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The influence of a new sole geometry while running

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Abstract

Running shoe construction influences the forces experienced by the human body while running. The aim of this study was to ascertain whether the new sole architecture of the *On* running shoe reduces ground reaction forces compared with running barefoot or with a conventional running shoe and whether it changes the physiological parameters of running in shoes. Thirty-seven trained male participants were studied while running at submaximal speeds wearing their conventional running shoe, wearing the *On* running shoe and while barefoot. Additional biomechanical and physiological values were investigated to determine whether the *On* running shoe induced any changes in these parameters compared with conventional running shoes. The *On* exhibited similar ground reaction forces as conventional shoes, and these were different from the forces experienced while running barefoot, showing that the *On* was more similar to typical shoed running. No difference was observed in running economy between the *On* and a conventional shoe model. However, a slightly lower heart rate (HR) (≈1.3%) and blood lactate concentration (≈5.5%) were observed during submaximal running with the *On* running shoe compared with a conventional running shoe, as well as a greater lateral deviation of the centre of pressure mid-stance. The ramifications of the reduced HR and blood lactate concentration for competitive performance are unknown.

Keywords: *running shoe design, ground reaction force, running economy, heart rate, running performance*

Introduction

A portion of modern society is becoming increasingly health-conscious, with a growing trend of incorporating activity into daily life (Lieberherr, Marquis, Storni, & Wiedenmayer, 2010). Running is a convenient exercise modality for the prevention and rehabilitation of health problems over a wide age range (Chakravarty, Hubert, Lingala, & Fries, 2008; Ravindran, Annida, Parthiban, & Sekarbabu, 2010). Understanding the physiology and biomechanics involved in running is important to athletes, researchers and sport shoe manufacturers (Novacheck, 1998). In healthy humans, running seems to be a highly reproducible movement because the physiological timing follows a certain pattern that is controlled on a subconscious level (Inman, Ralston, & Todd, 1981; Kramers-de Quervain, Stüssi, & Stacoff, 2008; Rose & Gamble, 1994). *On* (On AG, Zollikon, Switzerland, www.on-running.com), a new small shoe company, recently developed a new sole architecture called the CloudTec^{TM} system, which was designed based on the findings of Anderson (1996) to reduce ground reaction forces during running and potentially improve running economy as a result. Ground reaction forces determine the motion of the centre of mass during the stance phase of running. Vertical body movements and changes in horizontal velocity account for an energy expenditure of 0.6–0.7 horsepower at running speeds of 7.68–8.27 $m \cdot s^{-1}$ (Fenn, 1930). As summarised by Nigg (2009), barefoot running increases the external vertical loading rate and leads to an earlier impact peak compared with shoed running (de Wit & de Clercq, 2000). The fact that a change to the sole can influence running economy was shown by Roy and Stefanyshyn (2006). Specifically, their study showed that increasing the midsole longitudinal bending stiffness improved running economy. Additionally, a change in the lateral stability was observed for different sole designs (Stacoff, Steger, Stüssi, & Reinschmidt, 1996). These authors state that a larger lever arm of the centre of pressure (COP) increases the torque on the ankle joint, thus increasing the risk of injury.

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From a physiological point of view, successful long-distance running is determined by three factors: maximal oxygen consumption, the percentage of maximal oxygen consumption that can be sustained for a given distance and running economy. In a heterogeneous group of participants, running performance is correlated with maximal oxygen consumption. In a homogeneous group of runners (similar maximal oxygen consumption), those who can sustain a high fraction of maximal oxygen consumption will be faster. Additionally, running economy accounts for a large and significant amount of variation in performance (Conley & Krahenbuhl, 1980). Running economy is often expressed as either the relative oxygen consumption (ml^{-1} kg . min) needed to run at a given velocity or the oxygen consumption consumed when covering a given distance (ml^{-1} kg · min). Williams and Cavanagh (1987) identified biomechanical variables that showed significant differences between groups separated based on submaximal oxygen consumption.

Recently, Fletcher, Esau, and Macintosh (2009) showed that the caloric unit cost, which includes substrate utilisation and is normalised by distance, is a more sensitive expression for running economy than changes in speed. Furthermore, Kyröläinen, Belli, and Komi (2001) did not find an exclusive biomechanical parameter but did identify high braking forces as the main factor explaining running economy. The total vertical momentum and the net vertical momentum were significantly correlated with running economy (Heise & Martin, 2001). Applying an extra horizontal force, Chang, Huang, Hamerski, and Kram (1999) found that at a constant running speed, generating a horizontal force accounts for more than one-third of the metabolic costs. Recently, an intervention study by Moore, Jones, and Dixon (2012) showed that changes in running mechanics resulting from a 10-week running program impact running economy.

