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## Increasing the longitudinal bending stiffness of runners' habitual shoes: An appropriate choice for improving running performance?

Nicolas Flores, Guillaume Rao, Eric Berton, Nicolas Delattre

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3 **1 Increasing the longitudinal bending stiffness of runners' habitual shoes: an**  
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6 **2 appropriate choice for improving running performance?**  
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12 **3**  
13 **4 Submission type:** Original investigation  
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15 **5 Full names of the authors:** Nicolas Flores<sup>ab\*</sup>, Guillaume Rao<sup>b</sup>, Eric Berton<sup>b</sup>, Nicolas  
16  
17  
18 **6** Delattre<sup>a</sup>  
19

20  
21 **7 Institutional/corporate affiliations:** <sup>a</sup>Decathlon SportsLab, Movement Sciences Department,  
22  
23 **8** Villeneuve d'Ascq, France; <sup>b</sup>Aix Marseille Univ, CNRS, ISM, Marseille, France  
24  
25

26  
27 **9 Contact details for the corresponding author:** \*Nicolas Flores, Decathlon SportsLab,  
28  
29  
30 **10** nicolas.flores@decathlon.com, +33(0)760726430  
31

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47

48 **16 Abstract**  
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51 **17 Purpose:** This study analysed the effects of increasing the longitudinal bending stiffness  
52  
53 (LBS) of runners' habitual shoes on the metabolic energetic demand, lower limb muscle  
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56 **18** activations, and stride spatiotemporal parameters during a prolonged running session through  
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58  
59 **20** classical group investigation and a more individualised approach.  
60

1 **Methods:** Eleven recreational male participants ran overground for 40 min at 95% of their  
2 ventilatory anaerobic threshold with low (participants' own shoes) or high LBS shoes (stiff  
3 carbon plate inserted under insole). The net energetic cost of running, lower leg muscle  
4 activations, and spatiotemporal parameters were measured during the prolonged running. The  
5 variables of interest were analysed for one minute in seven time intervals, which were five  
6 minutes apart.

7 **Results:** There were no main effects of LBS or interaction effects with running duration on  
8 the group averaged variables of interest. Overall, the participant-specific metabolic effects  
9 induced by an increased shoe LBS were not beneficial. Beneficial metabolic effects were  
10 more able to occur when the increased LBS decreased (or did not increase) the ground contact  
11 time relative to their habitual shoes, and for the taller runners.

12 **Conclusions:** Increasing the LBS in runners' habitual shoes did not induce systematic  
13 metabolic effects to all the runners. This study suggested that a shoe LBS intervention was  
14 likely not beneficial for performance purposes if the runners' shoe habits were too much  
15 disrupted.

16  
17 **Keywords:** footwear, running shoes, shoe flexibility, longitudinal bending stiffness, running  
18 economy, subject-specific, performance.

## 19 **Introduction**

20 Since the first published scientific investigation twenty years ago,<sup>1</sup> the shoe longitudinal  
21 bending stiffness (LBS) has recently experienced a resurgence of interest in the scientific and  
22 industrial community, and sports competitions due to its potential beneficial effects for  
23 endurance running. The turning point in the footwear community occurred in 2017 when large  
24 benefits on the metabolic energetic demand to cover a given distance at a given speed (i.e.

1 improved running economy) was shown with Nike VaporFly 4% shoes.<sup>2-5</sup> These shoes were  
2 designed with a substantial energy return midsole foam, and stiff curved carbon plates  
3 inserted into the midsoles to increase the LBS. Several personal and world race records have  
4 been broken in runners wearing these shoes,<sup>6,7</sup> thus generating a lot of debates about  
5 potential unfair advantages brought by the shoes.<sup>8-11</sup> This has recently led the World  
6 Athletics to change shoe regulations. In road events, the maximum sole thickness allowed is  
7 actually 40 mm and only one rigid plate can be embedded in the sole. Nowadays, almost  
8 every running footwear company proposes one performance shoe model equipped with a stiff  
9 carbon plate. Taken together, these events suggest that the presence of stiff carbon plates in  
10 the shoes really makes beneficial differences on running economy and performance. Do the  
11 scientific studies support this suggestion?

12         The initial study that paved the way for the presence of carbon plate in running shoes  
13 has reported an improvement of running economy (expressed in consumed millilitre of  
14 oxygen per kilogram per minute) by 1% on average in a group of runners with an intermediate  
15 shoe LBS compared to more flexible and stiffer shoes.<sup>12</sup> Since then no systematic group  
16 differences were found in the subsequent studies. Five studies did not show any significant  
17 effect on running economy of an increased shoe LBS compared to more flexible shoes<sup>13-15</sup>  
18 or over a range of different LBS,<sup>16,17</sup> and one study showed a significant poorer running  
19 economy with an increased LBS compared to more flexible shoes<sup>18</sup> (see Ortega et al.<sup>19</sup> for  
20 an exhaustive review on this topic). These recent results suggest that there is no unique shoe  
21 LBS that induces running economy benefits systematically to all the runners, and the effects  
22 may even be detrimental.

1  
2  
3 The initial study of shoe LBS was also a pioneer in suggesting participant-specific  
4  
5 2 optimisations of the LBS. Indeed, this study showed that heavier runners benefited more from  
6  
7 3 an intermediate increase of shoe LBS.<sup>12</sup> This result has led the following studies to consider  
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9  
10 4 the participant-specific effects in their analyses. Oh and Park<sup>20</sup> showed an individual optimal  
11  
12 5 LBS for the running economy according to the stiffness of the runner's metatarsophalangeal  
13  
14 6 (MTP) joint, thus several LBS were suitable to several groups of runners with similar MTP  
15  
16 7 stiffnesses. McLeod et al.<sup>21</sup> and Čigoja et al.<sup>17</sup> identified an individual optimal LBS based on  
17  
18 8 running economy measurements but without highlighting any explanatory variables. Madden  
19  
20 9 et al.<sup>13</sup> and Flores et al.<sup>22</sup> reported participant-specific benefits of an increased shoe LBS  
21  
22 10 associated with biomechanical changes induced by an increased LBS. It was previously  
23  
24 11 reported that reduced distal lower limb muscle activation during the braking phase were  
25  
26 12 associated with greater ankle dorsiflexion.<sup>22</sup> This study suggested that this may enhance the  
27  
28 13 energy storage in the elastic components that can be returned economically during push-off.  
29  
30 14 In line with this, an increased LBS have been shown to induce lower ankle plantarflexion  
31  
32 15 amplitude, slower ankle plantarflexion velocity, and greater Achilles tendon energy return  
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34 16 during push-off,<sup>13,17,22,23</sup> which could contribute to increase performance. While the  
35  
36 17 participant-specific benefits induced by an increased shoe LBS are well acknowledged, the  
37  
38 18 individual characteristics and/or the running biomechanical changes associated with metabolic  
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40 19 improvements remain disputed and not systematic. Indeed, the above-mentioned studies did  
41  
42 20 not find the same variables explaining the metabolic benefits induced by an increased LBS  
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44 21 (for example, the runners' mass has never been highlighted as an explanatory variable in the  
45  
46 22 subsequent studies).

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58 23 These previous results have exclusively been shown during short running durations.  
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60 24 Whether the effects of the shoe LBS are metabolically beneficial or not during a prolonged

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3 1 run remain unknown. This question was recently partially addressed,<sup>24</sup> by showing that an  
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6 2 increased shoe LBS induced a delay in the distal-to-proximal work redistribution during  
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8  
9 3 prolonged running. These authors suggested that using proximal muscles with greater volume  
10  
11 4 (i.e. *quadriceps*) should be more detrimental than using distal muscles with lower volume (i.e.  
12  
13 5 *triceps surae*).<sup>25</sup> Because the running economy was not measured in this previous study,<sup>24</sup>  
14  
15  
16 6 the metabolic benefits attributed to an increased shoe LBS during prolonged running remain  
17  
18 7 speculative.

21 8       While a lot of useful and relevant information is available regarding the LBS effects  
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23  
24 9 on the metabolic demand and the running biomechanics during short duration,<sup>19</sup> only  
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26  
27 10 assumptions can be made concerning the metabolic effects of the LBS during longer running  
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30 11 exposure where only the running biomechanics was measured.<sup>24</sup> The current study aimed to  
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33 12 investigate these previous independent findings in the same study. The purpose was to analyse  
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36 13 the effects of increasing the longitudinal bending stiffness of runners' habitual shoes on  
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39 14 metabolic demand, lower limb muscle activations, and stride spatiotemporal parameters  
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42 15 during a prolonged running session through classical group investigation and a more  
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45 16 individualised approach. Based on the assumption from Cigoja et al.<sup>24</sup>, it was hypothesised  
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47  
48 17 that an increased shoe LBS would limit and/or delay the increase in metabolic energetic  
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51 18 demand. As highlighted in numerous studies,<sup>12,13,17,20–22</sup> it was expected that the benefits  
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54 19 induced by an increased shoe LBS would also be participant-specific, especially according to  
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57 20 individual characteristics and/or biomechanical changes induced by an increased LBS relative  
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60 21 to their shoe habits.

