Flexer 2.0, Exeter Research, Inc., Brentwood, NH, USA) was used to measure the shoe LBS. The design and the principle of use of this device, as well as the shoe preparation and setup on the device, were well described in the study of Crandall, Frederick, Kent, Lessley, and Sherwood (2015). The dynamic test consisted of 30 continuous cycles of flexion from  $0^\circ$  (flat) to  $30^\circ$  and back to  $0^\circ$  at 3.3 Hz. The last 5 cycles were kept for analysis. The torque required to flex the shoe forefoot (the upper was not removed) from  $10^\circ$  to  $30^\circ$  enabled to compute the shoe LBS.

## **Experimental protocol**

The experiment was divided in two sessions performed in two separate days with at least 48 hours rest between each one. The first session was an incremental running test and the second session was dedicated to test the experimental conditions through a repeated-measures design.

In the first session, the participants performed an incremental test. The test started by 5 min warm-up of running at 1.94 m/s with participants’ own running shoes on a treadmill (Saturn 300/100 r, h/p/cosmos, Germany) with 1% gradient. The speed was then increased by 0.28 m/s every minute. An open-circuit expired-gas analysis system (K5, Cosmed, Italy) recorded breath-by-breath data. The device was calibrated before each participant with a reference gas containing known concentrations of oxygen and carbon dioxide, and with a 3.0 L syringe to ensure an accurate volume air measurement. The incremental running test aimed to identify the ventilatory anaerobic threshold (VAT) and the respiratory compensation point (RCP) for each participant (Mezzani et al., 2009). From this test, two speeds were kept for the next steps: the speed equal to 90% of the speed that elicited VAT will be referred to ‘slower speed’ ( $3.28 \pm 0.28$  m/s); the speed equal to the average between the speeds that elicited VAT and RCP will be referred to ‘faster speed’ ( $4.01 \pm 0.27$  m/s).

The second session took place in a 50 m laboratory including a concrete runway track with the data capture systems located at 15 m from one side of the laboratory thus allowing participants to run 35 m before being into data capture space. Participants first performed a 4 min warm-up at the slower speed and 4 min warm-up at the faster speed with their own running shoes on the runway. Then participants ran under four different experimental conditions (low location/slower speed, low location/faster speed, high

location/slower speed, and high location/faster speed) in a random order. A force plate (9287CA, Kistler, Switzerland) recorded GRF at 2000 Hz. A twelve camera optical motion capture system (Oqus 7 Camera series, Qualisys, Sweden) recorded at 200 Hz the three dimensional coordinates of twenty-five retro-reflective markers placed directly on the skin of the trunk and the right lower limb as follows: sternal notch, xiphoid process, seventh cervical vertebrae, ninth thoracic vertebrae, right and left anterior superior iliac spines, right and left posterior superior iliac spines, four markers in the thigh lateral part, medial and lateral condyles, three markers in the leg lateral part, medial and lateral malleolus, second toe, first and fifth metatarsal heads, calcaneus tuberosity, medial and lateral calcaneus aspects. Due to potential difference in forefoot bone length, width, and shape between participants, the second toe, and the first and fifth metatarsal head markers were on the participants' feet skin through 2 cm × 2 cm cut-out holes in the shoe upper (Shultz & Jenkyn, 2012). The calcaneus markers were placed on the heel counter of the shoe upper. For the slower speed, participants ran continuously in the laboratory at the targeted speed (imposed speed visually controlled with ground marks and a metronome) while five valid trials were recorded from the fifth minute of running. For the faster speed, five valid trials were recorded from the second minute to avoid unwanted fatigue. A trial was valid when the participants ran at the right speed (visual inspection that the participant crossed the ground marks at each metronome beep during the whole experiment duration) and kept their running pattern before landing with the right foot fully on the force plate. For each experimental condition, the participants ran continuously from the first to the last minute without any rest or latency periods between trials. Ten minutes rest was observed between each experimental condition.

### **Data analysis**

The GRF data were low-pass filtered at 40 Hz with a critically damped filter. A 10 N threshold on the vertical GRF was used to detect the initial contact and toe-off. The braking and propulsion phases were considered by negative and positive values on the anteroposterior GRF, respectively. The amplitude of the centre of pressure (COP) trajectory was determined in the coordinate system of the motion capture system as the distance between the calcaneal tuberosity marker when the foot was flat on the ground (used as a standardised initial position) and the final position of the COP in the anteroposterior direction.

The retro-reflective markers coordinates were low-pass filtered at 20 Hz with a Butterworth filter. As previously recommended (Kristianslund, Krosshaug, & van den Bogert, 2012), when used as inverse dynamics input data, the raw GRF data were low-pass filtered at an identical cut-off frequency than the filter of the marker coordinates with a critically damped filter. The angle, the angular velocity, and the net joint torque of the hip, the knee, the ankle and the MTP joints of the right lower limb were computed in the sagittal plane during the stance phase using Visual3D (v6 Professional, C-Motion, USA). The segment inertia parameters were obtained from de Leva (1996). The net MTP joint torque was computed when the centre of pressure location was anterior to the axis between the heads of the first and fifth metatarsals (Roy & Stefanyshyn, 2006). The net joint power for each lower limb joint was then computed

by multiplying at each time instant the joint angular velocity by the net joint torque. Positive and negative joint works were determined by trapezoidal integration of the net joint power curve (Stefanyshyn & Nigg, 1997). As described previously (Moore et al., 2016), the alignment of the leg axis with the resultant GRF was finally computed in the sagittal plane during the stance phase.

