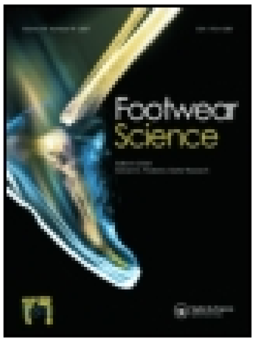

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Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent

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ABSTRACT

The primary footwear components of interest to improve performance are midsole material, weight, and longitudinal bending stiffness. Little is known about the effects of varied longitudinal bending stiffness across a range of running speeds. The purpose of this study was to identify changes in spatiotemporal variables, horizontal ground reaction forces, subjective comfort, and metabolic cost at different running speeds in response to varied longitudinal bending stiffness. Ten highly trained males ran at 14, 17 and 20 km/h in shoes with varying longitudinal bending stiffness (normal 5.9, stiff 10.5 and very stiff 17.0 N-m/rad). Ground reaction forces, metabolics and subjective comfort assessments were collected. There were significant changes ($p < .05$) in contact time, stride frequency, and stride length between shoe conditions at all three speeds. Peak propulsive force decreased with increased bending stiffness at all three speeds, but there was no change in braking or propulsive impulse. The patterns of changes in stride length and stride frequency were different between speeds. At 14 km/h, most participants elicited a minimum metabolic rate in the normal shoe. However, at 17 km/h an increased number of participants were more economical in the stiff shoe, despite it weighing an extra 50 g compared to the normal shoe. Running speed had an influence on subjective comfort, with participants tending to prefer the normal shoe at 14 km/h and the stiff shoe at 17 km/h. These results suggest that an optimal bending stiffness to reduce metabolic cost and improve comfort may be running speed dependent.

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Gait; comfort; shoe; performance; metatarsophalangeal

Introduction

Recent advances in footwear engineering have been redefining the potential for footwear to influence distance running performance (Hoogkamer et al., 2018). Changes in shoe weight (Franz, Wierzbinski, & Kram, 2012; Frederick, 1984; Hoogkamer, Kipp, Spiering, & Kram, 2016), midsole material (Worobets, Wannop, Tomaras, & Stefanyshyn, 2014), longitudinal bending stiffness (LBS) (Madden, Sakaguchi, Wannop, & Stefanyshyn, 2015; Roy & Stefanyshyn, 2006), and subjective comfort (Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009) have all been demonstrated to influence metabolic cost during running, an indicator of performance (Hoogkamer et al., 2016).

Increased LBS alters mechanics of the metatarsophalangeal (MTPJ) and ankle joint during running (Willwacher, König, Braunstein, Goldmann, & Brüggemann, 2014; Willwacher, König, Potthast, & Brüggemann, 2013). For best performance, a shoe with a high energy storage and return midsole and a stiff carbon fibre plate has been shown to reduce the energetic cost of running by 4% (Hoogkamer et al., 2018). Joint level mechanical analysis reveals that the carbon fibre plate within the shoe acts as a lever rather than spring (Hoogkamer, Kipp, & Kram, 2019). Interpretation of the mechanism behind the 4% improvement remains difficult, however, because with the interaction of the very high energy return foam and carbon fibre plate it is unknown how either characteristic behaves and contributes to mechanical or energetic changes in isolation. Flores, Delattre, Berton, and Rao (2019) sought to address this gap, however a primary limitation to their study is that the foam used in the footwear only returned 62% energy, compared to 87% in Hoogkamer et al. (2018), and participants only ran at an average 10 km/h, compared to speeds of 14–18 km/h for energetic cost analysis and 16 km/h for joint level mechanics analysis previously reported (Hoogkamer et al., 2018, 2019).

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No study has investigated the effect of altering only LBS at a range of running velocities. Previous findings have shown that sagittal plane MTPJ moment and stiffness increase linearly with running speed, which will influence the ability of the foot to bend a shoe about the MTPJ axis (Day & Hahn, 2019). Increasing LBS of a shoe, in proportion to the increase in MTPJ moment or stiffness, may be a mechanism to maximize the contribution of footwear to improving distance running performance (Day & Hahn, 2019). Natural changes in mechanics of the foot and leg across speeds, notably an increase in MTPJ and ankle moments (Day & Hahn, 2019; Kelly, Cresswell, & Farris, 2018; Schache et al., 2011), may affect an optimal interaction between the biological limb and shoe.

The purpose of this study was to investigate the effects of varied LBS at different running speeds. We investigated changes in spatiotemporal parameters, ground reaction forces, subjective comfort, and metabolic cost. Based upon previous literature (Flores, Delattre, et al., 2019; Hoogkamer et al., 2018; Willwacher et al., 2013), we hypothesized that an increase in LBS would cause an increase in contact time and stride length, and a decrease in stride frequency and peak propulsive force across speeds. For comfort-related metrics we hypothesized that total shoe comfort, measured by questionnaire responses regarding individual components of footwear (Luo et al., 2009), would be different across speeds and that an increase in LBS would be more preferable at faster running speeds. Lastly, we hypothesized that at 14 km/h a less stiff shoe would result in the lowest metabolic cost, whereas at 17 km/h a stiffer shoe would exhibit the lowest metabolic cost.

Materials and methods

Participants

Ten competitive male runners were recruited for this study (26 ± 6 years, 1.78 ± 0.04 m, 63.9 ± 4.0 kg, 101 ± 34 (range 64–160) km/week, 15:04 ± 0:38 (range 13:59–16:00) (min:sec) 5000 m personal best). To be included, participants had to have a 5000 m personal best under 16:00, no lower extremity injury in the previous 6 months, and currently running over 50 km/week. Participants provided written informed consent prior to data collection. This study was approved by the Institutional Review Board at the University of Oregon.