The aim of this study was to analyse the influence of the new cushioning system of the *On* running shoe (*On*) on the biomechanics experienced during running compared with those experienced with individual conventional running shoes (sh) and barefoot running (bf). Furthermore, this study assessed whether the new sole geometry would influence decelerating forces, vertical and horizontal momenta, and physiological parameters and thus measurably improve running economy compared with conventional shoes.

Methods

Participants

In total, 37 male participants with an average age of 36.1 ± 7.6 years, a height of 180.6 ± 6.6 cm, and a body mass of 72.3 ± 6.9 kg completed the study. The inclusion criteria were an average running speed of 13.5 km · h^{-1} over a distance of 10 km, completion of a weekly training distance of >40 km, male gender, age between 20 and 50 years and good overall health (based on a health questionnaire given to the participants). The athletes were familiar with running on a treadmill. The study was approved by the Ethical Committee of the ETH of Zurich. After receiving detailed information about the study, each participant provided informed written consent.

Shoe

The new sole geometry of the *On* (Figure 1) includes deformable open cells in the sole. The manufacturer postulates that these cells should absorb harmful horizontal and vertical impacts and enable a "barefoot take-off". The average mass of the *On* in this study was 343 ± 30 g (range 302–410 g), and the average mass of the conventional shoes in the sh group was 345 ± 48 g (range 275–479 g). Each participant received a pair of *On* at least 2 weeks before the first test to break them in. For the sh measurements, participants used their own conventional running shoes. This set-up was chosen to study whether runners experienced any benefit by changing from their own conventional shoes to the *On* with the new sole design.

Measurements

The ground reaction forces experienced while running were measured bf, with conventional sh, and with *On*. Because all participants were accustomed

Figure 1. The *On* running shoe with a novel sole design incorporating deformable open structures.

to running with shoes, we refrained from testing bf running on the treadmill to prevent overuse or injury. Each participant performed an incremental test to exhaustion on the treadmill (pulsar 3p, HP cosmos, Traunstein, Germany), followed by two submaximal tests (one with sh, one with *On*), with most tests performed within a 3-week period. The two submaximal treadmill tests were completed in a random order on different days at the same time of day.

Gait analysis

After their anthropometric data were collected, the participants warmed up by running for 5 min. The measurements of the ground reaction force in the three conditions were randomised. For each condition, at least five valid trials, including at least one double step, were recorded at a speed chosen by the subject. The measurement set-up consisted of five force plates (two type 9281B, two 9285B, and one 9281C; KISTLER Instrumente AG, Winterthur, Switzerland) belonging to the movement analysis lab of the Institute for Biomechanics, ETH Zurich (Dettwyler, Stacoff, & Stüssi, 2003). The dimensions of each plate were 400 x 600 mm^2, and the measurement frequency was 2 kHz. To supervise the measurements, all trials were video-recorded from a frontal view. No differentiation between strike patterns was introduced, because only the general changes of the ground reaction forces were of interest in this study.

Treadmill tests

Ventilation, oxygen consumption and carbon dioxide production were continuously measured breath-by-breath (open system) using a spirometry system (Oxycon Pro, Viasys Healthcare, Würzburg, Germany). Heart rate (HR) was recorded using a RS800CX device (Polar, Kempele, Finland). Measurements of step frequency and step length were performed with a running sensor (S3 affixed to the left running shoe; Polar, Kempele, Finland) and transferred to the HR monitor. Blood samples of 20 μl were taken from the earlobe, and blood lactate concentration was subsequently analysed enzymatically and amperometrically with a BIOSEN C_line Sport® analyser (EFK-diagnostics, Barleben, Germany). Periodically, participants rated their perceived level of exertion during treadmill tests using the CR10 scale (Borg & Kaijser, 2006). During all treadmill tests, the runners wore a security belt to prevent falls.

The incremental test to exhaustion was performed purely to determine peak velocity (v_{peak}) as a baseline. The treadmill speed was set to 9 km · h^{-1} for 5 min, and the velocity was then increased by 1.5 km · h^{-1} every minute until volitional exhaustion. The incline of the treadmill was set at 1% during all tests to compensate for air resistance (Jones & Doust, 1996). The submaximal test began with a warm-up at 50% v_{peak} for 5 min, and the speed was then increased to 60% and 70% of v_{peak} for 15 min each. Every 5 min at 60% and 70% of v_{peak}, participants rated their perceived level of exertion, and blood samples were collected.