## Statistical analysis

### Scalar parameters

Scalar parameters were the anteroposterior amplitude of the COP ( $COP_{AP}$ ) and the positive and negative work for each lower limb joint. First, ANOVA assumptions (normality and homogeneity of residuals) were checked. When ANOVA assumptions were met, a two-way repeated measures ANOVA was used to evaluate the main effects of ‘stiff plate location’ and ‘running speed’ factors, and the interaction of these factors, on the scalar parameters. When ANOVA assumptions were not met, a permutation procedure was performed. Alpha level was set to  $\alpha = 0.05$ . Post-hoc pairwise comparisons with a Bonferroni correction ( $\alpha = p/6 = 0.008$ ) were performed when the interaction effect was significant. The partial omega squared was computed to determine effect sizes of significant results (Lakens, 2013).

### Waveforms

A Statistical Parametric Mapping procedure (Pataky, Robinson, & Vanrenterghem, 2013; Pataky, Vanrenterghem, & Robinson, 2015) evaluated the main effects of ‘stiff plate location’ and ‘running speed’ factors, and their interaction, on the GRF, the alignment between the resultant GRF and the leg, the lower limb joint angles and net joint torques waveforms during the ground stance phase ( $\alpha = 0.05$ ).

## Results

The shoe LBS was significantly lower ( $t_{1,18} = 3.64$ ;  $p = 0.003$ ; Cohen’s  $d = 1.63$ ) for the high stiff plate location compared to the low stiff plate location (Table 1).

**Table 1.** Longitudinal bending stiffness (LBS) values of each pair of shoes (averaged for left and right feet) and on average (SD) for the low and high location conditions.

	Pair of shoes	LBS (Nm/deg)
Low location	N°1	0.29
	N°2	0.27
	N°3	0.28
	N°4	0.29
	N°5	0.30
	<b>Mean</b>	<b>0.28 (0.01)</b>
High location	N°1	0.24
	N°2	0.26
	N°3	0.25
	N°4	0.28
	N°5	0.27
	<b>Mean</b>	<b>0.26 (0.02)</b>



### **Interaction effect**

The interaction between the stiff plate location and the running speed induced a significant effect ( $p = 0.008$ ;  $\omega_p^2 = 0.37$ , large effect) only on the  $COP_{AP}$  (Table 2), but post-hoc pairwise comparisons with Bonferroni correction failed to reach significance ( $p > 0.008$ ). No effect of the interaction on the  $COP_{AP}$  was thus considered.

### **Effect of the running speed**

In both shoe conditions, the faster speed ( $4.01 \pm 0.27$  m/s) induced significant changes ( $p < 0.05$ ) compared to the slower speed ( $3.28 \pm 0.28$  m/s) such as: more vertical and anteroposterior GRF (Figure 2), more hip range of motion, less ankle and knee range of motion (Figure 3), more torque at each lower limb joint (Figure 4), more positive and negative work at each lower limb joint (Table 2), an increased alignment between the resultant GRF and the runners' leg around midstance, and a decreased alignment before toe-off (Figure 5).

### **Effect of the stiff plate location**

The high location decreased vertical GRF from 60% to 99% of the stance phase ( $F_{1,13} > 16.04$ ;  $p < 0.001$ ) and decreased propulsive anteroposterior GRF from 91% to 97% of the stance phase ( $F_{1,13} > 16.08$ ;  $p = 0.002$ ) compared to the low location (Figure 2).

The high location induced more MTP dorsiflexion from 70% to 86% ( $F_{1,13} > 13.31$ ;  $p < 0.001$ ), and more ankle plantarflexion from 73% to 93% of the stance phase ( $F_{1,13} > 9.67$ ;  $p = 0.020$ ) than the low location (Figure 3). Compared to the low location, the high location induced less MTP dorsiflexion torque from 63% to 83% ( $F_{1,13} > 10.44$ ;  $p = 0.009$ ), less ankle plantarflexion torque from 70% to 96% ( $F_{1,13} > 14.06$ ;  $p < 0.001$ ), less knee extension torque from 57% to 64% ( $F_{1,13} > 13.56$ ;  $p = 0.010$ ), and less hip flexion torque from 86% to 89% of the stance phase ( $F_{1,13} > 14.80$ ;  $p = 0.026$ ) compared to the low location (Figure 4). The positive joint work was lower at the knee joint ( $p = 0.014$ ;  $\omega_p^2 = 0.33$ , large effect) for the high location compared to the low location (Table 2).

The high location induced more alignment between the leg and the resultant GRF than the low location from 82% to 90% of the stance phase ( $F_{1,13} > 14.37$ ;  $p = 0.003$ ) compared to the low location (Figure 5).