## 22 23 **Methods**

## 1 *Participants*

2 Eleven male novice runners (Table 1), stating running at least once a week and being able to  
3 run for one hour at least at 10 km/h, volunteered to participate in the experiment. All  
4 participants gave their written informed consent to all the procedures performed during the  
5 experiment that were in accordance with the university ethical rules. The participants stated  
6 being healthy and free from injury in the previous year.

## 7 *Shoe conditions*

8 Two shoe conditions were used in this study. The control shoe condition was the participants'  
9 own running shoes (Table 1 and Supplementary material A), that they used during their usual  
10 running activity (low LBS). The use of participants' own running shoes should permit  
11 observation of their habitual running biomechanics without being influenced by unfamiliar  
12 shoe features<sup>26</sup> other than the LBS investigated in the study. The second shoe condition was  
13 obtained by the addition of thin (0.9 mm) stiff straight carbon plates under the insoles of the  
14 participant's own running shoes (high LBS). One size of carbon plates has been used, and we  
15 ensured that the plates were functionally well inserted in all the participants' shoes to not  
16 induce discomfort during running. The shoe LBS (Table 1) was measured with a mechanical  
17 manual bending test (see Supplementary material B for full details about the procedure) based  
18 on the study of Worobets and Wannop<sup>27</sup>. The high LBS condition was on average  $263 \pm 89\%$   
19 stiffer than the low LBS. To answer to the current study's purpose concerning the choice to  
20 increase the LBS in runners' habitual shoes (with associated advantages and disadvantages),  
21 the shoe mass was not equalised between both shoe conditions. Thus the high LBS conditions  
22 (317 g on average) were 20 g per shoe heavier due to the carbon plate than the low LBS  
23 conditions (297 g on average).

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3 \*\*\* Table 1 near here \*\*\*  
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6 **2 *Experimental protocol***  
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9 3 The experiment was composed of three sessions performed on three different days with at  
10 4 least 48 hours rest between each session. From the welcome of the participant to the end of  
11 5 the session, the first session lasted 1 hour and both subsequent sessions each lasted 2 hours.  
12 6 On average, the three sessions were performed within 11 days.  
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19 7 In the first session, an incremental test was performed. The test started with a 5-min  
20 8 warm-up of running at 1.94 m/s with participants' own running shoes on a treadmill (Saturn  
21 9 300/100r, h/p/cosmos, Germany) with 1% slope gradient. The speed was then increased by  
22 10 0.28 m/s every minute. An open-circuit expired-gas analysis system (K5, Cosmed, Italy)  
23 11 recorded breath-by-breath the rate of oxygen uptake ( $\dot{V}O_2$ ) and the rate of carbon dioxide  
24 12 production ( $\dot{V}CO_2$ ). The device was calibrated before each test with a reference gas  
25 13 containing known concentrations of oxygen and carbon dioxide, using a 3.0 L syringe to  
26 14 ensure an accurate volume air measurement. The incremental running test aimed to identify  
27 15 the ventilatory anaerobic threshold (VAT) for each participant. The VAT was identified  
28 16 through the onset increase of ventilation versus oxygen uptake ratio ( $\dot{V}_E/\dot{V}O_2$ ) and end-tidal  
29 17 partial pressure of oxygen ( $P_{ET}O_2$ ), in the presence of still decreasing or constant ventilation  
30 18 versus carbon dioxide production ratio ( $\dot{V}_E/\dot{V}CO_2$ ) and  $P_{ET}CO_2$ .<sup>28</sup> The speed equal to 95% of  
31 19 the speed that elicited VAT was kept for each participant and was imposed in both subsequent  
32 20 sessions of prolonged running.  
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53 21 The subsequent sessions were performed on the field **to consider realistic road running**  
54 22 **conditions** while keeping as much as possible of the data quality. The participants ran for a  
55 23 prolonged duration with either the low LBS or the high LBS shoe condition, in a randomised  
56 24 order. Due to potential fatigue accumulation, a prolonged running session was dedicated to  
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1 only one shoe condition, thus the low and high LBS shoe conditions were performed during  
2 separate sessions. Each participant performed both sessions at the same time of day. In each  
3 session, the experimental protocol was identical. The participants were equipped with the  
4 expired-gas analysis system, which was calibrated before each session as described above,  
5 and surface electromyograms (EMG; Trigno Avanti, Delsys, Massachusetts, USA), which were  
6 used to record muscle activations at 1926 Hz. After skin preparation, the EMG electrodes  
7 were located according to the recommendations of surface electromyography for the non-  
8 invasive assessment of muscles (SENIAM) at the level of superficial muscles *vastus lateralis*  
9 (VL), *gastrocnemius medialis* (GM), and *tibialis anterior* (TA). The SENIAM procedure for  
10 sensor placement was reproduced as accurately as possible by the same researcher between  
11 both sessions. The three sensors were firmly secured with a medical adhesive strap to avoid  
12 any artifacts due to sweating, vibrations, displacement, or detachment of the sensors  
13 throughout the entire duration of the experiments. The EMG sensors were connected to a  
14 datalogger (Trigno Personal Monitor, Delsys, Massachusetts, USA) located in an armband,  
15 thus allowing wireless EMG acquisitions during the outdoor prolonged run. A watch (Fenix 3,  
16 Garmin, Kansas, USA) paired with an accelerometer mounted on a heart rate strap (HRM-  
17 Run, Garmin, Kansas, USA) was used to measure accelerations of the upper body from which  
18 were computed the stride cadence, the ground contact time, and the vertical oscillation of the  
19 upper body.<sup>29</sup> To obtain day-specific respiratory reference values, the participants first  
20 performed 5 min sitting at rest on a chair without moving or speaking. Finally, the participants  
21 ran continuously for 40 min outdoor over a loop with hard concrete surface (Supplementary  
22 material C) at the targeted speed identified in the first session (imposed speed visually  
23 controlled with ground marks in each 20 m and a metronome). Gas exchanges data, EMG  
24 data, and spatiotemporal data were recorded during the whole duration of the experiment.

## 25 ***Data analysis***

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3 1 The  $\text{VO}_2$ , the  $\text{VCO}_2$ , the respiratory exchange ratio (RER), and the ambient temperature were  
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5 2 measured from the open-circuit expired-gas analysis system. For each subject, the averaged  
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7 3  $\text{VO}_2$  and the  $\text{VCO}_2$  during the last minute of the sitting rest were subtracted from those  
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9 4 measured during the prolonged run to offset the day-specific respiratory reference values of  
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11 5 the participants between both sessions. Then, the net metabolic energetic cost of running was  
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13 6 computed from caloric equivalent based on the Péronnet and Massicotte<sup>30</sup> equation and  
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15 7 expressed in net metabolic power (W/kg). The net energetic cost of running, the RER, and the  
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17 8 ambient temperature were averaged during 1 min for seven time intervals: from 9 to 10 min  
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19 9 (baseline measurement), from 14 to 15 min, from 19 to 20 min, from 24 to 25 min, from 29 to  
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21 10 30 min, from 34 to 35 min, and from 39 to 40 min.  
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28 11 The EMG data were band-pass filtered [10-400 Hz] with a zero time-lag fourth order  
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30 12 Butterworth filter to remove signal noise and artifacts. Then, these data were rectified and  
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32 13 low-pass filtered at 15 Hz with a critically damped filter to smooth the signal.<sup>31</sup> For each  
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34 14 muscle, activations were normalised by the maximal activation recorded in the seven time  
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36 15 intervals during the session. For each time interval, this normalised EMG signal was  
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38 16 integrated during the entire minute. Because of EMG sensor location (on muscles, thus on  
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40 17 wobbling masses) and the range of accelerometry measurements from EMG sensors ( $\pm 2$  g),  
41  
42 18 the accelerometer signal was too noisy to accurately identify heel strike and toe off events.  
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44 19 The integration of EMG activations thus took into account both aerial and stance phases. Data  
45  
46 20 of GM activations is missing for participant 3 in the low LBS condition and participant 10 in  
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48 21 both LBS conditions, likely due to the fact that the left foot in the aerial phase hit the  
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50 22 supporting right leg where the GM sensor was located, thus disconnecting this sensor. A  
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52 23 firmer protection than the medical strap or the recording of another *triceps surae* muscle  
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54 24 would enable avoiding such an issue.  
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3 1 Raw data measured by the torso strap sensor were saved in the watch and then  
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5 2 imported on Garmin Connect software. This software automatically computed the stride  
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7 3 cadence, ground contact time, and vertical oscillation of the upper body from raw data, which  
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9 4 were saved on '.fit' files. These '.fit' files were imported on Golden Cheetah software (v3.3.0)  
10  
11 5 to extract the computed data at each second of the prolonged running in a more conventional  
12  
13 6 '.txt' format. The flight time (in seconds) was computed from the measured stride cadence  
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15 7 and ground contact time (in seconds), and the vertical and leg stiffnesses were also computed  
16  
17 8 based on ground contact and flight times.<sup>32</sup> The stride cadence, the ground contact time, the  
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19 9 vertical oscillation of upper body, the vertical stiffness, and the leg stiffness were averaged  
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21 10 during 1 min for the seven time intervals. Data of stride spatiotemporal parameters is missing  
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23 11 for participant 1 in the low LBS condition and participant 4 in the high LBS condition due to  
24  
25 12 an issue while saving raw data.  
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32 13 Individual data were then reorganised to allow the investigation of the individual  
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34 14 beneficial or detrimental metabolic effects induced by the increase of the LBS in the  
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36 15 participant's habitual shoes during a prolonged run. For each participant, the metabolic, EMG,  
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38 16 and stride spatiotemporal data induced by the high LBS condition were subtracted to those  
39  
40 17 induced by the low LBS condition. This procedure has been done for the seven time intervals  
41  
42 18 for all the variables. At a given time interval, negative or positive values thus respectively  
43  
44 19 indicated that an increased LBS in the participant's habitual shoes induced decreased (i.e.  
45  
46 20 better running economy) or increased (i.e. poorer running economy) net energetic cost of  
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48 21 running, and decreased or increased muscle activations and spatiotemporal responses,  
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50 22 compared to a lower habitual LBS.  
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### 56 23 ***Statistical analysis***