Statistics

Data analysis. The force plates were calibrated as previously described (Lorenzetti et al., 2012). The coordinate system of the force plates was defined as follows: *x* represents the medio/lateral direction, with positive values corresponding to the right; *y* represents the gait direction; and *z* is in the vertical direction (Figure 4). The ground reaction forces, especially *fy max dec*, were analysed according to Stüssi (1977) and Stüssi, Aebersold, and Debrunner (1978) (Figure 2) and normalised to BW. The force loading rates (*LR_c*1) and the decay rate (*DR_c*2) before take-off were calculated between 50 N to BW + 50 N and normalised by BW. To describe the path of the COP, *dist x max* was chosen, the maximal lateral deviation from the longitudinal axis of the COP (Figure 4). Additionally, the decelerating horizontal forces in the running direction, *fy max dec*, and the time and momentum integrals, *integral fz tot, integral fz net* and *integral fy tot*, were calculated for the stance phase. The *integral fy tot* is the sum of the deceleration momentum against the running direction at the beginning of the stance

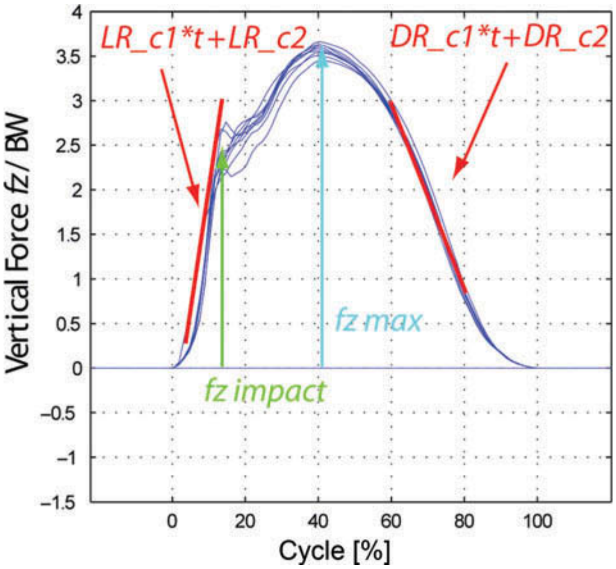

Figure 2. Nine stance phases of a participant. The kinetic parameters were defined as the force loading and decay rates, *LR_c*1 *and DR_c*1, respectively, and the maximal vertical force, *fz max dec* (Stüssi, 1977; Stüssi et al., 1978).

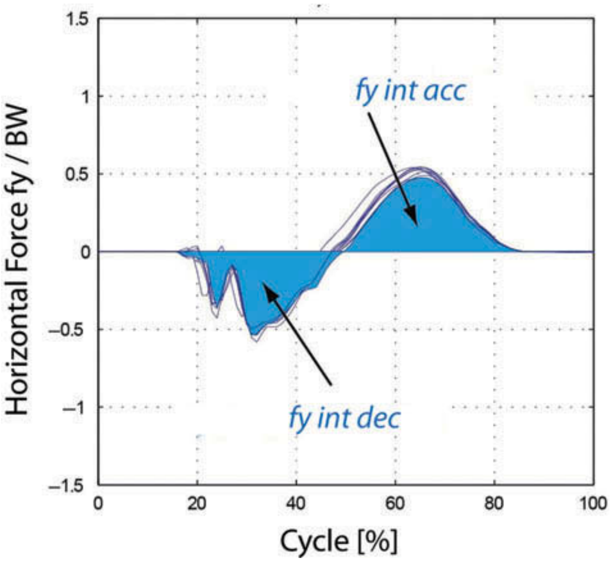

Figure 3. Forces in the running direction for the nine stance phases of a participant. The area under the curve represents the time integral, the momentum during the deceleration phase (*integral fy int dec*) and the momentum during the acceleration phase (*integral fy acc*) (Stüssi, 1977; Stüssi et al., 1978).

phase (*integral fy dec*) and the acceleration momentum in the running direction at the end of the stance phase (*integral fy acc*) (Figure 3). These parameters were averaged over at least five valid trials. All calculations were performed using MATLAB® version 7.9 (The MathWorks Inc., Natick, MA, USA).