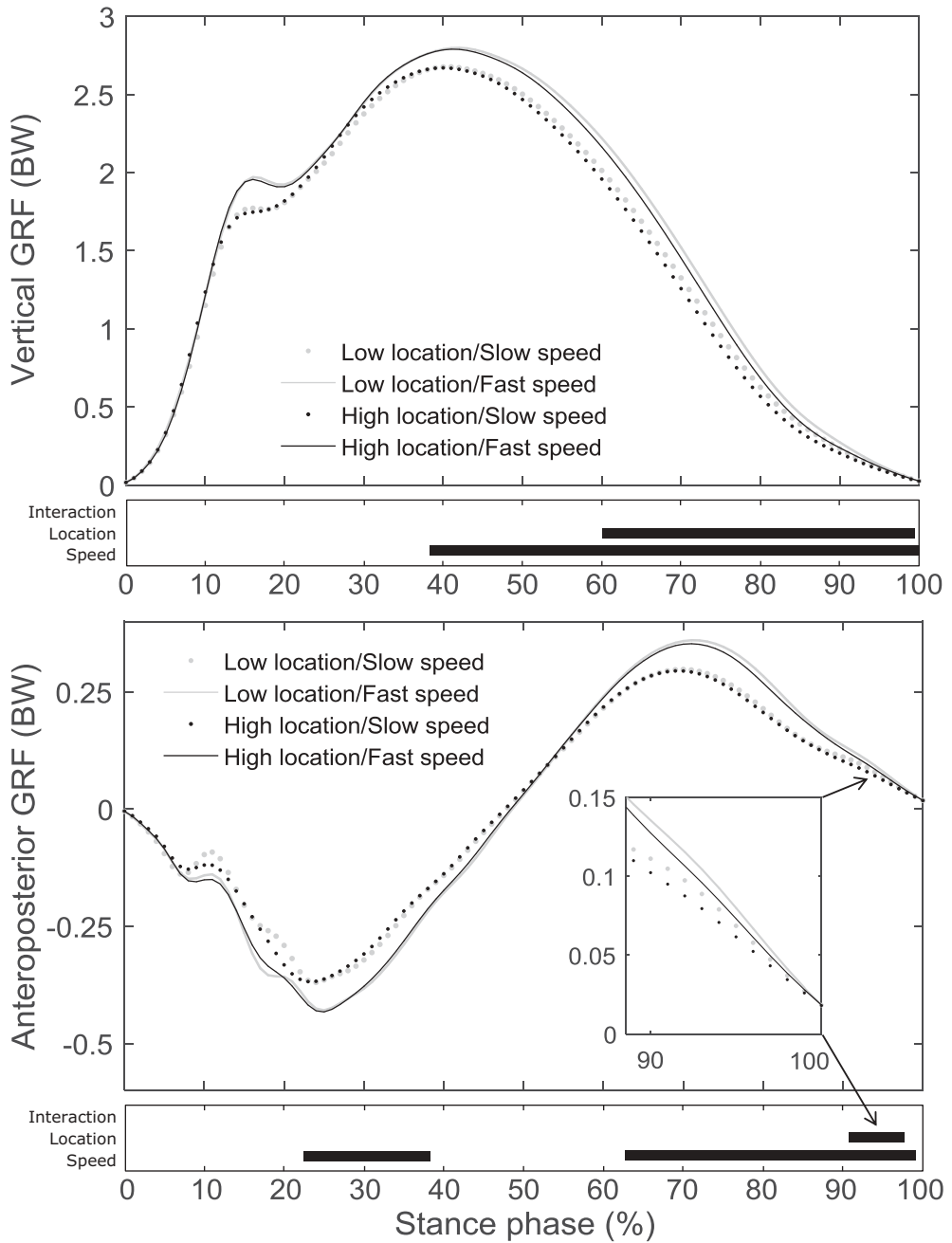
## **Discussion and implications**

The purpose of this study was to investigate the effects of the stiff plate location into the shoes, first mechanically on the longitudinal bending stiffness, and then on the biomechanical features previously reported to be influenced by the shoe longitudinal bending stiffness while running at two different speeds. The main result was that a change in stiff plate location into the shoe (12 mm difference in vertical position at the shoe forefoot in the present study) induced significant modifications on the running biomechanics during the propulsion phase, that is: the high stiff plate location decreased GRF, increased MTP dorsiflexion and ankle plantarflexion, decreased torques at each lower limb joint, decreased the positive work at the knee, and induced an increased alignment between the resultant GRF and the runner's leg compared to the low stiff plate location.