Table 1. Physical properties of footwear used.

Shoe	Plates (*n*)	Plate thickness (mm)	Shoe mass (g)	Stiffness (N-m/rad)
Normal	0	0	239	5.9
Stiff	1	3	292	10.5
Very stiff	2	6	346	17.0

Footwear bending stiffness test

Three shoe conditions (normal, stiff, very stiff) were tested in this study (Table 1). Longitudinal bending stiffness of the shoes was modified by inserting full-length 3D printed plates (Nylon 11) underneath the insole, matching the shape of the shoe footbed (Epic React Flyknit size US10, Nike, Beaverton, OR). The normal condition was defined by the use of no plate, stiff condition had one plate, and the very stiff condition had two plates. Individual plates had a mass of ∼50 g.

Longitudinal bending stiffness was quantified using a custom set-up (Figure 1). The testing set-up was designed to best mimic a previously described mechanical testing procedure (Hoogkamer et al., 2019). The shoe was anchored upside down on a table using a c-clamp, with the forefoot bending axis aligned on the edge of the table. A carabiner was used to connect a strain gauge to the heel loop of the shoe. The strain gauge voltage was amplified using a SparkFun HX711 (SparkFun Electronics, Niwot, CO) load cell amplifier and powered via an Arduino Mega2560 microcontroller (Arduino, Somerville, MA) sampling at 10 Hz. Linear displacements of the heel point and the strain gauge attachment point were measured using standard tape measures affixed to the table structure. One test cycle consisted of pulling vertically downward on the strain gauge attached to the shoe. Three test cycles were conducted for each shoe condition. The loading phases of each test cycle were all completed in the same time duration, ∼5 s. Video of the test cycles was recorded on an iPhone 7S (Apple, Cupertino, CA) for the purpose of assessing linear displacements of the heel point and heel loop.

Force data were output from the strain gauge in pounds and converted to Newtons. The angular

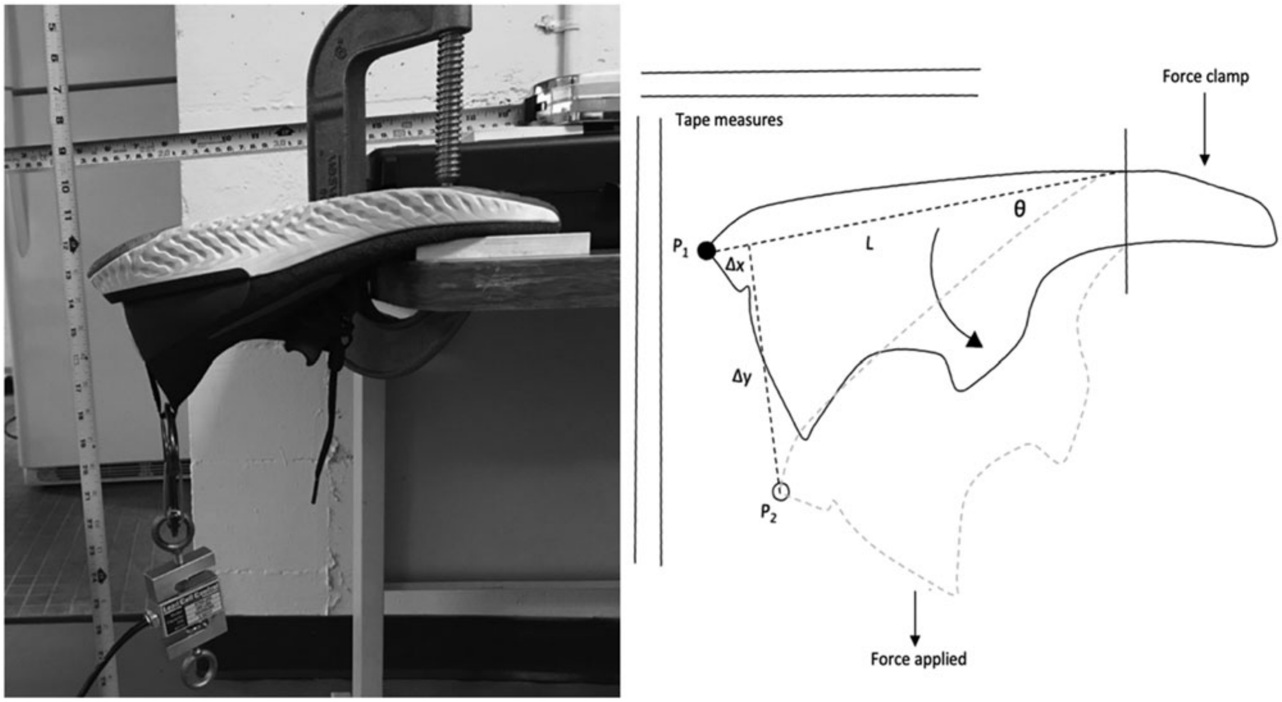

Figure 1. Set-up of mechanical stiffness test (left) and depiction of linear distances used to quantify bending angle and longitudinal bending stiffness (right).

displacement of the shoe was quantified from linear displacement data (Figure 1). The horizontal and vertical displacements of the heel tip of the shoe were recorded at the beginning and end of each loading cycle. These linear displacements were then used to quantify angular displacement using the following equation:

$$\theta_{bend} = \tan^{-1} \frac{\Delta y}{L - \Delta x} \tag{1}$$

Where 'L' is the distance from the heel tip to the forefoot rotation axis of the shoe, and Δx and Δy are the respective linear displacements of the heel tip. The horizontal displacement of the heel loop throughout the loading phase was quantified to account for the change in moment arm of the pulley about the forefoot rotation axis. Because start and end coordinates of the heel tip and pulley were recorded, it was assumed that translations occurred in a linear fashion.