The v_{peak} was calculated as follows: $v_{\mathrm{com}} + (t/60\ \mathrm{s} \times 1.5\ \mathrm{km\ h^{-1}})$, where v_{com} corresponds to the velocity of the last completed step and t refers to the time of the last incomplete step. Maximal oxygen consumption represents the highest average of 15 breaths, and $\mathrm{HR_{max}}$ was determined to be the highest HR value recorded over a 5-s period. HR data were read and processed using the software Polar Trainer 5 (Polar, Kempele, Finland). The averages of three 30-s periods (at the end of every 5 min) of HR, ventilation, oxygen consumption and step analysis were calculated for both 60% and 70% of v_{peak}. The means of the three blood lactate measurements and the ratings of perceived exertion were also determined. Running economy represents the caloric unit cost and was calculated as $\mathrm{kcal \cdot kg^{-1} \cdot min^{-1}}$, where kcal equals the product of oxygen consumption and the caloric equivalent.

Statistical analysis. A Kolmogorov–Smirnov test was performed to ensure a normal distribution. A two-sided paired *t*-test was used to determine significant differences between groups during the treadmill test. In gait analysis, a one-way repeated measures ANOVA was applied (SPSS, version 19, Chicago, IL, USA). Pearson's correlation coefficient was computed to investigate the relationship between various parameters. Furthermore, the Cohen's effect size was determined. The correlation between the ground reaction force and running economy was determined (although no significant difference was found) to observe individual changes, because all participants completed the sh trial with their own preferred shoes. To consider the day-to-day variation in physiological parameters, the coefficient of variation (CV) of individual data was determined. Individual changes in HR, depending on footwear, were estimated by defining a realistic threshold for actual changes of 1.5 times the CV, defined as the standard deviation relative to the mean (Hopkins, 2000). Lamberts and Lambert (2009) and Lamberts, Lemmnik, Durandt, and Lambert (2004) reported the lowest HR CV to be 1.4% at an intensity eliciting 85–90% $\mathrm{HR_{max}}$. Thus, an individual relative difference of > ±2.1% was assessed as an actual change, whereas relative differences within ±2.1% were assigned to diurnal variations and therefore were treated as negligible. The level of significance was defined as $P < 0.05$.

Results

The maximal deceleration ground reaction force was increased and the vertical ground reaction force was decreased during bf running compared with shoed (sh and *On*) running (Table I). The load rates (*LR_c*1) and the decay rate (*DR_c*1) were only different between shoed and bf running. Bf running resulted in a less vertical total and net momentum (Table II). No significant differences were observed in the maximum forces and momenta between the two shoed conditions or in the horizontal momentum between the bf and shoed conditions. The *On* yielded the largest lateral deviation of *dist x max* (Table III). Additionally, the COP paths are visually distinct between conditions (Figure 4). The differences between shoed and bf running are larger than those between the two shoe conditions. The average running speed was $3.8\ \mathrm{m \cdot s^{-1}}$ with a typical standard deviation of $0.6\ \mathrm{m \cdot s^{-1}}$ between subjects and $0.2\ \mathrm{m \cdot s^{-1}}$ within tests for a single subject.

There was no difference in running economy at submaximal intensities between the sh and *On* conditions (Table IV). Furthermore, no correlations were detected in individual differences between the sh and *On* conditions in forces and running economy (RE) (△*fy max dec* sh-*On* vs. △RE sh-*On*: $y = 0.032x + 0.005$, $R^2 = 0.0004$, ns.; △*integral fy dec* sh-*On* vs. △RE sh-*On*: $y = 0.416x + 0.005$, $R^2 = 0.001$, ns.; △*integral fz tot* sh-*On* vs. △RE sh-*On*: $y = 0.004x + 0.006$, $R^2 = 0.000$, ns.; △*integral fz net* sh-*On* vs. △RE sh-*On*: $y = -0.558x + 0.007$, $R^2 = 0.005$, ns.).

The stance time was shorter for bf running (0.22 ± 0.02 s) than for shoed running

Table I. Normalised parameters of the ground reaction force including corresponding *p*-values and Cohen's effect size *d*. *Fz max* is the maximal vertical normalised force, *fy max dec* is the maximal braking force, and *LR_c*1 and *DR_c*1 are the vertical loading and decay rates, respectively. Values marked with * indicate significant differences.

