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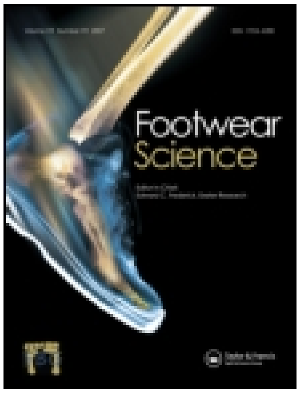
Matthew F Moran, *Sacred Heart University*
Beau Kjerulf Greer, *Sacred Heart University*



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Matthew F. Moran [a] & Beau K. Greer [a]

[a] Department of Physical Therapy and Human Movement Science , Sacred Heart University , Fairfield , CT , USA

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Influence of midsole ‘actuator lugs’ on running economy in trained distance runners

Matthew F. Moran* and Beau K. Greer

Department of Physical Therapy and Human Movement Science, Sacred Heart University, Fairfield, CT, USA

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Introduction: Previous investigations reported the influence of running shoe design on running economy (RE) and determined that both shoe weight and midsole properties (hardness, stiffness, comfort) can alter RE. External forefoot actuator lugs have been reported to provide enhanced energy return during shoe mechanical testing, but it was unclear if this design feature would provide any improvement of RE. The current investigation measured the effects of external forefoot actuator lugs on RE in 12 highly-trained male distance runners during four submaximal running velocities.

Methods: All runners voluntarily completed a maximal graded exercise treadmill protocol followed 5–7 days later by eight randomised 6 min submaximal level-grade treadmill runs with two randomised footwear conditions (WL = with lugs, WOL = without lugs). Oxygen consumption, heart rate (HR), rating of perceived effort (RPE), and sagittal plane high-speed video were collected. RE (metres run per millilitre O_2 per kg of body mass), stance duration (ST), stride rate (SR), and foot strike (FS) were computed for each trial. Data were analysed with factorial repeated-measures analysis of variance (ANOVA).

Results: RE, averaged over all submaximal velocities, was significantly greater ($p < 0.05$) in the WL condition (4.96 ± 0.12 $m \cdot ml^{-1} \cdot kg^{-1}$) as compared to the WOL condition (4.91 ± 0.10 $m \cdot ml^{-1} \cdot kg^{-1}$). Only one subject displayed a lower RE in the WL condition. No significant differences were found between HR ($p > 0.05$), ST ($p > 0.05$), or SR ($p > 0.05$) between footwear conditions, but running in the WL condition lowered RPE ($p < 0.05$).

Conclusions: The presence of external forefoot actuator lugs improved RE by ~1%, although the mechanisms explaining this improvement are not clear.

Keywords: running economy; footwear; performance; running; midsole

1. Introduction

Factors influencing distance running performance have received substantial attention from the footwear, coaching and scientific communities. Despite this interest there exists some uncertainty regarding which factors notably improve running performance and which have only negligible influence. Footwear is typically a controlled variable in laboratory studies as it is well known that several design features (e.g., weight, midsole hardness, midsole bending stiffness, comfort) may influence running energetics (Frederick *et al.* 1982, Frederick *et al.* 1986, Roy and Stefanyshyn 2006, Luo *et al.* 2009). Midsole hardness varies between footwear options from hard minimalist shoes to highly compliant midsoles designed for increased shock absorption. The relationship between midsole hardness and stiffness with energy cost appears to operate as a u-shape curve with an optimal hardness and stiffness producing a minimum of energy expenditure (Bosco and Rusko 1983, Roy and Stefanyshyn 2006). Frederick *et al.* (1986) demonstrated that the energy cost of treadmill running could be reduced by more than 2% through an alteration of midsole hardness and wedge composition. Similarly, Roy and Stefanyshyn (2006) reported approximately 1% energy savings while running with an optimal midsole longitudinal bending stiffness. Even an increased footwear comfort level produced an energy savings of 0.7%, although design differences between the five tested shoe conditions could contribute to these savings as well (Luo *et al.* 2009).