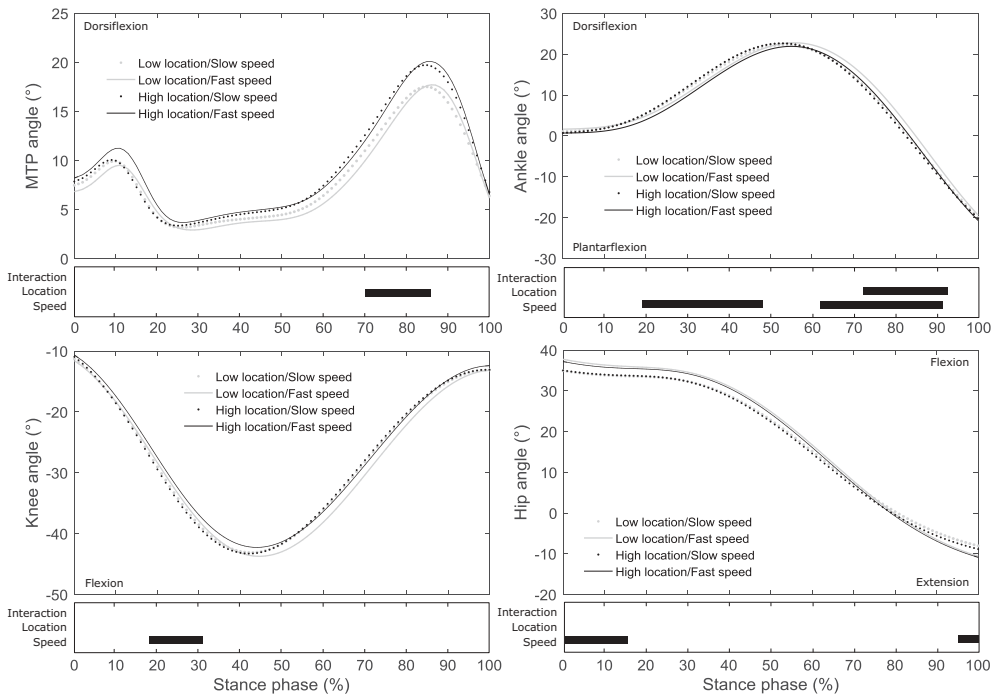


Table 2. Mean (SD) of biomechanical parameters for the four experimental conditions. <sup>L</sup>, <sup>S</sup> and <sup>I</sup> indicated significant ( $p < 0.05$ ) effect of the stiff plate location, the running speed, and the interaction, respectively.

	Low location/Slow speed	Low location/Fast speed	High location/Slow speed	High location/Fast speed	Main effect location	Main effect speed	Interaction effect
COP amplitude (m) <sup>I</sup>	0.247 (0.014)	0.255 (0.013)	0.254 (0.013)	0.249 (0.012)	F = 0.05; $p = 0.828$	F = 0.43; $p = 0.529$	<b>F = 9.64</b> ; $p = 0.008$
MTP positive work (J/kg) <sup>S</sup>	0.017 (0.006)	0.023 (0.007)	0.020 (0.006)	0.024 (0.006)	F = 4.41; $p = 0.055$	<b>F = 44.03</b> ; $p < 0.001$	F = 4.02; $p = 0.066$
MTP negative work (J/kg) <sup>S</sup>	-0.083 (0.029)	-0.100 (0.029)	-0.089 (0.026)	-0.099 (0.025)	F = 0.72; $p = 0.416$	<b>F = 12.64</b> ; $p = 0.003$	F = 1.93; $p = 0.192$
Ankle positive work (J/kg) <sup>S</sup>	0.725 (0.137)	0.775 (0.136)	0.736 (0.134)	0.772 (0.138)	F = 0.18; $p = 0.680$	<b>F = 15.09</b> ; $p = 0.002$	F = 1.42; $p = 0.253$
Ankle negative work (J/kg) <sup>S</sup>	-0.481 (0.184)	-0.541 (0.163)	-0.485 (0.181)	-0.535 (0.163)	F = 0.01; $p = 0.914$	<b>F = 15.36</b> ; $p = 0.002$	F = 0.69; $p = 0.418$
Knee positive work (J/kg) <sup>L</sup>	0.380 (0.099)	0.414 (0.104)	0.377 (0.099)	0.383 (0.097)	<b>F = 8.38</b> ; $p = 0.014$	F = 2.73; $p = 0.120$	F = 3.94; $p = 0.067$
Knee negative work (J/kg)	-0.495 (0.130)	-0.522 (0.151)	-0.500 (0.132)	-0.496 (0.153)	F = 1.16; $p = 0.302$	F = 0.42; $p = 0.528$	F = 3.30; $p = 0.094$
Hip positive work (J/kg) <sup>S</sup>	0.113 (0.054)	0.155 (0.062)	0.111 (0.057)	0.148 (0.067)	F = 0.95; $p = 0.352$	<b>F = 26.63</b> ; $p < 0.001$	F = 0.143; $p = 0.706$
Hip negative work (J/kg) <sup>S</sup>	-0.179 (0.102)	-0.228 (0.106)	-0.173 (0.097)	-0.220 (0.100)	F = 2.14; $p = 0.168$	<b>F = 29.53</b> ; $p < 0.001$	F = 0.03; $p = 0.862$



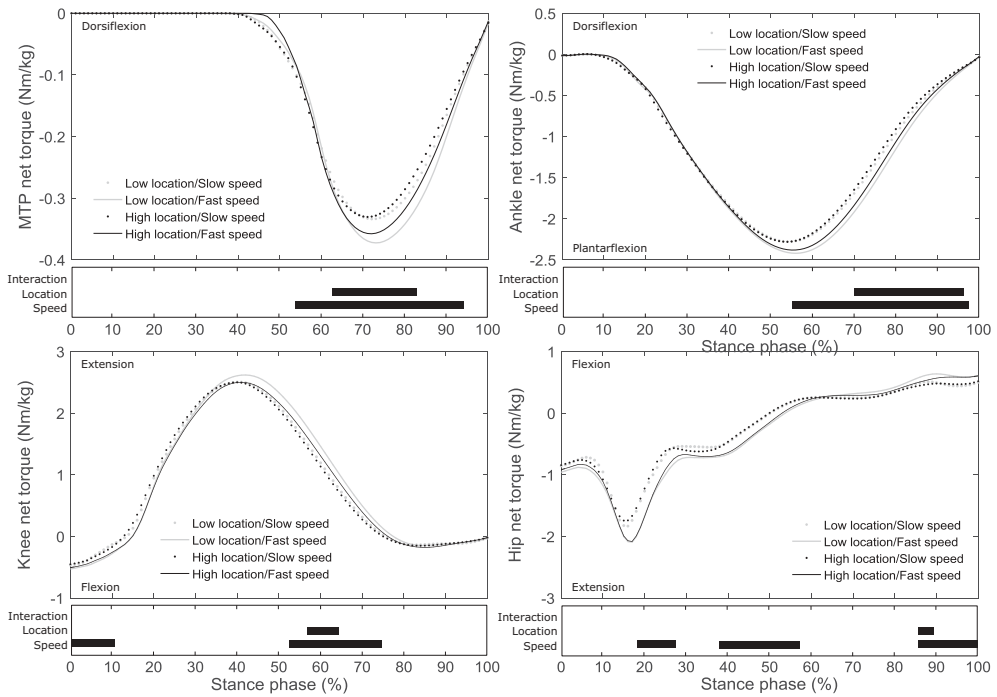
**Figure 2.** Mean vertical and anteroposterior ground reaction force time- and weight-normalised. Negative and positive values are braking and propulsive forces, respectively. Standard deviations are not presented for more clarity. Significant main effects of the interaction, the location and the speed are highlighted (black horizontal bars at the bottom of the figure) during corresponding time periods.