Condition		*fz max* *[BW]*	*fy max dec* *[BW]*	*LR_c*1 *[BW/s)]*	*DR_c*1 *[BW/s]*
bf		2.77 ± 0.24	0.39 ± 0.07	61.0 ± 51.1	−9.9 ± 2.1
On		2.83 ± 0.24	0.37 ± 0.06	22.3 ± 4.7	−8.5 ± 1.5
sh		2.82 ± 0.24	0.37 ± 0.06	21.6 ± 5.7	−8.6 ± 1.5
bf*On	***P***	**< 0.000***	**0.001***	**< 0.000***	**< 0.000***
	d	0.24	0.30	1.07	0.79
bf*sh	***P***	**< 0.000***	**< 0.000***	**< 0.000***	**< 0.000***
	d	0.22	0.34	1.09	0.73
***On*sh**	***P***	0.580	0.530	0.159	0.219
	d	0.02	0.04	0.14	0.06

Note: bf = barefoot, sh = conventional shoe, *On* = *On* running shoe.

Table II. Normalised vertical and horizontal momentum parameters including corresponding *p*-values and Cohen's effect size *d*. *Integral fy tot* is the momentum in the gait direction over the entire standing phase, *integral fy dec* and *integral fy acc* are the braking and accelerating momentum in the gait direction, respectively, *integral fz tot* is the total momentum against gravity, and *integral fz net* is the net momentum against gravity. Highlighted values indicate significant differences.

Condition		*integral fy tot* *[BW. s]*	*integral fy dec* *[BW. s]*	*integral fy acc* *[BW. s]*	*integral fz tot* *[BW. s]*	*integral fz net* *[BW. s]*
bf		0.004 ± 0.010	−0.055 ± 0.008	0.058 ± 0.007	0.345 ± 0.047	0.081 ± 0.017
On		0.003 ± 0.011	−0.054 ± 0.008	0.057 ± 0.007	0.375 ± 0.022	0.088 ± 0.016
sh		0.004 ± 0.012	−0.053 ± 0.008	0.057 ± 0.008	0.374 ± 0.022	0.088 ± 0.017
bf*On	***P***	0.556	0.449	0.115	**< 0.000***	**0.001***
	d	0.06	0.07	0.16	0.82	0.41
bf*sh	***P***	0.855	0.159	0.091	**< 0.000***	**< 0.000***
	d	0.02	0.15	0.19	0.78	0.45
***On*sh**	***P***	0.637	0.287	0.654	0.325	0.320
	d	0.03	0.07	0.03	0.05	0.05

Note: bf = barefoot, sh = conventional shoe, *On* = *On* running shoe.

Table III. The maximum lateral deviation of the path of the centre of pressure [mm], corresponding *p*-values and Cohen's effect size *d* are given. Highlighted values indicate significant differences.

Condition		*dist x max R* [mm]	*dist x max L* [mm]
bf		14.05 ± 18.70	−11.71 ± 18.24
On		26.46 ± 8.74	−26.51 ± 8.30
Sh		22.34 ± 10.60	−22.84 ± 9.78
bf*On	***P***	1.04	**< 0.000***
	d	0.85	1.04
bf*sh	***P***	**0.009***	**0.001***
	d	0.54	0.76
***On*sh**	***P***	**0.006***	**0.003***
	d	0.42	0.40

Note: bf = barefoot, sh = conventional shoe, *On* = *On* running shoe, *dist x max R* = right foot, *dist x max L* = left foot.

(0.23 ± 0.02 s) in both conditions ($P < 0.05$). Because the differences were small, these parameters were not normalised. No differences were observed in the step frequency upon gait analysis. The stride length was shorter during the bf condition (bf: 1.25 ± 0.24 m, sh: 1.36 ± 0.23 m, *On*: 1.39 ± 0.21 m, $P < 0.05$). The freely chosen velocities observed during the gait analysis were 3.68 ± 0.72, 3.82 ± 0.64, and 3.91 ± 0.59 $\text{m} \cdot \text{s}^{-1}$ for the bf, *On*, and sh conditions, respectively. A significant difference was observed in the chosen velocities between the bf and sh conditions ($P < 0.05$) but not between bf and *On* conditions. The velocity during submaximal running on the treadmill at both 60% and 70% of v_{peak} corresponded to speeds of 3.18 ± 0.19 and 3.71 ± 0.22 $\text{m} \cdot \text{s}^{-1}$ and intensities of 67 ± 5% and 78 ± 6% maximal oxygen consumption and 78 ± 5% and 88 ± 4% HR_{max}, respectively.