Bending angle, dynamic moment arm, and force data were extrapolated to 101 data points per loading cycle and averaged across test cycles. Strain gauge force was multiplied by the dynamic moment arm to estimate shoe extension torque throughout the test cycles. The average LBS of each shoe was quantified based on the slope of the moment-angle curve (Oh & Park, 2017). While comparing bending stiffness across different test set-ups is difficult, the current values were similar to those reported in Hoogkamer et al. (2019), which used a similarly oriented set-up. The normal shoe is of comparable stiffness to their most flexible shoe (Adios Boost), and the very stiff shoe is of comparable stiffness to that of their most stiff shoe (Vaporfly 4%).

Data collection

Participants visited the lab on two occasions. A screening test was completed on the first day to ensure that participants exhibited steady-state metrics running at 17 km/h (RER < 1.0, VO$_2$ and VCO$_2$ deviate less than 10% between 15-s averages during last 2 min of the 5 min screening trial) (McClave et al., 2003; Reeves, Davies, Bauer, & Battistutta, 2004).

Upon successful completion of the screening process, running trials assessing spatiotemporal parameters and ground reaction forces were conducted on a force instrumented treadmill (Bertec Inc., Columbus, OH). Ground reaction force data were collected at 1000 Hz. Participants ran at three speeds, 3.89, 4.70 and 5.56 m/s (14, 17, 20 km/h), in three different footwear conditions of varying LBS

(Table 1). Data were collected at each speed for ∼10 strides. The order of footwear was randomized between participants. Each participant completed the three speeds in ascending order and then switched shoes. The rest between conditions was self-selected.

Participants visited the lab a second time to perform a series of metabolic analyses after a self-selected warm-up. Twelve 5-min running trials were completed on a high-speed treadmill (Woodway, Waukesha, WI) set to 1% grade (Jones & Doust, 1996). Six trials were run at 14 km/h and six at 17 km/h. The three shoe conditions from the first day were used again. Each shoe was worn for two trials at each speed. The order of shoe testing within each speed was randomized. The 14 km/h trials were completed before the 17 km/h trials. Measures of $\dot{V}O_2$ and $\dot{V}CO_2$ were taken with an open-circuit expired-gas analysis system (Parvomedics TrueOne 2400, Sandy, UT). The rest between trials was ∼5 min. Participant body mass was assessed between each trial while wearing shoes to account for changes in hydration and shoe mass.

Subjective dynamic comfort assessments were completed for each shoe at each speed immediately after the participants finished the second trial in each shoe. The following factors were rated: forefoot cushioning, rearfoot cushioning, forefoot flexibility, stability, heel-to-toe transition, and weight (Luo et al., 2009). A five-point scale was used for rating: 5 meaning ‘not acceptable’, 3 meaning ‘not great but acceptable’, and a 1 meaning ‘just right’. Ratings were averaged across all factors to determine an overall comfort score for each shoe at each speed. Participants were blinded to their previous assessments of the other shoes.

Data analysis

A custom MATLAB (version 2016b; Mathworks, Natick, MA) programme was used to calculate contact time, stride length, stride frequency, and anterior–posterior ground reaction force impulses. Ground reaction force data were filtered using a low-pass zero-lag 4th order Butterworth with a 20 Hz cut-off and down-sampled to 200 Hz (*fs*). The stance phase was defined as the phase when the vertical ground reaction force exceeded 5% of body weight. Braking and propulsive impulses were quantified by integrating the area under the positive and negative regions of the anterior-posterior ground reaction force. Contact time, stride frequency, and stride length were calculated from filtered ground reaction force data using the following equations:

$$\text{Contact time (s)} = \text{frames stance phase} \times fs \tag{2}$$

$$\text{Step frequency (Hz)} = 1/(\text{frames between ipsilateral foot contacts}/fs) \tag{3}$$

$$\text{Stride length (m)} = (\text{frames between ipsilateral foot contacts}/fs) \times \text{treadmill belt speed (m/s)} \tag{4}$$

Metabolic data were analyzed by averaging submaximal (RER < 1.0) $\dot{V}O_2$ and $\dot{V}CO_2$ consumption over the last 2 min of each stage. Metabolic rate (W/kg) was quantified using the Brockway equation (Brockway, 1987).

Statistical analysis

Repeated measures analysis of variance (ANOVA, $\alpha < 0.05$) tests were used to analyze braking and propulsive impulses, peak propulsive force, stride frequency, stride length, contact time, metabolic rate and subjective comfort between footwear conditions at each speed. For comfort assessments, overall shoe score and individual factors were analyzed. Greenhouse–Geisser adjustments were used when Mauchley’s test of Sphericity was significant (<.05). Pairwise comparisons with Bonferroni adjustments ($\alpha = 0.05/3 = 0.0167$) were used *post-hoc* to further analyze a significant effect of shoe. Effect sizes (partial eta squared, η^2) were calculated and defined as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), or large ($\eta^2 = 0.14$) (Cohen, 1988).

Results

Altering LBS resulted in changes in spatiotemporal variables across speeds (Table 2). There was a significant effect of LBS on contact time at 14 km/h ($p = .01$, $\eta^2 = 0.402$) and 20 km/h ($p = .001$, $\eta^2 = 0.566$), but not at 17 km/h ($p = .057$, $\eta^2 = 0.272$). Additionally, there was a significant effect of LBS on stride frequency at 14 ($p < .001$,

Table 2. Spatiotemporal and ground reaction force variables across shoe conditions at three running speeds.