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3 1 Due to some issues during the experiments, statistical analyses were performed on 9  
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5 2 participants for the GM activations and spatiotemporal parameters, and on 11 participants for  
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7 3 all other variables.  
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11 4 *Classical group-based investigation*  
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14 5 ANOVA assumptions (normality and homogeneity of residuals) were met for the VL  
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16 6 activations, the cadence, and the ground contact time, thus a two-way repeated measures  
17  
18 7 ANOVA ( $\alpha=0.05$ ) was used to evaluate the main effects of 'LBS' and 'running duration'  
19  
20 8 factors, and the interaction of these factors, on these variables. All other variables were non-  
21  
22 9 parametrically analysed with a permutation procedure ( $\alpha=0.05$ ), which was performed  
23  
24 10 through the Matlab open-source code (v.0.4.3, <http://www.spm1d.org>). The permutation  
25  
26 11 procedure consists of calculating the test statistic  $F$  values for a large number of re-orderings  
27  
28 12 (i.e. permutations) of the observations (i.e. data). For example in our data, one permutation  
29  
30 13 consists in permuting an observation induced by a given shoe condition for a given participant  
31  
32 14 at a given time interval with another observation induced by the other shoe condition for a  
33  
34 15 given participant at a given time interval. For each permutation, the test statistic  $F$  value is  
35  
36 16 computed. This results in a number of  $F$  values equal to the total number of permutations,  
37  
38 17 which tends to generate a Gaussian distribution of the frequency of  $F$  values. Then, the critical  
39  
40 18 test statistic threshold ( $F^*$ ) is computed as the 95<sup>th</sup> percentile of this distribution to ensure that  
41  
42 19 only  $\alpha=5\%$  of all permutations exceed the  $F^*$ . If the  $F$  value computed from the original  
43  
44 20 observations exceed  $F^*$ , this provides sufficient evidence to reject the null hypothesis (i.e.  
45  
46 21 observing a significant effect).<sup>33</sup> The partial omega squared ( $\omega_p^2$ ) effect size was finally  
47  
48 22 computed and interpreted as: trivial effect  $\leq 0.02 <$  small effect  $\leq 0.13 <$  medium effect  $\leq 0.26$   
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51 23  $<$  large effect.<sup>34</sup>  
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3 1 When a significant main effect of running duration or the interaction between the LBS  
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5 2 and the running duration was observed, post-hoc pairwise comparisons were made between  
6  
7 3 the baseline and subsequent time intervals through the 'emmeans' package on RStudio  
8  
9 4 (v.3.4.1, Massachusetts, USA). This resulted in six post hoc comparisons, thus the alpha level  
10  
11 5 was corrected as  $\alpha=0.05/6=0.008$ .  
12  
13  
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15 6 All the statistical results (two main factors and interaction) are presented in the results  
16  
17 7 section, but for the purpose of the study, only those concerning the LBS main factor and the  
18  
19 8 interaction between the LBS and the running duration are discussed.  
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### 23 9 *Individual approach*

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26 10 A correlation approach was used in an exploratory way by screening for potential candidate  
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28 11 variables partially involved in the variation of the net energetic cost of prolonged running  
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30 12 when the shoe LBS was investigated. This enabled to understand in which conditions a given  
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32 13 individual was more able to benefit from a shoe LBS intervention.  
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36 14 Pearson correlations were performed, at the first and the last time interval of the  
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38 15 prolonged run, between the individual variations of the net energetic cost of running induced  
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40 16 by an increased LBS and ten potential explanatory variables. These potential explanatory  
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42 17 variables were the individual variations of the cadence, the body vertical oscillation, and the  
43  
44 18 ground contact time induced by an increased LBS, the individual variations of the TA, the  
45  
46 19 GM, and the VL activations induced by an increased LBS, the participants' mass, height,  
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48 20 speed and the relative increase of the shoe LBS.  
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53 21 The correlations kept for results and discussion sections should combine  $p<0.1$  with a  
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55 22 large effect size. A large effect size was identified by a Pearson regression coefficient ( $r$ )  
56  
57 23 lower than -0.5 or greater than 0.5.<sup>35</sup>  
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1 of the run, whereas in three middle time intervals of the run the number of participants  
2 benefiting from an increased LBS was slightly greater (6 vs. 5). Furthermore, 2 runners  
3 always benefited from an increased LBS of their habitual shoes (participants 2 and 4), 4  
4 runners always benefited from their habitual shoes (participants 8, 9, 10, and 11), and 5  
5 runners randomly benefited either from their habitual shoes or an increased LBS throughout  
6 the prolonged running duration (right column in Table 2). This non-homogeneous  
7 participants' responses was revealed by a non-significant Chi-Square test ( $\chi^2=0.09$ ;  $p>0.05$ )  
8 indicating that the number of participants benefiting from the low or high LBS ( $n=6$ ) or those  
9 unbenefited ( $n=5$ ) was not different than what would be expected if there was no effect of shoe  
10 LBS (50% of beneficiaries and 50% of unbenefited in the sample of participants). This result  
11 strengthens the individual approach to highlight in which conditions a given individual was  
12 more able to benefit from a shoe LBS intervention.

13 \*\*\* Table 2 near here \*\*\*

14 Based on the criteria set in the statistical section, four significant correlations were  
15 identified during the prolonged running (Figure 4; see Supplementary Material D for more  
16 results).

17 At baseline (from 9 to 10 min), the individual variation of the net energetic cost of  
18 running induced by an increased LBS was correlated with the individual variation of the  
19 ground contact time ( $p=0.067$ ;  $r=0.63$ ), the individual variation of the body vertical oscillation  
20 ( $p=0.070$ ;  $r=-0.63$ ), and the individual variation of TA activations ( $p=0.094$ ;  $r=-0.53$ ) induced  
21 by an increased LBS.

22 At the last time interval (from 39 to 40 min), the individual variation of the net  
23 energetic cost of running induced by an increased LBS was correlated with the height of the  
24 participants ( $p=0.019$ ;  $r=-0.69$ ).

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3 \*\*\* Figure 4 near here \*\*\*  
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9  
10 **Discussion**

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12 4 For the first time, this study investigated the effects of increasing the LBS of runners' habitual  
13 5 shoes on metabolic demand, lower limb muscle activations, and stride spatiotemporal  
14 6 parameters during a prolonged running session, through classical group investigation and a  
15 7 more individualised approach. Over the mean group of participants, **the shoe LBS had no**  
16 8 **effect on the metabolic energetic demand.** Nevertheless, participant-specific metabolic  
17 9 energetic responses to an increased LBS have been highlighted. Depending on the time  
18 10 interval of the prolonged run, these participant-specific metabolic responses were correlated  
19 11 with the variations of spatiotemporal parameters or muscle activations induced by an  
20 12 increased LBS, and with the participant's height.