At both 60% and 70% of v_{peak}, the *On* condition exhibited a lower HR (−1.3 ± 2.3% and −1.4 ± 2.5%, respectively) and blood lactate concentration (−4.9 ± 13.3 and −6.8 ± 16.0%, respectively) compared with the sh condition, but no measurable differences were observed in ventilation, step frequency, step length and rating of perceived exertion (RPE) between the sh and *On* conditions (Table IV).

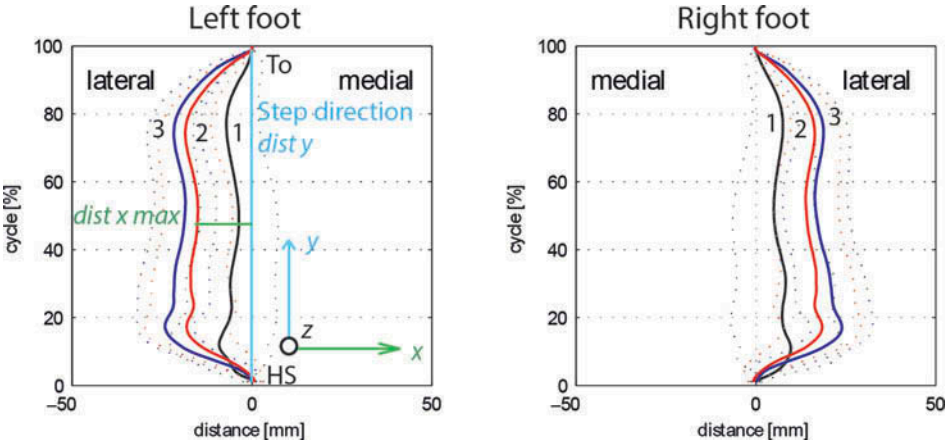

Figure 4. Lateral deviation of the COP for all participants, *dist x*. 1 Black: barefoot; 2 red: conventional; 3 blue: On running shoe. 'To' indicates toe off and 'HS' represents heel strike. The lateral deviation, *dist x*, represents a measure of the mediolateral stability of the foot.

Individual relative differences in submaximal HR between the *On* and sh conditions are illustrated in Figure 5. Based on these individual differences, participants were divided into subgroups according to whether they exhibited a relative difference in HR >−2.1%, called an "advantage", a difference of ≤−2.1% and ≥+2.1%, called "unchanged", or a difference of >+2.1%, called a "disadvantage". A total of 29.7% of the participants benefited from running with the *On*, while 64.8% demonstrated no change in HR and 5.4% had an elevated HR in the *On* condition compared with the sh condition. Differences in HR between sh and *On* conditions correlated with differences in blood lactate concentration at 70% of v_{peak} but not at 60% of v_{peak} (Table V). However, differences in HR were independent of individual running speeds with regard to v_{peak}, RPE and shoe weight (Table V).

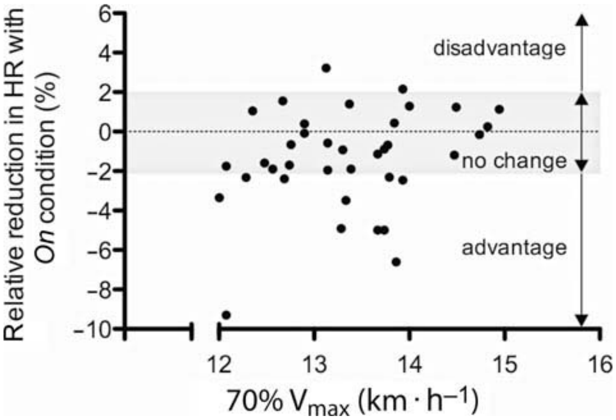

Figure 5. Individual relative differences in submaximal HR between the *On* and the conventional shoe models. "No change": difference in HR of less than 2.1% between shoe models; "advantage": decrease in HR of >2.1% with the *On* compared with the conventional shoe; "disadvantage": increase in HR of >2.1% with the *On* compared with the conventional shoe.

Table IV. Mean ± SD values of physiological parameters during submaximal tests at 60% and 70% of peak velocity (v_{peak}) with conventional and *On* running shoes.