	Normal	Stiff	Very stiff	*p*-Value
Spatiotemporal variables				
14 km/h				
Contact time (s)	0.207 ± 0.009[c]	0.210 ± 0.011	0.212 ± 0.011[a]	**.010**
Stride length (m)	2.62 ± 0.10[c]	2.66 ± 0.10	2.67 ± 0.10[a]	**<.001**
Stride frequency (Hz)	1.49 ± 0.06[b,c]	1.47 ± 0.06[a]	1.46 ± 0.06[a]	**<.001**
17 km/h				
Contact time (s)	0.188 ± 0.010	0.188 ± 0.010	0.189 ± 0.011	.057
Stride length (m)	3.02 ± 0.15[c]	3.05 ± 0.15	3.05 ± 0.15[a]	**.016**
Stride frequency (Hz)	1.56 ± 0.08[c]	1.54 ± 0.08	1.54 ± 0.08[a]	**.005**
20 km/h				
Contact time (s)	0.165 ± 0.009[b,c]	0.169 ± 0.010[a]	0.170 ± 0.010[a]	**.001**
Stride length (m)	3.34 ± 0.18	3.38 ± 0.17	3.34 ± 0.16	.051
Stride frequency (Hz)	1.67 ± 0.09	1.66 ± 0.09	1.67 ± 0.09	**.048**
Horizontal ground reaction force				
14 km/h				
Braking impulse (N-s)	14.9 ± 2.0	15.0 ± 1.9	15.2 ± 2.1	.465
Propulsive impulse (N-s)	13.7 ± 1.3	13.8 ± 1.2	13.6 ± 1.3	.240
Peak propulsive force (N)	230 ± 21[b,c]	224 ± 21[a,c]	215 ± 21[a,b]	**<.001**
17 km/h				
Braking impulse (N-s)	16.3 ± 2.1	16.4 ± 2.5	16.2 ± 2.3	.729
Propulsive impulse (N-s)	15.2 ± 1.5	15.2 ± 1.3	15.1 ± 1.4	.746
Peak propulsive force (N)	281 ± 27[c]	276 ± 26	266 ± 24[a]	**.002**
20 km/h				
Braking impulse (N-s)	17.2 ± 2.6	17.2 ± 2.7	17.1 ± 2.4	.767
Propulsive impulse (N-s)	16.0 ± 1.7	16.1 ± 1.7	15.8 ± 1.6	.071
Peak propulsive force (N)	334 ± 33[b,c]	326 ± 32[a,c]	316 ± 31[a,b]	**<.001**

Pairwise comparisons showing significant ($p < .05$) differences: [a]different from normal, [b]different from stiff, [c]different from very stiff.

$\eta^2 = 0.636$), 17 ($p = .005$, $\eta^2 = 0.445$) and 20 km/h ($p = .048$, $\eta^2 = 0.287$). Finally, there was a significant effect of LBS on stride length at 14 ($p < .001$, $\eta^2 = 0.616$) and 17 km/h ($p = .016$, $\eta^2 = 0.368$), but not at 20 km/h ($p = .051$, $\eta^2 = 0.282$).

Horizontal ground reaction forces were affected by a change in LBS (Table 2, Figure 2). There was a significant effect of LBS on peak propulsive force at 14 ($p < .001$, $\eta^2 = 0.712$), 17 ($p = .002$, $\eta^2 = 0.505$), and 20 km/h ($p < .001$, $\eta^2 = 0.701$). However, braking impulse was not significantly different between conditions at 14 ($p = .465$, $\eta^2 = 0.082$), 17 ($p = .782$, $\eta^2 = 0.035$) or 20 km/h ($p = .767$, $\eta^2 = 0.029$). Likewise, propulsive impulse was not significantly different between conditions at 14 ($p = .249$, $\eta^2 = 0.145$), 17 ($p = .746$, $\eta^2 = 0.032$), or 20 km/h ($p = .071$, $\eta^2 = 0.255$).

There was an effect of LBS on metabolic rate at both 14 and 17 km/h (Table 3). Metabolic rate was significantly different between shoes at 14 ($p = .002$, $\eta^2 = 0.532$) and 17 km/h ($p = .002$, $\eta^2 = 0.652$). One participant had issues with their nose clip staying on during the 14 km/h trials, resulting in analysis for 14 km/h metabolic data on only nine of the ten participants.

Overall subjective comfort was significantly different between shoes at 14 ($p = .013$, $\eta^2 = 0.384$) and 17 km/h ($p = .001$, $\eta^2 = 0.515$) (Table 4). Individual factors that were significantly different in comfort at 14 km/h were forefoot cushioning ($p < .001$, $\eta^2 = 0.555$) and flexibility ($p = .005$, $\eta^2 = 0.450$), with the very stiff shoe being ranked worse than the normal and stiff shoe for both variables. Rearfoot cushioning, stability, heel–toe transition, and weight were not significantly different in perceived comfort between shoes at 14 km/h. At 17 km/h, forefoot cushioning ($p = .031$, $\eta^2 = 0.320$), rearfoot cushioning ($p = .037$, $\eta^2 = 0.307$), flexibility ($p < .001$, $\eta^2 = 0.585$), and weight ($p = .003$, $\eta^2 = 0.484$) were all ranked significantly more comfortable in the normal and stiff shoe compared to the very stiff shoe. However, there were no significant pairwise comparisons for rearfoot cushioning at 17 km/h. Stability and heel–toe transition were not significantly different in perceived comfort between shoes at 17 km/h.