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34 ***Classical group-based investigation***

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37 14 An increase of the LBS in runners' habitual shoes did not induce a significant effect  
38 15 on the net energetic cost during the prolonged running. This result was not in line with the  
39 16 initial hypothesis, which was based on the only one study<sup>24</sup> that has investigated the shoe  
40 17 LBS effect during prolonged running. By measuring a delay in the distal-to-proximal joint  
41 18 work redistribution during a prolonged submaximal run under the anaerobic threshold, this  
42 19 previous study suggested that an increased shoe LBS might have beneficial repercussions on  
43 20 the metabolic demand. At similar running intensity (95% of the VAT), we did not observe  
44 21 such supposed metabolic benefits on the mean group of participants. This running intensity  
45 22 may have been too low to increase the net energetic cost of prolonged running (i.e. inducing  
46 23 fatigue). As previously recommended,<sup>36</sup> the used running intensity allowed an appropriate  
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3 1 calculation of the energetic cost of running, while taking account the aerobic metabolism as  
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5 2 the main contributor to the metabolic demand ( $RER < 1$ ). If an increased shoe LBS really acts  
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7 3 in a beneficial way by limiting or delaying the onset of the energetic cost increase, this  
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9 4 putative beneficial effect could be observed in presence of fatigue. Future studies using  
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11 5 similar running intensity than in the current one should thus consider longer running duration  
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13 6 ( $> 40$  min) to potentially induce  $VO_2$  drift and thus fatigue. As it is, the lack of average effect  
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15 7 of the shoe LBS on the metabolic demand was in line with almost all the previous studies  
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17 8 using shorter duration of running.<sup>13–17</sup>

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10 9 All the variables were analysed from a baseline set to 9 min of running (about 1.7 km  
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12 10 based on the imposed speed of 3.11 m/s on average). This baseline was set to only measure an  
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14 11 eventual effect of the LBS in the duration of the prolonged running, while avoiding measuring  
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16 12 the adaptation effects due to reaching a steady-state  $VO_2$ ,<sup>37</sup> a stable biomechanical  
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18 13 pattern,<sup>38,39</sup> a stable neuromuscular system,<sup>40</sup> or stable mechanical shoe properties.<sup>41</sup>  
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20 14 Likely stabilised following this adaptation period, all the measured variables were unaffected  
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22 15 by the shoe LBS. This is different from what can be expected from previous studies as an  
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24 16 increased shoe LBS was known to have several influences on the running biomechanics.<sup>19</sup>  
25  
26 17 Therefore, at the group level, further assumptions can be made from the current prolonged  
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28 18 running. The physiological and biomechanical effects of an increased LBS may not occur at  
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30 19 all, or occur too early during this adaptation period, or be too subtle to be measured with  
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32 20 enough resolution on the field, or may not be systematic between the participants.

### 21 ***Individual approach***

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23 22 The time-courses of all the measured variables during the prolonged running were  
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25 23 highly participant-specific within-session and between-session (Figure 1, Figure 2, and Figure  
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3 1 3). This lack of non-systematic individual responses might be one explanation to the non-  
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5 2 significant effects of the shoe LBS at the group level. The observed individual variability was  
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7 3 in line with several studies highlighting participant-specific effects of the shoe LBS according  
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9 4 to the task characteristics,<sup>18</sup> the participants' characteristics<sup>12,20</sup> and biomechanics.<sup>13,21,22</sup>  
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11 5 In the current study, correlation analyses were used on individual variations induced by an  
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13 6 increased shoe LBS to highlight such potential associations. It can be noted that in our sample  
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15 7 of participants, an increased LBS mainly induced unclear (5 out of 11 runners) and  
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17 8 detrimental (4 out of 11 runners) metabolic effects. The correlations were thus interpreted in  
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19 9 terms of « less detrimental metabolic effect » rather than « more beneficial metabolic effect »  
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21 10 induced by an increased shoe LBS.  
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28 11 At baseline of the prolonged run, the correlations showed that an increased shoe LBS  
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30 12 was less able to induce detrimental metabolic effect if this shoe intervention decreased (or did  
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32 13 not increase) the ground contact time, increased (or did not decrease) the body vertical  
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34 14 oscillation, or increased (or did not decrease) the TA activations relative to the runners'  
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36 15 habitual shoes with lower LBS. These results were surprising as an increased shoe LBS was  
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38 16 reported to induce longer ground contact time,<sup>19</sup> and because the metabolic demand has been  
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40 17 shown to be inversely proportional to the ground contact time<sup>42</sup> (regardless of any shoe  
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42 18 intervention). Willwacher et al.<sup>43</sup> suggested that an increased ground contact time with an  
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44 19 increased shoe LBS may reflect a weakness of strength capability of the ankle plantarflexors.  
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46 20 On this basis, the current runners might not be strong enough to benefit from such LBS  
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48 21 increase in their habitual shoes. On the other hand, the change of LBS may be functionally too  
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50 22 different from the habitual shoes of some runners to maintain their habitual biomechanical  
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52 23 pattern. As a result, unusual adjustments in the stride spatiotemporal parameters may have  
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54 24 occurred to meet the requirements of the experiment, while inducing a greater energetic cost.  
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3 1 The ground contact time is generally inversely associated with the body vertical  
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5 2 oscillation and the aerial time.<sup>44</sup> This may explain why the variations of the ground contact  
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8 3 time and the body vertical oscillations were simultaneously identified as explanatory variables  
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10 4 in the correlations. This may explain why the variation of TA activations was also an  
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12 5 explanatory variable. Indeed, with the TA muscle being mainly activated during the aerial  
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14 6 phase (Supplementary material E), the greater TA activations identified as less detrimental in  
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16 7 the correlations should be due to a consequence of longer activation durations during longer  
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18 8 aerial phases (due to shorter ground stance phases) rather than greater activation magnitudes.  
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23 9 At the last time interval of the prolonged run, the greater the participants' height, the  
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25 10 lower the detrimental metabolic effects induced by an increased shoe LBS. Why the  
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27 11 participants' height may potentiate the metabolic effects of an increased shoe LBS was  
28  
29 12 unknown, but some hypotheses are presented. Greater height may imply greater mass and/or  
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31 13 greater body segment lengths. Additional correlation analyses confirmed this for the mass  
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33 14 ( $p=0.002$ ;  $r=0.82$ ) and the shoe size used as surrogate indicator of foot length ( $p=0.034$ ;  
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35 15  $r=0.64$ ), although both these variables did not directly correlate with the variation of the net  
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37 16 energetic cost induced by an increased shoe LBS in the current study. It has been shown that  
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39 17 the greater the participants' mass, the greater the metabolic benefits induced by an  
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41 18 intermediate increase of shoe LBS.<sup>12</sup> The taller runners, and also the heavier, were thus less  
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43 19 affected by an increased LBS. Greater shoe size may imply greater forefoot bone length,  
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45 20 likely resulting in a greater lever arm of the ground reaction force relative to MTP and ankle  
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47 21 joint centers (i.e., gearing effect) during push-off.<sup>45</sup> This gearing effect, amplified by the high  
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49 22 LBS shoes,<sup>43</sup> may favour lower excursion of muscle fibres and slower shortening velocity of  
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51 23 the *triceps surae* muscle.<sup>17,46</sup> These muscle responses have been associated with lower  
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3 1 metabolic energetic cost,<sup>47</sup> especially in participants benefiting from an increased shoe LBS  
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6 2 when surrogate measures were used.<sup>13,22</sup>  
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10 3 According to the instant of the prolonged run, different explanatory variables were  
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12 4 involved in the participant-specific metabolic effects induced by an increased shoe LBS. This  
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14 5 could be due to the observed variability in the time-courses of the physiological and  
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16 6 biomechanical variables between the participants. Similar variability has previously been  
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18 7 reported during prolonged running where spatiotemporal parameters can either increase,  
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21 8 decrease, or remain constant over time depending on the runner.<sup>48,49</sup> Because there was no  
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24 9 unique time-course of the biomechanical pattern over time (with or without shoe  
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26 10 intervention), a given correlation observed at an initial time interval of the run may not remain  
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28 11 at a later time interval because the correlated variables did not evolve similarly for each  
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31 12 runner. Furthermore, an increased shoe LBS may affect runners differently in a fatigue state  
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33 13 than in a non-fatigue state. This induced even more variability in the time-courses of the  
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35 14 physiological and biomechanical variables between the participants. This assumption seemed  
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37 15 to be corroborated with the number of participants benefiting from an increased shoe LBS  
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39 16 throughout the prolonged run. This number of participants followed an inverted “U-shape”  
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41 17 where the greatest number of participants benefiting from an increased LBS (n=6) occurred at  
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43 18 the half of the prolonged running. Before and after, a lower number of participants benefited  
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45 19 from an increased shoe LBS (n=4).  
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50 20 This study had some limitations highlighted for readers. **While the current protocol**  
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52 21 **included a prolonged running session close to the VAT, the running duration and/or intensity**  
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54 22 **were not important enough to induce an increase in the net energetic cost (i.e. inducing**  
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56 23 **fatigue) in any of the shoe LBS conditions.** The habitual shoe of the runners have been used,  
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58 24 which may differ in several features not measured, such as midsole foam viscoelasticity, sole  
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3 1 geometry, or shoe mileage. Thus, the beneficial (or detrimental) effects of an increased LBS  
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5 2 for some runners may have been potentiated by the appropriate (or not) interaction with these  
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8 3 other shoe features.<sup>50</sup> The difference in mass between both shoe LBS conditions (20 g on  
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10 4 average) may have slightly influenced the metabolic results by about 0.2% based on the  
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13 5 relationship between shoe mass and metabolic demand.<sup>51</sup> A point of awareness was that the  
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15 6 results came from two different prolonged running sessions performed in two different days  
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17 7 with low or high LBS shoes. In order to offset the results obtained from two different days,  
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19 8 physiological data were normalised by the day-specific respiratory reference values of the  
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21 9 participants recorded during a sitting rest before each running session. Nevertheless, it cannot  
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23 10 be ensured that the current results, while reflecting individual variations in responses to LBS  
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25 11 interventions, were not influenced by other unwanted effects. Furthermore, EMG results may  
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27 12 have been influenced by EMG placement between sessions thus it cannot be definitively  
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29 13 ensured that the sensors were exactly placed in the same location between both sessions.  
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31 14 Although firmly secured with medical straps, the sensors' abilities to record muscle  
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33 15 activations could have been affected by the accumulation of sweat. This study had a small  
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35 16 sample size resulting in low statistical power regarding the net energetic cost of prolonged  
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37 17 running ( $1-\beta=0.28$  for the LBS main effect;  $1-\beta=0.40$  for the interaction effect). A *post hoc*  
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39 18 power analysis (G\*Power v3.1.9.4) showed that, for achieving at least 0.80 power, 45 and 24  
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41 19 participants would have been needed to rule-out the Type II error possibilities for the LBS  
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43 20 main effect and the interaction effect, respectively. In correlation analyses, considering large  
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45 21 correlations ( $r<-0.5$  or  $r>0.5$ ) on 11 participants with an alpha level set to 0.1 resulted in 0.50  
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47 22 statistical power (while 23 participants would have been needed to achieve at least 0.80  
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49 23 power).<sup>35</sup> Therefore, findings from this study should be considered with caution. We would  
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51 24 suggest the future studies to include the explanatory variables highlighted in the current study  
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53 25 (i.e. ground contact time and height). This would enable to investigate shoe LBS effects with  
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3 1 more powerful experimental designs on the explanatory variables highlighted in the current  
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5 2 study. As it is, the current findings are suitable for male novice/recreational runners. As the  
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8 3 height (in this study) and the mass<sup>12</sup> are explanatory variables of the metabolic demand, it is  
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10 4 hypothesised that female runners may require a shoe LBS tuning different from males due to  
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13 5 their morphological specificities.  
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## 19 7 **Conclusion**