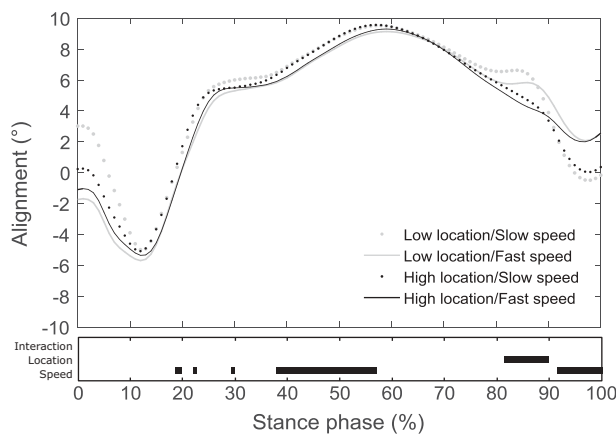
**Figure 3.** Mean lower limb joint angles time-normalised. Standard deviations are not presented for more clarity. Significant main effects of the interaction, the location and the speed are highlighted (black horizontal bars at the bottom of the figure) during corresponding time periods.

It was expected that the stiff plate location would influence the shoe LBS by altering the mechanical behaviour of the layers composing the shoe midsole during bending. In line with this assumption, the mechanical testing showed slightly lower LBS in the high location ( $0.26 \pm 0.02$  Nm/deg) compared to low location ( $0.28 \pm 0.01$  Nm/deg). Due to potential uncertainties reported (Crandall et al., 2015), it could not be definitively concluded if this subtle difference in LBS was due to the stiff plate location or to the error of measurement of the mechanical testing device. Nevertheless, the stiff plate location induced several biomechanical changes during running. This suggests that it is of importance to take the stiff plate location into account when designing a shoe to not produce different effects on running biomechanics than those initially accounted for.

The running biomechanics is indeed altered by the stiff plate location in particular during the propulsion phase. The high location allowed more MTP dorsiflexion and induced less MTP joint torque than the low location. These results were in line with those of previous studies that observed similar but greater biomechanical changes at the MTP joint when the shoe LBS is highly altered (Madden et al., 2016; Oh & Park, 2017; Stefanyshyn & Nigg, 2000b; Willwacher et al., 2013). The greater MTP dorsiflexion was associated with more ankle plantarflexion, likely due to the coupling occurring between the MTP joint motion and the ankle joint motion during the propulsion phase (Zatsiorsky, 1998). In addition, reduced torques in each lower limb joint were observed when the stiff plate was located high in the shoe. The kinematics adjustments at distal joints combined with reduced torques in each lower limb joint contributed to a change



**Figure 4.** Mean lower limb net joint torques time- and weight-normalised. Standard deviations are not presented for more clarity. Significant main effects of the interaction, the location and the speed are highlighted (black horizontal bars at the bottom of the figure) during corresponding time periods.



**Figure 5.** Mean alignment between the resultant ground reaction force and the leg time-normalised. Negative and positive values indicated respectively a more forward and a more backward orientation of the resultant ground reaction force compared to the leg. The closer the values are to zero, the more the alignment is increased. Standard deviations are not presented for more clarity. Significant main effects of the interaction, the location and the speed are highlighted (black horizontal bars at the bottom of the figure) during corresponding time periods.

in the orientation of the lower limb kinematic chain and/or the resultant GRF in the sagittal plane (van Ingen Schenau et al., 1992). This resulted in an increased alignment between the resultant GRF and the runner's leg and less positive work performed by the knee joint without being compensated by the joint work in other lower limb joints with the high location. A little change of stiff plate location into the shoe had thus important biomechanical consequences that could influence the metabolic cost of running because occurring during the propulsion phase of running. Indeed, during the propulsion phase, the energy from the shoe should be returned in the right direction (Stefanyshyn & Nigg, 2000a), as it was the case in the present study with the resultant GRF more aligned with the runners' leg with the high location. This can enable runners to perform less active muscular work to propel the body upward and forward (Fletcher & MacIntosh, 2017), as it was the case in the present study with less hip, knee, ankle, and MTP joint torques and less positive work at the knee joint with the high location.