Discussion

The purpose of this study was to investigate the effects of varying LBS on spatiotemporal variables, horizontal ground reaction forces, subjective comfort, and metabolic cost at different running speeds. In support of our hypotheses, we observed significant changes in most, but not all, dependent

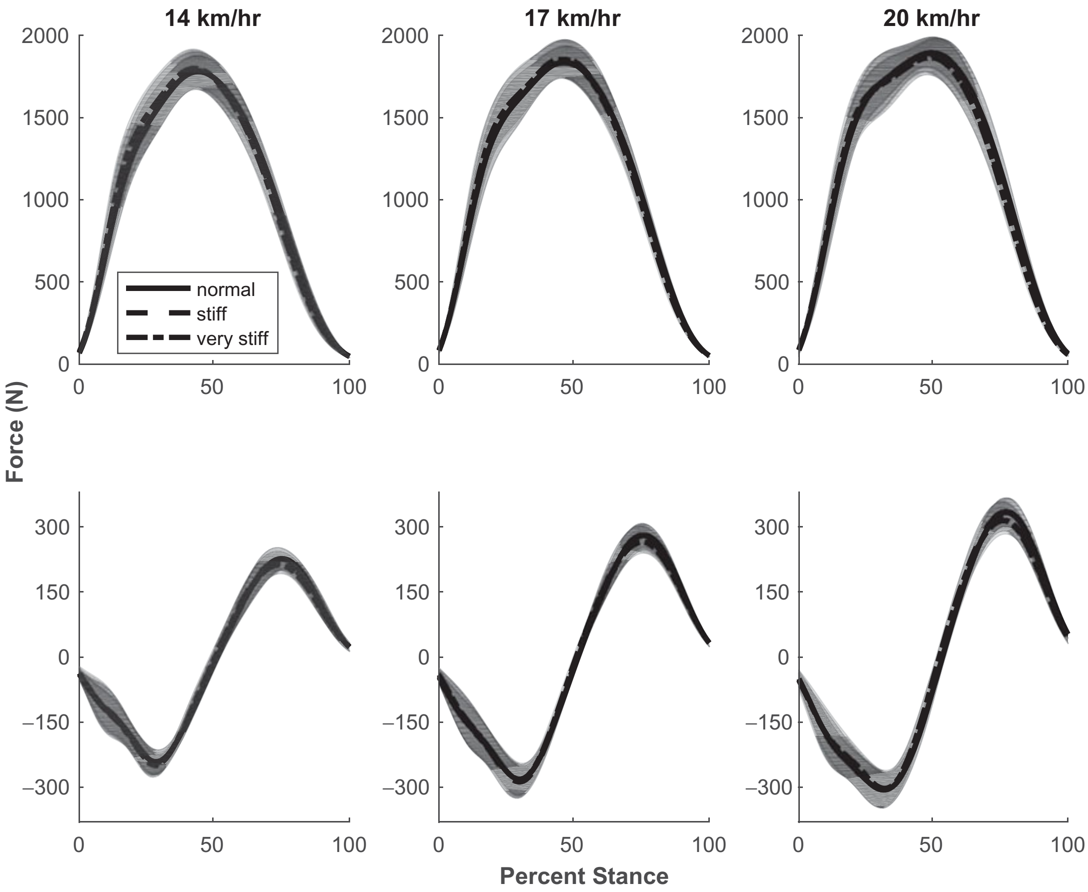

Figure 2. Vertical (top) and anterior–posterior (bottom) ground reaction forces across shoe conditions at three speeds.

Table 3. Normalized oxygen uptake (running economy), metabolic rate, and non-normalized gas volumes across shoe conditions at two running speeds.

	Normal	Stiff	Very stiff	*p*-Value
14 km/h				
$\dot{V}O_2$ (ml/kg/min)	45.33 ± 3.26^c	45.86 ± 3.48	46.24 ± 3.31^a	**.005**
Metabolic rate (W/kg)	14.42 ± 1.06^c	14.61 ± 1.08	14.76 ± 1.07^a	**.002**
$\dot{V}O_2$ (L/min)	2.86 ± 0.28^c	2.89 ± 0.30	2.92 ± 0.27^a	**.002**
$\dot{V}CO_2$ (L/min)	2.46 ± 0.26^c	2.49 ± 0.28	2.51 ± 0.27^a	**.026**
17 km/h				
$\dot{V}O_2$ (ml/kg/min)	57.30 ± 3.43^c	57.13 ± 3.84^c	$58.58 \pm 3.57^{a,b}$	**.006**
Metabolic rate (W/kg)	18.21 ± 1.14^c	18.22 ± 1.15^c	$18.75 \pm 1.21^{a,b}$	**.002**
$\dot{V}O_2$ (L/min)	3.61 ± 0.31^c	3.60 ± 0.30^c	$3.70 \pm 0.32^{a,b}$	**.001**
$\dot{V}CO_2$ (L/min)	3.20 ± 0.33^c	3.21 ± 0.31^c	$3.33 \pm 0.35^{a,b}$	**.001**

Pairwise comparisons showing significant ($p < .05$) differences: [a]different from normal, [b]different from stiff, [c]different from very stiff.

Table 4. Subjective dynamic comfort assessments across shoes at two running speeds. A value of 1 means preferred, 5 means not preferred.