22 8 To the question: “is it an appropriate choice to increase the longitudinal bending stiffness in  
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24 9 habitual shoes of runners for improving performance?”, the answer from this study would be:  
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27 10 “it depends”. At a mean group level, an increased shoe LBS did not limit and/or delay the  
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29 11 increase of the net metabolic energetic cost during a prolonged running. However, participant-  
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31 12 specific metabolic (beneficial or detrimental) effects induced by an increased LBS have been  
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34 13 highlighted. These participant-specific metabolic effects were associated with the variation of  
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36 14 the ground contact time at the beginning and the height of the participants at the end of the  
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38 15 prolonged run. The results of this study increased the body of knowledge concerning the  
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41 16 potential explanatory variables associated with specific metabolic effects of shoe LBS.  
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43 17 However, future studies are still needed to be able to recommend, with more certainty, the  
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45 18 appropriate increase of shoe LBS to a given runner who needs it, based on his individual  
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47 19 characteristics and/or biomechanics. Indeed, the metabolic effects of an increased LBS were  
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50 20 more detrimental than the use of habitual shoes with lower LBS for most of the participants in  
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52 21 the current study. This study thus suggested that a shoe LBS intervention was likely not  
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54 22 beneficial for performance purposes if the runners’ shoe habits were too much disrupted.  
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## 57 23 **Acknowledgements**

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4  
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6  
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9 4 of the manuscript.  
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#### 13 5 14 15 16 6 **Declaration of interest statement**

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18  
19 7 NF and ND are members of the company Decathlon™ in the research department. NF, GR,  
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21 8 EB, and ND declared that the results of the study are presented clearly, honestly, and without  
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23 9 fabrication, falsification, nor inappropriate data manipulation.  
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3 **1 Figure captions**  
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6 **2 Figure 1.** Time-course of the net metabolic energetic cost during the prolonged running  
7 duration with low (left) and high (right) LBS shoes. Participants with long dotted lines had  
8 lower energetic cost during the prolonged run with the low LBS shoes, those with full lines  
9 had lower energetic cost during the prolonged run with the high LBS shoes, and those with  
10 short dotted lines had randomly lower energetic cost during the prolonged run either with low  
11 or high LBS shoes (see Table 2 for corresponding data).  
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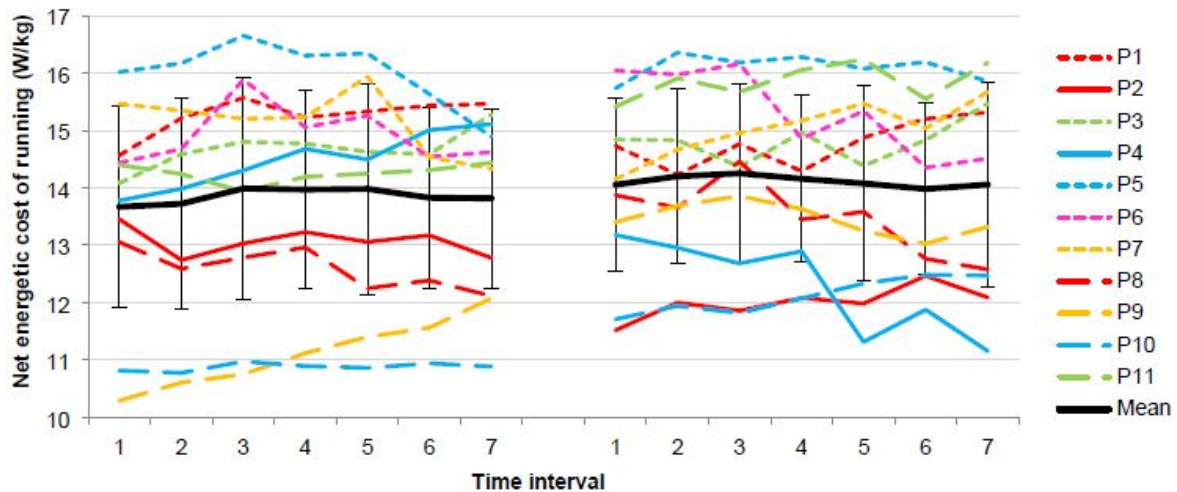
22 **9 Figure 2.** Time-course of the activations of TA, GM, and VL muscles during the prolonged  
23 running duration with low (left) and high (right) LBS shoes. Data of GM activations is  
24 missing for participants 3 and 10. \* indicated a significant main effect of the running duration.  
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32 **13 Figure 3.** Time-courses of the stride cadence, the body vertical oscillation, the ground contact  
33 time, the leg stiffness, and the vertical stiffness during the prolonged running duration with  
34 low (left) and high (right) LBS shoes. Data is missing for participants 1 and 4.  
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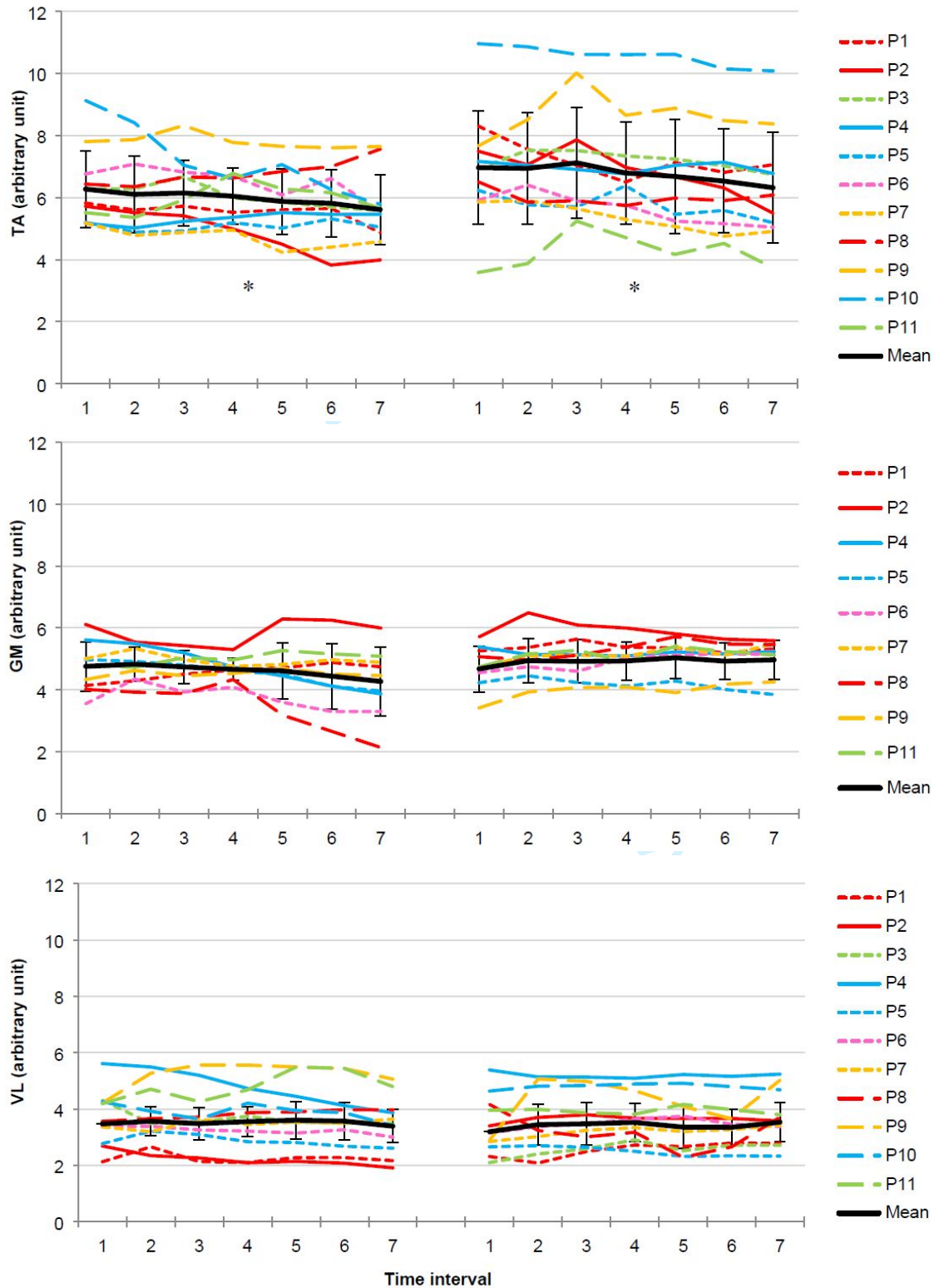
41 **17 Figure 4.** Correlations between the individual variations of the net energetic cost induced by  
42 an increased LBS in participants' habitual shoes and the individual variations of the ground  
43 contact time (top left), the body vertical oscillation (top right), the TA activations (bottom  
44 left) induced by an increased LBS, and the participants' height (bottom right). Dark and grey  
45 points respectively indicated the participants benefiting from the high LBS and low LBS  
46 condition, while white points indicated unclear participants (based on Table 2). Data is  
47 missing for participants 1 and 4 for spatiotemporal variables.  
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## Figure captions