	60% of v_{peak}		70% of v_{peak}	
	sh	*On*	Sh	*On*
Cuc (kcal/kg/km)	1.10 ± 0.11	1.10 ± 0.10	1.11 ± 0.11	1.11 ± 0.10
Heart rate (bpm)	141 ± 11	139 ± 12**	160 ± 12	158 ± 13**
Lac (mmol^{-1}min^{-1})	1.5 ± 0.5	1.4 ± 0.5*	2.7 ± 1.2	2.5 ± 1.1*
VO$_2$ (l · min^{-1})	3.1 ± 0.4	3.1 ± 0.4	3.6 ± 0.5	3.6 ± 0.5
Ventilation (l min^{-1})	70 ± 12	69 ± 10	90 ± 15	89 ± 15
SF (steps · min^{-1})	82 ± 4	82 ± 3	85 ± 4	85 ± 3
Step length (m)	1.15 ± 0.08	1.16 ± 0.07	1.32 ± 0.08	1.32 ± 0.08
RPE	2.9 ± 1	2.9 ± 0.9	4.8 ± 1.4	4.9 ± 1.4

Note: Cuc = caloric unit cost, Lac = blood lactate concentration, VO$_2$ = oxygen consumption, SF = step frequency, RPE = rating of perceived exertion; * Significantly different between the conventional (sh) and the *On* running shoe (*On*), $P < 0.05$, ** $P < 0.01$.

Table V. Correlation between difference in HR (conventional – *On* running shoe) vs. various other parameters at 60% and 70% of v_{peak}.

Difference HR sh – *On* vs.	Intensity (% of v_{peak})	R^2	*P*-value
Difference lac (sh – *On*)	60	0.095	0.063
	70	0.261	0.001
v_{peak}	60	0.001	0.823
	70	0.058	0.152
Difference RPE	60	0.060	0.143
	70	0.012	0.516
Difference shoe weight	60	0.003	0.739
	70	0.004	0.707

Note: HR = heart rate, sh = conventional shoe, *On* = *On* running shoe, lac = blood lactate concentration, v_{peak} = peak velocity, RPE = rating of perceived exertion.

Discussion

The new sole geometry of the *On* yielded no substantial differences in either ground reaction forces or running economy compared with the sh condition. Nevertheless, an increased mediolateral deviation of the COP and a reduced HR and blood lactate concentration during submaximal running were observed in the *On* condition compared with the sh condition. The observed step frequency was similar in each condition during gait analysis, even though runners tend to adopt shorter strides. Shorter strides have already been observed at a running speed of $3.5\ \text{m} \cdot \text{s}^{-1}$ (bf: 1.28 m and sh: 1.33 m (de Wit & de Clercq, 2000)).

Bf running resulted in larger loading and decay rates before take-off compared with shoed running. Damping properties, including sole thickness, affect the rate of force development. As shown in previous studies, the differences between bf and shoed running are larger than those between different styles of shoes for the impact peak, ankle and knee stiffness (Hamill, Russell, Gruber, & Miller, 2011). This study examined the general ground reaction forces acting on the body in relation to change of the joint angles.

The maximal force *fz max*, the anterior–posterior forces, the loading and decay rates and the time integral did not vary between shoes. The range of total vertical momentum measured here is in agreement with the values reported by Heise and Martin (2001). Similar forces and behaviours were observed for bf running and sh running with three different midsole thicknesses (Hamill et al., 2011). As we found no differences in maximal deceleration or vertical forces, in the loading and decay rates, as well as in the decelerating, accelerating and vertical momenta, this study provides no kinetic evidence for a change in running economy between the two shoed conditions. In a study of the braking and push-off phases based on the orientation of the horizontal force, 3D ground reaction force curves, curves of angular velocity and the moments and power of the ankle, knee and hip were all found not to be predictive of running economy (Kyröläinen et al., 2001). This is consistent with previous findings (Williams & Cavanagh, 1987) that no single biomechanical variable or small subset of variables can explain differences in economy, with economy instead related to a weighted sum of many variables.

The path of the COP differed between shoes, with a larger mediolateral deviation observed for the *On*. This greater instability might be a potential injury risk. Dixon (2006) noted that the COP deviation has a low correlation with the range of motion of the rear foot. However, a larger mediolateral deviation can be an indication of decreased lateral stability (Stacoff et al., 1996) of the foot, which may be due to the fact that the sole of the *On* is more flexible or soft. A larger stability demand is normally correlated with increased muscle activity (Nigg, 2009). This implies that runners who are not familiar with *On* need to become accustomed to greater muscular loads. Furthermore, an increased muscle activity normally leads to elevated oxygen consumption (Bigland-Richie & Woods, 1976) and thus an elevated running economy. Because we observed no change in running economy, it is possible that the slightly lower oxygen consumption required for running with the *On* sole could have equalised the slightly higher oxygen consumption due to the increased muscle activity (greater instability) of the entire shoe, or that these small changes were not measurable at all. This is supported by the findings of Kelly, Girard, and Racinais (2011) that foot orthotics reduce muscular activity whereat the changes are too small to alter the aerobic costs.