It was expected that the effects of the stiff plate location on running biomechanics would depend on the running speed, due to the differences in terms of loadings and lower limb biomechanics between the slower and the faster speed. The running speed difference (slower:  $3.28 \pm 0.28$  m/s; faster:  $4.01 \pm 0.27$  m/s) was indeed enough to induce significant changes as previously observed (Arampatzis, Brüggemann, & Metzler, 1999; Fukuchi, Fukuchi, & Duarte, 2017), that is: the faster speed increased vertical and propulsive GRF, increased hip joint range of motion, and increased net torques and work in all lower limb joints compared to the slower speed. The lack of significant interaction effect on running biomechanics suggested that adding a stiff plate into the shoe did not require specific location among speeds performed in the present study, which mainly corresponded to speeds performed by recreational runners (Gordon et al., 2017).

From endurance running performance perspectives, the high stiff plate location might be more beneficial than the low location. Indeed, the effects induced by the high location supported previous results stating that the stiff plate improved running economy if the MTP dorsiflexion is not restricted, thus allowing a greater transmission of the ankle joint torque on the ground push-off (Oh & Park, 2017). Furthermore, it has been shown that an increased alignment between the resultant GRF and the runner's leg during propulsion, as induced by the high location in the present study, was associated with better running economy (Moore et al., 2016). Finally, less positive work generated at the knee joint together with less net knee and hip torques may avoid an early onset on fatigue during prolonged running duration (Alexander, 1991; Sanno, Willwacher, Epro, & Brüggemann, 2018). When introducing a stiff plate into the shoe, it should be done in a high location to induce biomechanical responses associated with lower metabolic cost of running.

It should be pointed out that locating the stiff plate high in the shoe may increase the plantar pressure under the (fore-)foot as shown for shoes with different cushioning materials (Shorten, 2000). This might expose runners to lower perceived comfort (Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009; Mündermann, Nigg, Humble, & Stefanyshyn, 2003) and/or higher risk of injury of metatarsal bones (Firminger, Fung, Loundagin, & Edwards, 2017), especially after prolonged running duration (Nagel, Fernholz, Kibele, & Rosenbaum, 2008). A compromise between the running performance optimisation and the runner protection must be found in the shoe design.

The results presented in this study should be read in view of some limiting considerations. The running speeds have been imposed relative to the participants' physiological ability rather than absolute speeds for three main reasons. First, to allow for comparisons with previous studies analysing the effects of shoe LBS on running biomechanics at similar relative speeds (Flores et al., 2017; Madden et al., 2016; Oh & Park, 2017), second to ensure similar running intensities between participants of different physiological profiles or habits of training (Green, Crews, Bosak, & Peveler, 2003; Matthew Green, Hornsby, Pritchett, & Pritchett, 2014; Svedenhag & Sjödín, 1984), and third to avoid potential changes of the running biomechanics throughout the experiment due to accumulation of fatigue. Moreover, forefoot markers were placed on the foot skin while rearfoot markers were on the heel counter of the shoe upper. The forefoot markers placed on the foot skin enabled to record the forefoot movements more accurately, especially those of the second toe in the sagittal plane, which could not have been possible from forefoot markers located on the shoe upper. On the contrary, it was considered that the location of the calcaneus markers on the heel counter of the shoe upper was acceptable to record the rearfoot trajectory during the stance phase, even if the range of motion can be underestimated in the sagittal plane (Alcantara, Trudeau, & Rohr, 2018; Trudeau et al., 2017).

## Conclusion

This study showed that the stiff plate location into the shoe midsoles altered ground reaction forces and biomechanics in the lower extremity during the propulsion phase of running. The results provided practical evidence for footwear manufacturers suggesting that stiff plates located high into the shoes could be beneficial from a performance perspective by inducing less lower extremity joint torques, less positive work at the knee joint and an increased alignment between the resultant GRF and the runners' leg, but care should be taken not to generate discomfort and/or higher risk of injury of the foot bones. Future studies should include metabolic measures together with comfort and plantar pressure measurements to provide further assessments of the influence of the stiff plate location in order to meet the best compromise between the running performance and the runner protection during a prolonged running duration.

## Acknowledgments

Authors would like to thank Stéphane Charnet, Bao Kiet Phan, Thao Nguyen Diep Xuan and their teams (Kalenji, Decathlon) for their help during the design of the shoe prototypes. Authors also thank Dr Cédric Morio (Decathlon SportsLab) for all the discussions and advices provided concerning this study, and Mikku Knudsen (Decathlon SportsLab) for his English review of the manuscript.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## ORCID