**Figure 1.** Time-course of the net metabolic energetic cost during the prolonged running duration with low (left) and high (right) LBS shoes. Participants with long dotted lines had lower energetic cost during the prolonged run with the low LBS shoes, those with full lines had lower energetic cost during the prolonged run with the high LBS shoes, and those with short dotted lines had randomly lower energetic cost during the prolonged run either with low or high LBS shoes (see Table 2 for corresponding data).

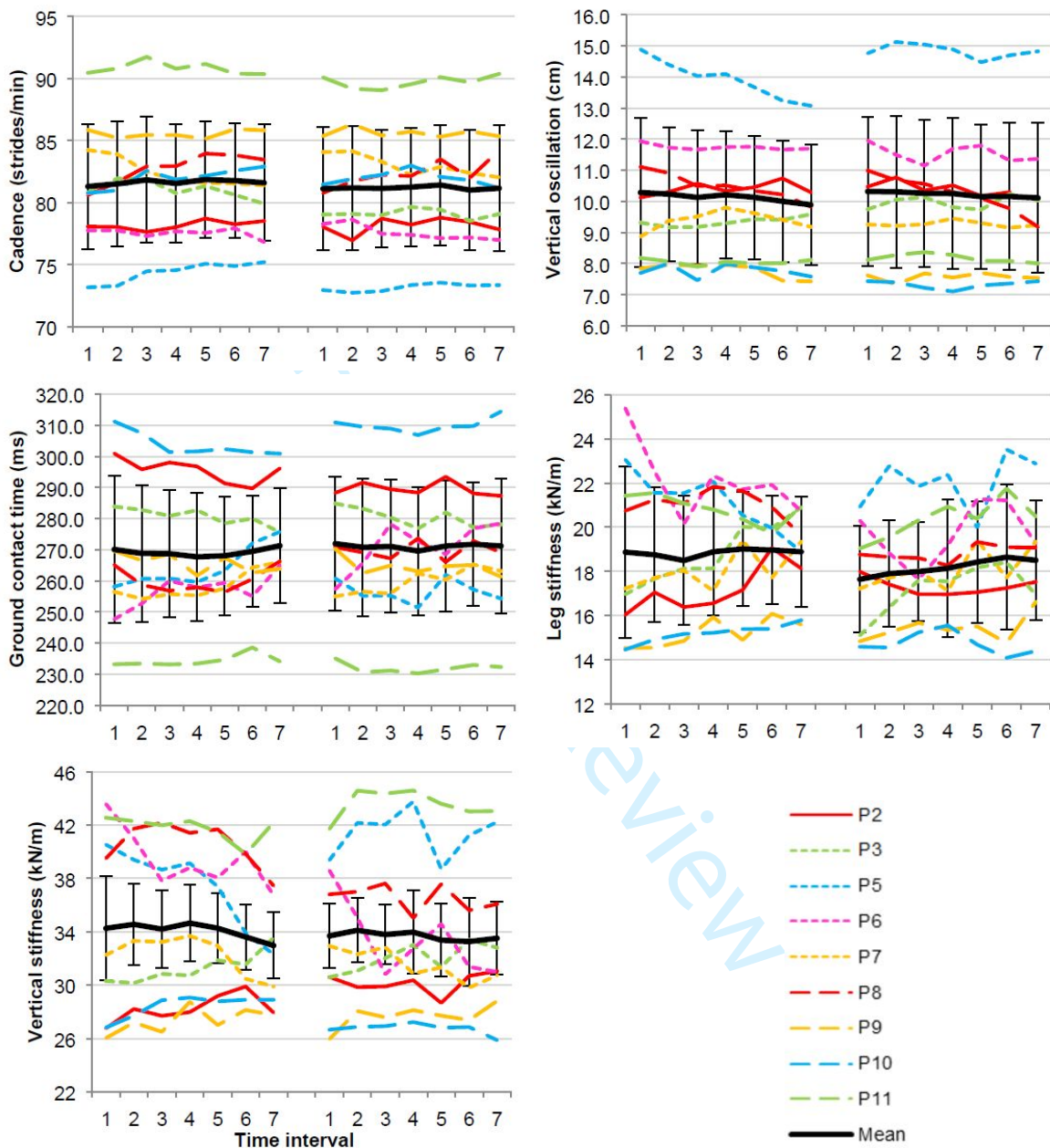


**Figure 2.** Time-course of the activations of TA, GM, and VL muscles during the prolonged running duration with low (left) and high (right) LBS shoes. Data of GM activations is missing for participants 3 and 10. \* indicated a significant main effect of the running duration.

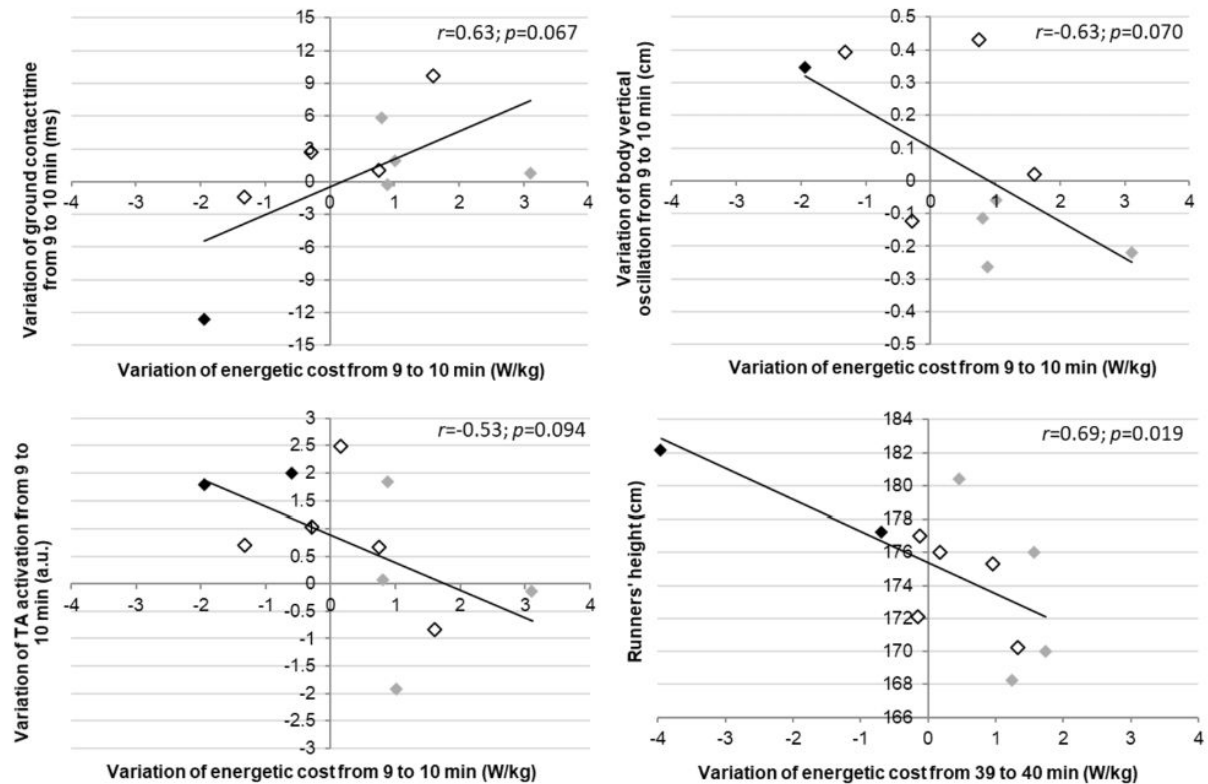




**Figure 3.** Time-courses of the stride cadence, the body vertical oscillation, the ground contact time, the leg stiffness, and the vertical stiffness during the prolonged running duration with low (left) and high (right) LBS shoes. Data is missing for participants 1 and 4.