	Normal	Stiff	Very stiff	*p*-Value
14 km/h				
Total	2.2 ± 0.8	$2.0^c \pm 0.8$	$3.1^b \pm 1.0$	**.013**
Forefoot cushioning	2.6 ± 1.3^c	2.4 ± 1.3^c	$4.6 \pm 0.8^{a,b}$	**.001**
Rearfoot cushioning	1.8 ± 1.0	2.0 ± 1.4	2.8 ± 1.8	.120
Flexibility	2.2 ± 1.0^c	2.2 ± 1.4^c	$4.0 \pm 1.1^{a,b}$	**.005**
Heel–toe transition	2.2 ± 1.4	2.0 ± 1.1	2.6 ± 1.8	.439
Stability	2.8 ± 1.5	1.6 ± 1.3	1.8 ± 1.4	.068
Weight	1.8 ± 1.4	2.0 ± 1.1	2.6 ± 1.3	.286
17 km/h				
Total	2.1 ± 0.7^c	1.9 ± 0.5^c	$3.2 \pm 1.1^{a,b}$	**.001**
Forefoot cushioning	2.0 ± 1.1^c	2.0 ± 1.4	3.6 ± 1.6^a	**.031**
Rearfoot cushioning	1.8 ± 1.0	2.0 ± 1.1	3.2 ± 1.8	**.037**
Flexibility	2.8 ± 1.5^c	2.0 ± 1.1^c	$4.0 \pm 1.1^{a,b}$	**<.001**
Heel–toe transition	2.0 ± 1.1	2.0 ± 1.1	2.4 ± 1.6	.717
Stability	2.4 ± 1.6	1.6 ± 1.0	2.2 ± 1.7	.442
Weight	1.6 ± 1.3	1.6 ± 1.0^c	3.8 ± 1.7^b	**.003**

Pairwise comparisons showing significant ($p < .05$) differences: [a]different from normal, [b]different from stiff, [c]different from very stiff.

variables across the range of speeds tested in response to altered LBS (Tables 2–4).

Increasing LBS systematically increased contact time at 14 and 20 km/h, matching previous results (Flores, Delattre, et al., 2019; Willwacher et al., 2013, 2014). Interestingly, there was no significant change in contact time at 17 km/h, although the effect size was large ($\eta^2 = 0.272$). A potential reason for this may be that the stiffness of the shoe is more aligned to that of the MTPJ, whose stiffness increases with running speed (Day & Hahn, 2019). The assumed larger MTPJ moment at 17 km/h may be enough to overcome the increased LBS of the stiff shoe and maintain natural MTPJ dorsiflexion. This may help runners stay within their preferred movement path (Nigg et al., 2017) and maintain normal contact time by maintaining the ratio of the contributions to the net MTP moment generated by the body versus the shoe.

There was a significant decrease in stride frequency at all three speeds as LBS increased (Table 2). This contradicts Flores, Delattre, et al. (2019) who reported no change in stride frequency with increased LBS. However, their testing speed was only 10 km/h, compared to the 14, 17 and 20 km/h speeds tested in the current study. A decreased stride frequency has been previously observed in footwear that reduces energetic cost by 4% (Hoogkamer et al., 2018). However, it is unknown if the carbon fibre plate or very compliant midsole material of large stack height is the primary mechanism behind the decreased stride frequency. We speculate that the small magnitude of the increase in observed contact time may be the primary cause of the decrease in stride frequency (Table 2).

Stride length increased with the use of stiffening plates at all three speeds tested (Table 2). At 14 km/h there was an average 4 cm longer stride using the stiff shoe, and an additional 1 cm longer stride using the very stiff shoe. At 17 km/h, stride length was the same for the stiff and very stiff shoe, but 3 cm longer than the normal shoe. We speculate that the increase in stride length may be due to the increase in the percentage of stance that the foot is in propulsion due to the increased LBS (Willwacher et al., 2013), and the subsequent effect on center-of-mass dynamics. Increased prosthetic toe–joint stiffness has been shown to increase center-of-mass push-off work during walking (Honert, Bastas, & Zelik, 2018). An increase in push-time may affect how far the center-of-mass travels anteriorly during stance, the mechanical work performed on it, and its subsequent take-off velocity. Increased push-phase duration during contact would also cause the foot to be positioned slightly more posterior with respect to the pelvis at toe-off, requiring that it be recovered further during swing phase to the next foot contact, increasing stride length. Both factors may contribute to the observed 3–5 cm increase in stride length at 14 and 17 km/h.

Interestingly, at 20 km/h, average stride length was the same for the normal and very stiff shoe, but 4 cm longer using the stiff shoe. While there were no changes in horizontal ground reaction force impulses between shoe conditions to explain the differences in stride length, there may be changes in joint level angular impulses in response to varying LBS (Oh & Park, 2017). During running, the ankle plantar flexors tend to act in a nearly isometric range, resulting in the Achilles tendon generating the majority of positive work (Lai, Schache, Lin, & Pandy, 2014). With increased footwear stiffness though, greater muscle force and ankle plantar flexor moment is required to overcome the stiff plates (Willwacher et al., 2014). However, increased LBS may provide a mechanism to increase required muscle force by altering ground reaction force gear ratios and slowing plantar flexor contraction velocity (Takahashi, Gross, Van Werkhoven, Piazza, & Sawicki, 2016). At the 20 km/h running speed, increased concentric contributions of the ankle plantar flexors in addition to the Achilles tendon contributions may have been required to overcome the very stiff shoe. Ankle plantar flexor fascicle shortening velocity may have been fast enough that it resulted in a large enough decrease in force generation capability that they were unable to generate enough force to overcome the very stiff shoe compared to the normal and stiff shoe. This may explain why contact time for the very stiff shoe was longer than the normal shoe, yet participants elicited the same stride length. The increased contact time may have been necessary to maintain propulsive impulse due to a compromised ability to generate a large enough ankle plantar flexor moment to overcome the very stiff shoe (Willwacher et al., 2014).