The correlation between sh – *On* differences in ground reaction force and running economy were analysed. Differences among individuals can be expected because individual shoes have greater deviations in material and cushioning properties from the *On* than other shoes. However, the horizontal ground reaction force was almost equivalent among all shoe models, indicating that no correlation was observed. Due to the fact that the ground reaction force represents the motion of the centre of mass of the entire participant, it is unlikely that a difference will be observed in the pattern of horizontal motion of the centre of mass.

Running economy, measured at submaximal velocities, is representative of race velocities at distances of over 10,000 m (Helgerud, Støren, & Hoff, 2010); therefore, no change in running economy during competition should be anticipated. The unchanged step frequency and the lack of differences between observed ground reaction forces coincide with the finding that running economy remains unchanged between the sh and *On* conditions.

HR was slightly lower at submaximal intensities (60% and 70% of v_{peak}) when wearing the *On* running shoe. At 70% of v_{peak}, the mean relative HR was between 85% and 90% of the $\mathrm{HR}_{\max}$, corresponding to the intensity where Lamberts and Lambert (2009) reported the least day-to-day variation. Furthermore, the relative HR was only slightly below the HR at the maximal lactate steady state (Fontana, Boutellier, & Knöpfli-Lenzin, 2009), and is therefore in accordance with reports of the HR of athletes running distances of 10,000 m and greater. Examination of the individual changes in HR revealed that approximately one-third of the athletes benefited from running with the *On* in the form of a substantially lower HR, while nearly two-thirds exhibited no change and only 2 out of the 37 participants were at a disadvantage while running with the *On*. Neither the individual performance level nor shoe weight exhibited correlations with differences in HR. Thus, the underlying cause of HR reduction in this subset of athletes remains unclear. One possible explanation for the fact that HR was slightly lower while RPE and running economy were similar could be that perceived effort has a stronger connection with oxygen consumption than with HR. Investigating the ways in which this reduced HR may affect performance during competition is beyond the scope of this study, because our primary aim was to investigate physiological differences under conditions of constant velocity. A time trial more closely resembling a competitive environment would have been affected by the mental aspects of competition. Any placebo effect of the *On* can be excluded, as no correlation was observed between HR differences and RPE.

Blood lactate concentration was significantly lower with the *On*, although the reproducibility of the finding of submaximal blood lactate concentration is rather low (CV of 23.9%; Bagger, Petersen, & Pedersen, 2003). Furthermore, athletes with a lower blood lactate concentration value while running with the *On* also had a lower HR at 70% of v_{peak}. This emphasises that some participants achieved a reduced load at the same velocity with the *On* compared with the conventional shoe. Little change was observed in blood lactate concentration at 60% of v_{peak}; therefore, no correlation was observed with differences in HR.

Adults tend to choose a walking and running velocity that optimise the oxygen costs (Holt, Hamill, & Andres, 1991; Holt, Hamill, & Slavin, 1991). The repeatability seems to be greater at self-selected running speed (Kong, Candelaria, & Tomaka, 2009). Furthermore, the self-selected running speed is highly reproducible, and this is why researchers might consider such a set-up when studying overground running mechanics with different foot–ground interface conditions (Kong et al., 2009). In our study, the self-selected running speed during the gait analysis was different between bf and the sh conditions, but not between the shoes and not between bf and *On* conditions. In partial agreement, other authors reported no difference in running speeds between shoed and bf conditions (Kong et al., 2009).

One limitation of this study is that further familiarisation with the new shoe could influence the measured biomechanical parameters. Furthermore, the variation within the sh condition could have been decreased using a standardised shoe. Due to individual variations in running gait, however, a standardised shoe might have different effects on different subjects. The question here is how to separate responders from non-responders. A more powerful statistical analysis might remove some of the weaker significant differences, such as for the variables *fz max*, *fy max dec* and *integral fz net*, but these do not influence the main outcome of this study.

In conclusion, the *On* did not reduce ground reaction forces or running economy during running, when compared with conventional shoes. The kinetic and momentum parameters measured with the *On* are closer to those measured under the sh condition than under the bf condition. However, HR and blood lactate concentration were slightly reduced in the *On* condition, while one-third of the athletes exhibited a significantly reduced HR while running with the *On*. Future studies examining other biomechanical parameters based on the kinematic or muscle activity might help to explain the sources of significant physiological effects.

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