**Figure 4.** Correlations between the individual variations of the net energetic cost induced by an increased LBS in participants' habitual shoes and the individual variations of the ground contact time (top left), the body vertical oscillation (top right), the TA activations (bottom left) induced by an increased LBS, and the participants' height (bottom right). Dark and grey points respectively indicated the participants benefiting from the high LBS and low LBS condition, while white points indicated unclear participants (based on Table 2). Data is missing for participants 1 and 4 for spatiotemporal variables.



**Table 1.** Characteristics of the participants and participants' own running shoes (see supplementary material A for pictures of the shoes).

Participant	Height (cm)	Mass (kg)	Speed at 95% of VAT (m/s)	Shoe brand and version	Shoe size (EU size)	Shoe mass (g)	Low LBS (Nm/deg)	High LBS (Nm/deg)
1	172.1	63.1	3.19	Nike Lunar Launch	44	246	0.070	0.233 (+231%)
2	177.2	75.6	2.92	Mizuno Wave Inspire 9	44	312	0.114	0.306 (+168%)
3	176.0	74.2	3.19	Nike Air Max	45	325	0.043	0.156 (+260%)
4	182.1	82.3	3.33	Nike Free Run 2	44	343	0.027	0.148 (+454%)
5	175.3	67.8	3.19	Asics Gel Innovate	44	286	0.057	0.206 (+263%)
6	177.0	68.3	3.19	Adidas Tubular	43	268	0.038	0.124 (+225%)
7	170.2	61.0	2.92	Kalenji Active Trail	41	257	0.099	0.398 (+304%)
8	180.4	78.4	3.19	Adidas Boost Supernova 9	44	338	0.067	0.162 (+143%)
9	168.2	58.2	2.78	Brooks Aduro 4	42	278	0.083	0.287 (+246%)
10	176.0	86.8	2.92	Adidas Terrex	45	352	0.047	0.149 (+220%)
11	170.0	64.9	3.33	Mizuno Wave Elixir 7	42.5	257	0.041	0.196 (+377%)
<b>Mean</b>	<b>175.0</b>	<b>71.0</b>	<b>3.11</b>		<b>43.5</b>	<b>297</b>	<b>0.062</b>	<b>0.215</b> (+263%)
<b>SD</b>	<b>4.4</b>	<b>9.2</b>	<b>0.19</b>		<b>1.5</b>	<b>39</b>	<b>0.027</b>	<b>0.084</b> (89%)

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**Table 2.** Individual (absolute and relative) variations of the net energetic cost of running induced by an increased LBS at each time interval of the prolonged running. Negative (dark grey cell) or positive (light grey cell) values respectively indicated that an increased LBS in the participant's habitual shoes induced decreased or increased net energetic cost of running compared to their lower habitual LBS. A beneficial shoe condition was unclear if negative and positive values were combined for a given participant.

Participants	$\Delta$ net energetic cost (W/kg)							Beneficial shoe condition
	From 9 to 10 min	From 14 to 15 min	From 19 to 20 min	From 24 to 25 min	From 29 to 30 min	From 34 to 35 min	From 39 to 40 min	
1	0.16 <i>1.1%</i>	-0.98 <i>-6.5%</i>	-0.80 <i>-5.2%</i>	-0.94 <i>-6.1%</i>	-0.45 <i>-3.0%</i>	-0.23 <i>-1.5%</i>	-0.15 <i>-0.9%</i>	Unclear
2	-1.94 <i>-14.4%</i>	-0.74 <i>-5.8%</i>	-1.17 <i>-9.0%</i>	-1.15 <i>-8.7%</i>	-1.07 <i>-8.2%</i>	-0.71 <i>-5.4%</i>	-0.69 <i>-5.4%</i>	High LBS
3	0.76 <i>5.4%</i>	0.24 <i>1.7%</i>	-0.43 <i>-2.9%</i>	0.19 <i>1.3%</i>	-0.24 <i>-1.7%</i>	0.25 <i>1.7%</i>	0.19 <i>1.2%</i>	Unclear
4	-0.60 <i>-4.3%</i>	-1.03 <i>-7.4%</i>	-1.62 <i>-11.3%</i>	-1.78 <i>-12.2%</i>	-3.18 <i>-21.9%</i>	-3.13 <i>-20.9%</i>	-3.95 <i>-26.2%</i>	High LBS
5	-0.28 <i>-1.8%</i>	0.19 <i>1.2%</i>	-0.47 <i>-2.8%</i>	-0.02 <i>-0.2%</i>	-0.26 <i>-1.6%</i>	0.56 <i>3.6%</i>	0.96 <i>6.5%</i>	Unclear
6	1.61 <i>11.1%</i>	1.29 <i>8.8%</i>	0.27 <i>1.7%</i>	-0.20 <i>-1.3%</i>	0.09 <i>0.6%</i>	-0.19 <i>-1.3%</i>	-0.11 <i>-0.8%</i>	Unclear
7	-1.31 <i>-8.5%</i>	-0.68 <i>-4.4%</i>	-0.25 <i>-1.6%</i>	-0.06 <i>-0.4%</i>	-0.47 <i>-2.9%</i>	0.50 <i>3.5%</i>	1.34 <i>9.4%</i>	Unclear
8	0.82 <i>6.3%</i>	1.06 <i>8.4%</i>	1.68 <i>13.1%</i>	0.49 <i>3.8%</i>	1.33 <i>10.9%</i>	0.38 <i>3.0%</i>	0.46 <i>3.8%</i>	Low LBS
9	3.11 <i>30.3%</i>	3.08 <i>29.1%</i>	3.11 <i>28.9%</i>	2.51 <i>22.6%</i>	1.85 <i>16.2%</i>	1.46 <i>12.7%</i>	1.25 <i>10.3%</i>	Low LBS
10	0.89 <i>8.3%</i>	1.17 <i>10.8%</i>	0.84 <i>7.7%</i>	1.18 <i>10.8%</i>	1.47 <i>13.5%</i>	1.54 <i>14.1%</i>	1.58 <i>14.6%</i>	Low LBS
11	1.02 <i>7.1%</i>	1.67 <i>11.7%</i>	1.74 <i>12.5%</i>	1.86 <i>13.1%</i>	1.99 <i>13.9%</i>	1.24 <i>8.7%</i>	1.74 <i>12.1%</i>	Low LBS
<b>Number of participants benefiting from low LBS (<math>\Delta</math> net energetic cost &gt; 0)</b>	7	7	5	5	5	7	7	
<b>Number of participants benefiting from high LBS (<math>\Delta</math> net energetic cost &lt; 0)</b>	4	4	6	6	6	4	4	

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## Supplementary material A

**Figure A.** Pictures of the participant's habitual running shoes. The order of the shoes corresponds to the order of participants in each Table or Figure of the main document. The last picture is the stiff carbon plate used in this study.





## Supplementary material B

### *Procedure of the mechanical bending test*

A shoe last was cut at the metatarsophalangeal joint level (70% of the shoe last length) to remove the anterior part. This shoe last was inserted inside the shoe. The shoe was then secured upside down on a horizontal plate from its posterior part with a clamp. The anterior ending of the shoe last inside the shoe ( $B$ ) was identified and marked on the external part of the shoe (Figure B), and then marked on a graph paper perpendicularly located to the bending axis of the shoe forefoot. A horizontal straight line was drawn through  $B$  on the graph paper. A hook was then set on the shoe outsole at the anterior ending of the shoe. Either no mass ( $m=0$  kg), or  $m$  masses of 1 kg, 2 kg, and 3 kg were hung along the hook. The location of the hook ( $H$ ) was also marked on the graph paper (Figure B). A vertical straight line was drawn through  $H$  on the graph paper, which cut perpendicularly the horizontal straight line in a point  $O$  (Figure B). The length of  $[BO]_m$ , in meters, was the lever arm of the force applied by each  $m$  mass relative to the bending axis. The moment ( $M_m$ , in Nm, equation B1) applied to the anterior part of the shoe was thus computed as:

$$M_m = m \times g \times [BO]_m \quad (\text{B1})$$

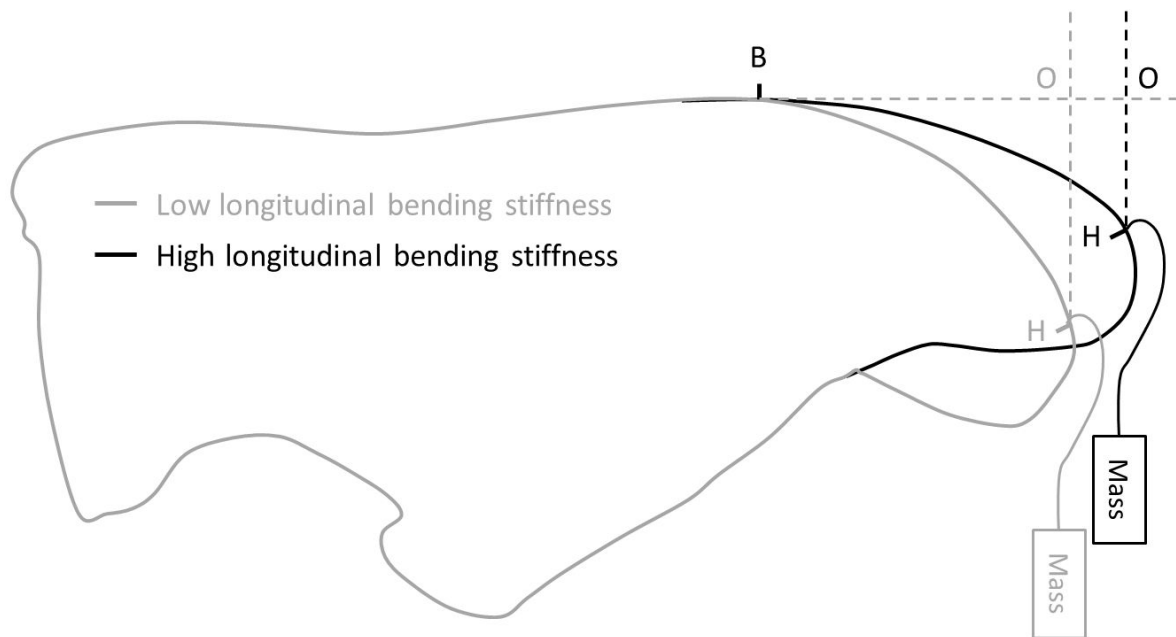
$g$  being the gravity constant value equal to  $9.81 \text{ m/s}^2$  and  $m$  being the mass equal to 0 kg, 1 kg, 2 kg, and 3 kg.

The length of  $[OH]_m$ , in meters, was the vertical displacement of the anterior part of the shoe due to the applied moment of force (for  $m=0$  kg, the length  $[OH]_0$  was the height of the curvature of the anterior part of the shoe, i.e. the toe spring). The bending angle ( $\hat{B}_m$ , in deg, equation B2) of the shoe was computed as:

$$\hat{B}_m = \tan^{-1} \left( \frac{[OH]_m}{[BO]_m} \right) \quad (\text{B2})$$

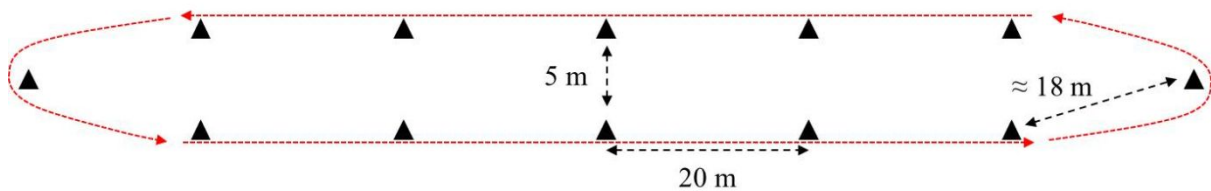
Finally, the bending stiffness value (in Nm/deg) was obtained through the slope of a linear regression fitting the four force moments ( $M_m$ ) and bending angles ( $\hat{B}_m$ ) plotted on a moment-angle graph.

**Figure B.** Schema illustrating the identification of the point of the anterior ending of the shoe last inside the shoe (or bending axis,  $B$ ), the location of the hook after a mass was hung ( $H$ ), and the lever arm of the force applied by the mass relative to the bending axis ( $O$ ) for the low (grey) and high (dark) longitudinal bending stiffness shoe conditions.



### Supplementary material C

**Figure C.** Picture of the experimental set-up with a participant running on the loop with hard concrete surface (top), and illustration of the loop set-up with its dimensions and the direction of running (bottom). The total distance of the loop was about 230 metres. Each straight line measured 80 metres. The ground marks in both extremities of the loop were located at around 18 metres from the previous ones, thus allowing the participants to turn behind the ground mark in a secure way thanks to a slight deceleration.





## Supplementary material D

**Table D1.** List of variables including in the correlation analyses. <sup>V</sup> indicates the variables presented in the main text for the correlations performed at the first and the last time intervals.

Variable	Description	Correlation analyses
$\Delta$ Net energetic cost (W/kg) <sup>V</sup>	Variation of the net energetic cost of running by subtracting values induced by the high LBS to those induced by the low LBS from 9 to 10 min, from 14 to 15 min, from 19 to 20 min, from 24 to 25 min, from 29 to 30 min, from 34 to 35 min, and from 39 to 40 min.	These variables were used in the correlation analyses only for identical time intervals than those of the net energetic cost of running  For example, $\Delta$ Cadence from 14 to 15 min was used in the correlation analyses as a potential explanatory variable for $\Delta$ Net energetic cost from 14 to 15 min.
$\Delta$ TA (a.u.) <sup>V</sup>	Variation of the lower limb muscle activations by subtracting values induced by the high LBS to those induced by the low LBS from 9 to 10 min, from 14 to 15 min, from 19 to 20 min, from 24 to 25 min, from 29 to 30 min, from 34 to 35 min, and from 39 to 40 min.	
$\Delta$ GM (a.u.) <sup>V</sup>		
$\Delta$ VL (a.u.) <sup>V</sup>		
$\Delta$ Cadence (stride/min) <sup>V</sup>	Variation of spatiotemporal parameters of running by subtracting values induced by the high LBS to those induced by the low LBS from 9 to 10 min, from 14 to 15 min, from 19 to 20 min, from 24 to 25 min, from 29 to 30 min, from 34 to 35 min, and from 39 to 40 min.	
$\Delta$ Vertical oscillation (cm) <sup>V</sup>		
$\Delta$ Ground contact time (ms) <sup>V</sup>		
$\Delta$ Vertical stiffness (kN/m)		
$\Delta$ Leg stiffness (kN/m)		
Mass (kg) <sup>V</sup>	Mass of the participant	These variables were used in the correlation analyses for all time intervals of the variation of the net energetic cost of running  For example, height was used in the correlation analyses as a potential explanatory variable for $\Delta$ Net energetic cost in each of the seven time intervals.
Height (cm) <sup>V</sup>	Height of the participant	
Speed (m/s) <sup>V</sup>	Imposed speed to the participant equal to 95% of the VAT speed	
Shoe size (EU size)	Size of the participant's own shoe	
Low LBS (Nm/deg)	LBS of the participant's own shoe	
$\Delta$ LBS <sup>V</sup>	Variation of LBS when adding a stiff plate	
Shoe mass (g)	Mass of the participant's own shoe	
Habitual cadence (stride/min)	Spatiotemporal parameter of running measured at baseline (from 9 to 10 min) with the participant's own shoe (low LBS) considered as the runners' habitual running technique	
Habitual vertical oscillation (cm)		
Habitual ground contact time (ms)		
Habitual vertical stiffness (kN/m)		
Habitual leg stiffness (kN/m)		

**Table D2.** Explanatory variables correlated with the variation of the net energetic cost of running induced by an increased shoe LBS according to the time interval of the prolonged running. Based on criteria set in the statistical section, only the significant correlated variables were presented while NS indicated non-significant correlation.

Explanatory variables	$\Delta$ net energetic cost						
	From 9 to 10 min	From 14 to 15 min	From 19 to 20 min	From 24 to 25 min	From 29 to 30 min	From 34 to 35 min	From 39 to 40 min
$\Delta$ ground contact time from 9 to 10 min	$p=0.067$ $r=0.63$	NS	NS	NS	NS	NS	NS
$\Delta$ vertical oscillation from 9 to 10 min	$p=0.070$ $r=-0.63$	NS	NS	NS	NS	NS	NS
$\Delta$ TA activations from 9 to 10 min and from 14 to 15 min	$p=0.094$ $r=-0.53$	$p=0.082$ $r=-0.55$	NS	NS	NS	NS	NS
$\Delta$ VL activations from 24 to 25 min	NS	NS	NS	$p=0.049$ $r=-0.60$	NS	NS	NS
Height	NS	NS	NS	$p=0.043$ $r=-0.62$	$p=0.094$ $r=-0.53$	$p=0.026$ $r=-0.66$	$p=0.019$ $r=-0.69$
Other variables at any time intervals	NS	NS	NS	NS	NS	NS	NS

**Supplementary material E**

**Figure E.** Typical VL (yellow), GM (red), and TA (blue) raw activations during a running cycle. Vertical dotted lines represented estimations of instants of heel strike (HS) and toe-off (TO).