Guillaume Rao  <http://orcid.org/0000-0002-7751-6959>

Eric Berton  <http://orcid.org/0000-0001-6239-3389>

## References

- Alcantara, R. S., Trudeau, M. B., & Rohr, E. S. (2018). Calcaneus range of motion underestimated by markers on running shoe heel. *Gait and Posture*, 63, 68–72. doi:10.1016/j.gaitpost.2018.04.035
- Alexander, R. M. (1991). Energy-saving mechanisms in walking and running. *The Journal of Experimental Biology*, 160, 55–69.
- American Society for Testing and Materials, F1976-13. (2013). Standard test method for impact attenuation of athletic shoe cushioning systems and materials. Retrieved from <https://www.astm.org/Standards/F1976.htm>
- Arampatzis, A., Brüggemann, G. P., & Metzler, V. (1999). The effect of speed on leg stiffness and joint kinetics in human running. *Journal of Biomechanics*, 32, 1349–1353. doi:10.1016/s0021-9290(99)00133-5
- Biewener, A. A., Farley, C. T., Roberts, T. J., & Temaner, M. (2004). Muscle mechanical advantage of human walking and running: Implications for energy cost. *Journal of Applied Physiology*, 97, 2266–2274. doi:10.1152/jappphysiol.00003.2004
- Carrier, D. R., Heglund, N. C., & Earls, K. D. (1994). Variable gearing during locomotion in the human musculoskeletal system. *Science*, 265, 651–653. doi:10.1126/science.8036513
- Crandall, J., Frederick, E. C., Kent, R., Lessley, D. J., & Sherwood, C. (2015). Forefoot bending stiffness of cleated American football shoes. *Footwear Science*, 7, 139–148. doi:10.1080/19424280.2015.1058427
- de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics*, 29, 1223–1230. doi:10.1016/0021-9290(95)00178-6
- Firminger, C. R., Fung, A., Loundagin, L. L., & Edwards, W. B. (2017). Effects of footwear and stride length on metatarsal strains and failure in running. *Clinical Biomechanics*, 49, 8–15. doi:10.1016/j.clinbiomech.2017.08.006
- Fletcher, J. R., & MacIntosh, B. R. (2017). Running economy from a muscle energetics perspective. *Frontiers in Physiology*, 8, 433. doi:10.3389/fphys.2017.00433
- Flores, N., Delattre, N., Berton, E., & Rao, G. (2017). Effects of shoe energy return and bending stiffness on running economy and kinetics. *Footwear Science*, 9, S11–S13. doi:10.1080/19424280.2017.1313894
- Fukuchi, R. K., Fukuchi, C. A., & Duarte, M. (2017). A public dataset of running biomechanics and the effects of running speed on lower extremity kinematics and kinetics. *PeerJ*, 5, e3298. doi:10.7717/peerj.3298
- Gordon, D., Wightman, S., Basevitch, I., Johnstone, J., Espejo-Sanchez, C., Beckford, C., ... Merzbach, V. (2017). Physiological and training characteristics of recreational marathon runners. *Open Access Journal of Sports Medicine*, 8, 231–241. doi:10.2147/OAJSM.S141657
- Green, J. M., Crews, T. R., Bosak, A. M., & Peveler, W. W. (2003). A comparison of respiratory compensation thresholds of anaerobic competitors, aerobic competitors and untrained subjects. *European Journal of Applied Physiology*, 90, 608–613. doi:10.1007/s00421-003-0892-5
- Green, J. M., Hornsby, J. H., Pritchett, R. C., & Pritchett, K. (2014). Lactate threshold comparison in anaerobic vs. aerobic athletes and untrained participants. *International Journal of Exercise Science*, 7, 329–338.
- Hamill, J., Bates, B. T., Knutzen, K. M., & Sawhill, J. A. (1983). Variations in ground reaction force parameters at different running speeds. *Human Movement Science*, 2, 47–56. doi:10.1016/0167-9457(83)90005-2



- Kristianslund, E., Krosshaug, T., & van den Bogert, A. J. (2012). Effect of low pass filtering on joint moments from inverse dynamics: Implications for injury prevention. *Journal of Biomechanics*, 45, 666–671. doi:10.1016/j.jbiomech.2011.12.011
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, 4, 863. doi:10.3389/fpsyg.2013.00863
- Luo, G., Stergiou, P., Worobets, J., Nigg, B., & Stefanyshyn, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science*, 1, 25–29. doi:10.1080/19424280902993001
- Madden, R., Sakaguchi, M., Tomaras, E. K., Wannop, J. W., & Stefanyshyn, D. (2016). Forefoot bending stiffness, running economy and kinematics during overground running. *Footwear Science*, 8, 91–98. doi:10.1080/19424280.2015.1130754
- Mezzani, A., Agostoni, P., Cohen-Solal, A., Corrà, U., Jegier, A., Kouidi, E., ... Vanhees, L. (2009). Standards for the use of cardiopulmonary exercise testing for the functional evaluation of cardiac patients: A report from the exercise physiology section of the European Association for Cardiovascular Prevention and Rehabilitation. *European Journal of Cardiovascular Prevention & Rehabilitation*, 16, 249–267. doi:10.1097/HJR.0b013e32832914c8
- Moore, I. S., Jones, A. M., & Dixon, S. J. (2016). Reduced oxygen cost of running is related to alignment of the resultant GRF and leg axis vector: A pilot study. *Scandinavian Journal of Medicine & Science in Sports*, 26, 809–815. doi:10.1111/sms.12514
- Morio, C., & Flores, N. (2017). Effect of shoe bending stiffness on lower limb kinetics of female recreational runners. *Computer Methods in Biomechanics and Biomedical Engineering*, 20, 139–140. doi:10.1080/10255842.2017.1382900
- Mündermann, A., Nigg, B. M., Humble, N. R., & Stefanyshyn, D. J. (2003). Orthotic comfort is related to kinematics, kinetics, and EMG in recreational runners. *Medicine & Science in Sports & Exercise*, 35, 1710–1719. doi:10.1249/01.MSS.0000089352.47259.CA
- Nagel, A., Fernholz, F., Kibele, C., & Rosenbaum, D. (2008). Long distance running increases plantar pressures beneath the metatarsal heads. *Gait & Posture*, 27, 152–155. doi:10.1016/j.gaitpost.2006.12.012
- Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture*, 7, 77–95. doi:10.1016/S0966-6362(97)00038-6
- Oh, K., & Park, S. (2017). The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion. *Journal of Biomechanics*, 53, 127–135. doi:10.1016/j.jbiomech.2017.01.014
- Oleson, M., Adler, D., & Goldsmith, P. (2005). A comparison of forefoot stiffness in running and running shoe bending stiffness. *Journal of Biomechanics*, 38, 1886–1894. doi:10.1016/j.jbiomech.2004.08.014
- Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, 46, 2394–2401. doi:10.1016/j.jbiomech.2013.07.031
- Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, 48, 1277–1285. doi:10.1016/j.jbiomech.2015.02.051
- Piana, E., Petrogalli, C., Paderno, D., & Carlsson, U. (2018). Application of the wave propagation approach to sandwich structures: Vibro-acoustic properties of aluminum honeycomb materials. *Applied Sciences*, 8, 45. doi:10.3390/app8010045
- Roy, J. P. R., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine & Science in Sports & Exercise*, 38, 562–569. doi:10.1249/01.mss.0000193562.22001.e8
- Sanno, M., Willwacher, S., Epro, G., & Brüggemann, G.-P. (2018). Positive work contribution shifts from distal to proximal joints during a prolonged run. *Medicine & Science in Sports & Exercise*, 50, 2507–2517. doi:10.1249/MSS.0000000000001707