Peak propulsive ground reaction force decreased at all three speeds with increased LBS, in support of previous observations (Flores, Delattre, et al., 2019). The decrease in peak propulsive force is most likely due to reduced MTPJ dorsiflexion influencing a more vertical orientation of the resultant ground reaction force. Horizontal forces are metabolically costly to generate, and thus if running speed can be maintained by decreasing the required posteriorly oriented force or time to generate such force, this could be a mechanism which could contribute to metabolic savings (Chang & Kram, 1999). However, the magnitude of difference in peak propulsive force is relatively small (15–20 N) and thus may have a negligible effect. There were also no changes in braking or propulsive impulses, most likely due to the increased contact time that

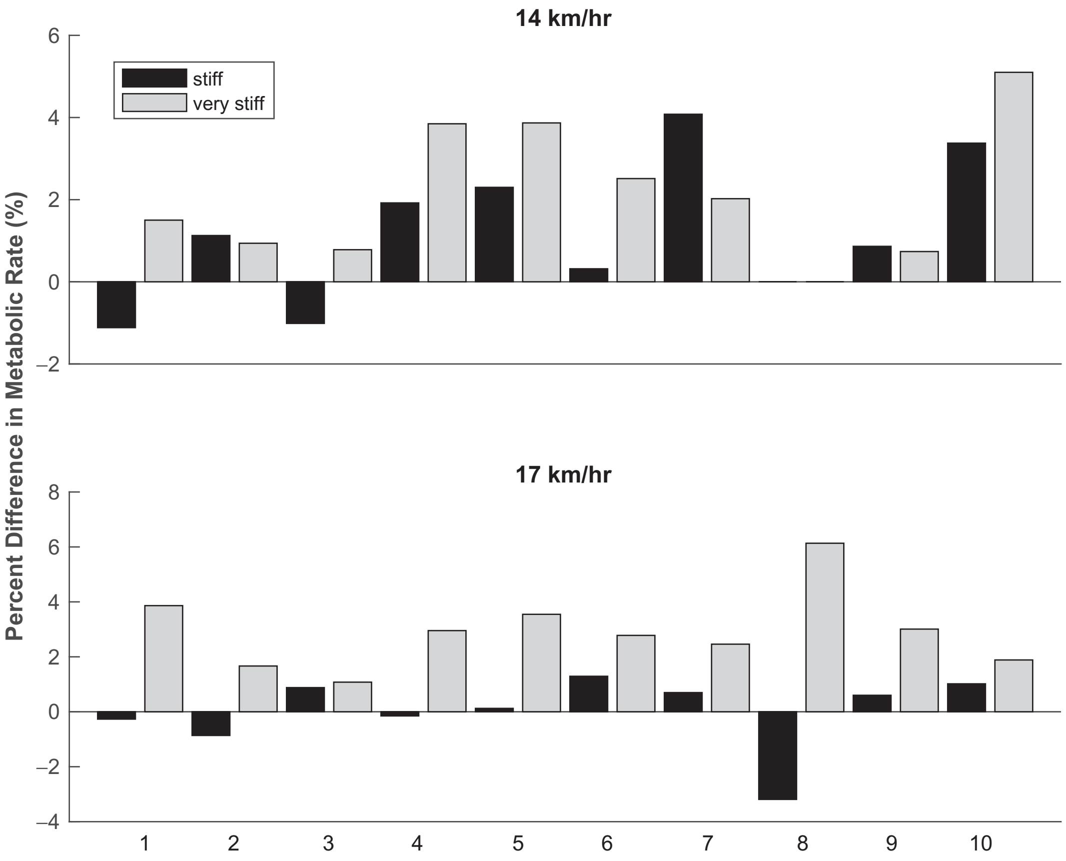

Figure 3. Individual participant differences in metabolic rate (W/kg) expressed as percent difference relative to normal shoe condition. Top is at 14 km/h ($n = 9$), bottom is at 17 km/h ($n = 10$). Participant number is denoted on the x-axis.

accompanied the decreased peak propulsive force. When the stiff plate snaps back to maintain shape during late stance after being deflected due to MTPJ dorsiflexion, it may offload a large enough magnitude of the required horizontal propulsive forces to influence a decrease in metabolic cost.

Increasing LBS affected metabolic rate at both speeds. One characteristic that is most likely influencing this observation was the difference in shoe mass as a result of the stiff plates. The stiff and very stiff shoes weighed 50 and 100 g more than the normal shoe (Table 1), most likely influencing a difference in energy cost by 0.5 ∼ 1.0% (Franz et al., 2012; Frederick, 1984; Hoogkamer et al., 2016). Because modern marathon racing shoes weigh 200 ∼ 250 g (Hoogkamer et al., 2018) we felt it unreasonable to add mass to make all shoes 350 g as participants in our study are most likely accustomed to running as faster speeds in lighter weight shoes. These differences in shoe mass should be explored in further detail at the paces examined in the present study.

At 14 km/h, seven of nine participants were most economical in the normal shoe (Figure 3). This is similar to previous studies showing that at a pace reflective of a normal training run, metabolic cost increases in an overly stiff shoe (Oh & Park, 2017; Roy & Stefanyshyn, 2006). This trend changed at 17 km/h, however, where 4 of 10 participants exhibited a lower metabolic rate wearing the stiff shoe, and three more were within 1.5% (Figure 3). For those participants that did not show a minimum energetic cost in the stiff shoe at 17 km/h, the percentage difference in metabolic rate between the stiff and normal shoes was less at 17 km/h than at 14 km/h.