- Shorten, M. R. (2000). Running shoe design: Protection and performance. In D. Tun (Ed.), *Marathon Medicine* (pp. 159–169). London: Royal Society of Medicine. Retrieved from <https://pdfs.semanticscholar.org/eec1/d10e03a3a4b36d5a44270db0a71c2c80bca6.pdf>
- Shultz, R., & Jenkyn, T. (2012). Determining the maximum diameter for holes in the shoe without compromising shoe integrity when using a multi-segment foot model. *Medical Engineering & Physics*, *34*, 118–122. doi:10.1016/j.medengphy.2011.06.017
- Stefanyshyn, D., & Fusco, C. (2004). Athletics: Increased shoe bending stiffness increases sprint performance. *Sports Biomechanics*, *3*, 55–66. doi:10.1080/14763140408522830
- Stefanyshyn, D. J., & Nigg, B. M. (1997). Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. *Journal of Biomechanics*, *30*, 1081–1085. doi:10.1016/S0021-9290(97)00081-X
- Stefanyshyn, D. J., & Nigg, B. M. (2000a). Energy aspects associated with sport shoes. *Sportverletzung Sportschaden*, *14*, 82–89. doi:10.1055/s-2000-7867
- Stefanyshyn, D. J., & Nigg, B. M. (2000b). Influence of midsole bending stiffness on joint energy and jump height performance. *Medicine and Science in Sports and Exercise*, *32*, 471–476. doi:10.1097/00005768-200002000-00032
- Stefanyshyn, D. J., & Wannop, J. W. (2016). The influence of forefoot bending stiffness of footwear on athletic injury and performance. *Footwear Science*, *8*, 51–63. doi:10.1080/19424280.2016.1144652
- Svedenhag, J., & Sjödin, B. (1984). Maximal and submaximal oxygen uptakes and blood lactate levels in elite male middle- and long-distance runners. *International Journal of Sports Medicine*, *5*, 255–261. doi:10.1055/s-2008-1025916
- Tinoco, N., Bourgit, D., & Morin, J.-B. (2010). Influence of midsole metatarsophalangeal stiffness on jumping and cutting movement abilities. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *224*, 209–217. doi:10.1243/17543371JSET69
- Trudeau, M. B., Jewell, C., Rohr, E., Fischer, K. M., Willwacher, S., Brüggemann, G.-P., & Hamill, J. (2017). The calcaneus adducts more than the shoe's heel during running. *Footwear Science*, *9*, 79–85. doi:10.1080/19424280.2017.1334712
- Turner, C. H., & Burr, D. B. (1993). Basic biomechanical measurements of bone: A tutorial. *Bone*, *14*, 595–608. doi:10.1016/8756-3282(93)90081-K
- van Ingen Schenau, G. J., Boots, P. J., de Groot, G., Snackers, R. J., & van Woensel, W. W. (1992). The constrained control of force and position in multi-joint movements. *Neuroscience*, *46*, 197–207. doi:10.1016/0306-4522(92)90019-X
- Willwacher, S., König, M., Braunstein, B., Goldmann, J.-P., & Brüggemann, G.-P. (2014). The gearing function of running shoe longitudinal bending stiffness. *Gait & Posture*, *40*, 386–390. doi:10.1016/j.gaitpost.2014.05.005
- Willwacher, S., König, M., Potthast, W., & Brüggemann, G. P. (2013). Does specific footwear facilitate energy storage and return at the metatarsophalangeal joint in running? *Journal of Applied Biomechanics*, *29*, 583–592. doi:10.1123/jab.29.5.583
- Zatsiorsky, V. M. (1998). *Kinematics of human motion* (pp. 292–293). Champaign, IL: Human Kinetics.