Participants' body mass was measured in-between each running trial to account for any change due to sweat loss or difference in shoe mass. Total mass fluctuated ∼0.1 kg between wearing the normal and very stiff shoe, entirely due to non-metabolically functioning mass. Thus, based upon the 1% increase per added 100-g theory (Frederick, 1984), it may be reasonable to extrapolate that the mechanism of increased LBS at 17 km/h may be more influential than the results show. If mass were equalized between shoes, or if a lighter material such as carbon fibre were used to make the stiffening plate, then perhaps the group mean improvement using the stiff shoes at 17 km/h would be even more pronounced. While changes in energetic cost are linear with increased weight, a limitation to this speculation is that the smallest change in weight tested in previous studies is 75 g. Thus, it is unknown if a 50 g increase in mass truly results in a 0.5% increase in energetic cost. Although metabolic rate pairwise comparisons were not significantly different between the normal and stiff shoe, the individual responses are what should be taken into consideration. A larger participant population would be of benefit to help address what characteristics determined individuals being a responder vs. non-responder to the stiff plates, as previously observed (Madden et al., 2015; Roy & Stefanyshyn, 2006).

The influence of LBS on subjective comfort appears to be speed dependent (Table 4). The main factors contributing to perceived comfort differences were forefoot cushioning, flexibility, and weight. The plates were placed directly underneath the insole, as opposed to being embedded in the midsole as in Hoogkamer et al. (2018). This is most likely the reason why the stiff plates were not preferred in regard to forefoot cushioning comfort. The very stiff condition was the worst rated for perceived flexibility comfort at both 14 and 17 km/h. This likely had an influence on the greater metabolic cost using this shoe (Luo et al., 2009). While across-speed comparisons were not statistically analyzed, average comfort for flexibility of the normal shoe was slightly worse at 17 km/h, increasing in score from 2.2 to 2.8, and slightly improved for the stiff shoe from 2.2 to 2.0. On an individual basis, four participants thought the flexibility of the stiff shoe was more comfortable at 17 km/h, four reported no change, and only two perceived it as worse. For the normal shoe, five participants thought the flexibility was worse at 17 km/h, three reported no change, and only two participants thought it was better. These subjective comfort results suggest that when designing shoes for faster running, they should be lightweight, soft in the forefoot, and stiffer than a conventional training shoe. We speculate that the reason for the preferred increase in stiffness is related to the increase in MTPJ moment and stiffness with running speed (Day & Hahn, 2019). It is likely that runners desire a stable or propulsive feeling from the shoe during push-off, as opposed to an overly flexible shoe that feels like it may be dissipating energy, or not contributing as much torque to push-off as it could, without inhibiting the runner's natural or preferred movement path or having to fight the overly stiff shoe.

A limitation to this study is that it is unknown how individuals will respond to greater LBS under fatigued conditions. Increasing LBS results in greater stress on the ankle plantar flexor muscle-tendon units (Willwacher et al., 2014). Without adequate strength or fatigue-resistance to maintain mechanics similar to those experienced in a non-fatigued state, detrimental compensations such as increased contact time or forward lean may occur (Willwacher et al., 2014). Additionally, positive joint work contributions shift from distal to proximal throughout the course of a run (Sanno, Willwacher, Epro, & Brüggemann, 2018). Secondly, in this study there was no longitudinal adaptation period. Because this study used very well trained distance runners (average 5000 m personal best 15:04), and it has been demonstrated that runners quickly adjust their mechanics to changes in surface stiffness (Ferris, Liang, & Farley, 1999), we feel that this may not necessarily be a limitation but is worth bringing to attention. It is worth noting, however, that participants could have experienced potential learning effects of running in plated footwear due to the 2-h duration of the study. Third, our location of the plates directly underneath the sock-liner may affect biomechanics differently than plates embedded within the midsole (Flores, Rao, Berton, & Delattre, 2019). It is also worth noting that running economy assessments were performed on a treadmill set to 1% grade, whereas biomechanical data were collected on a level treadmill. There may be changes in spatiotemporal parameters or joint level biomechanics between settings. It has also been assumed that the change in LBS is the mechanism responsible for the observed changes in gait mechanics, but the added mass of each plate or the additional 3 mm of height per plate could influence changes in mechanics as well. Lastly, due to the constraint of needing to find participants who were sub-maximal at 17 km/h and able to fit a male size 10 shoe, our participant numbers were limited. A *post-hoc* power analysis (G*Power) using the effect size from the VO_2 results ($\eta^2 = 0.565$) as input revealed a statistical power of 0.997 and a total required sample size of 6, ensuring our participant population of 10 resulted in adequate statistical power. However, more participants of varying foot strike patterns, anthropometrics, etc. would allow for potential advanced statistical methods such as a cluster or principal component analysis to identify characteristics that influence how someone responds to the increased LBS footwear.

Altogether, this study provides evidence that changes in spatiotemporal variables, metabolic cost, horizontal ground reaction forces, and subjective comfort arising from altering LBS are running speed dependent. Our results demonstrate that changes in LBS influence a reorganization of stride length and stride frequency, highlighting the complex interaction between internal and external factors that contribute to optimisation of energetic cost during running (Cavanagh & Kram, 1985; Cavanagh & Williams, 1982). We suggest that for footwear engineered for athletes with specific goal race paces, LBS should be heavily weighted both from a metabolic and perceived comfort standpoint.

Disclosure statement

No potential conflict of interest was reported by the authors.

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