Manipulation of shoe design features for both purported injury concerns and performance gains is not a novel concept within the running footwear community. Many manufacturers tout certain unique alterations, although many of these claims are not subjected to the rigours of scientific testing. Newton Neutral Trainer shoes (Newton Running Company, Inc., Boulder, CO) feature four actuator lugs positioned below the forefoot protruding from the outsole (Figure 1). According to unpublished manufacturer mechanical testing, Newton running shoes lower peak impact forces and increase the energy return ratio as compared to four control shoes (Newton Running – Comparative Mechanical Testing). Caution should be heeded when applying the findings of mechanical shoe testing to overground running

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*Corresponding author. Email: moranm@sacredheart.edu

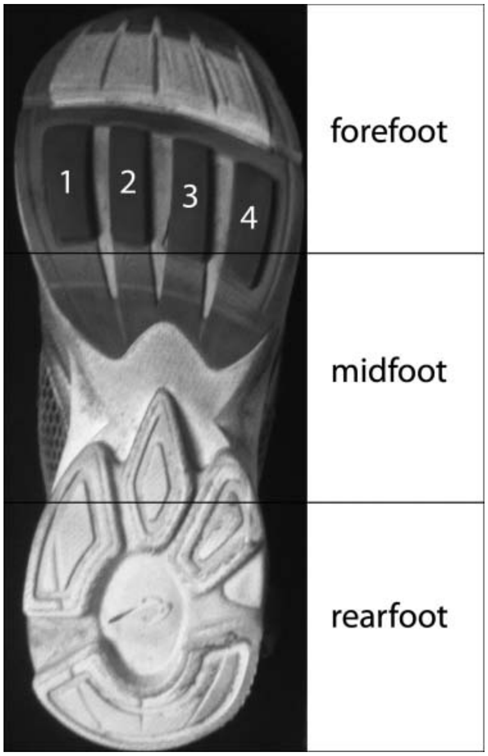

Figure 1. Four actuator lugs positioned in the forefoot of the with lug (WL) footwear condition. These lugs were removed for the without (WOL) condition.

as recovery of stored strain energy in the midsole is dependent on both running kinematics (e.g. foot strike) and velocity (Shorten 1993). Nigg and Segesser (1992) argue that it is not only the proportion of energy return but also the timing of such return that is critical for improving performance. Utilising a finite element modelling approach, Thomson *et al.* (1999) theorised that the amount of actual energy return, afforded by a shoe's midsole, is 3% of the total energetic cost of running and they openly questioned how much of this could actually be translated to an improvement in running economy (RE). RE is generally accepted as the best correlate to distance running performance (Daniels and Daniels 1992). RE, representative of overall energy expenditure, is computed by measuring the steady-state oxygen consumption (VO_2) at a given submaximal running velocity (Morgan *et al.* 1989). In light of these reports, it is difficult to draw conclusions on the efficacy of actuator lugs on improving RE based solely on unpublished mechanical testing.

The current investigation sought to quantify the potential effects of forefoot actuator lugs in the Newton Neutral Trainer shoe on the RE of highly-trained distance runners. A similar investigation that studied the influence of muscle activation and running energetics in two shoes only differing in their heel midsole region properties reported no differences in oxygen consumption (Nigg *et al.* 2003). It was hypothesised that footwear with forefoot actuator lugs as compared to identical footwear without forefoot lugs: (a) would have no significant influence on RE for all submaximal velocities, and (b) would have no significant influence on spatiotemporal gait characteristics (stance duration, stride rate, foot strike).

2. Methods

2.1. *Participants*

Twelve highly-trained male distance runners (age: 23.6 ± 4.2 years; body mass: 66.9 ± 7.7 kg; VO_2peak: 71.8 ± 6.9 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) volunteered for this study following recruitment from local running clubs. All research protocols were approved by the university's institutional review board and all participants granted informed consent prior to data collection. All participants were actively training and were injury-free for six months prior to initial testing. Data collection consisted of two respective sessions separated by at least five days but no more than seven days. The initial collection session measured maximal aerobic capacity (VO_2peak) which was subsequently used to standardise velocity during the second data session. The second collection session consisted of eight running economy trials where running speed and footwear were manipulated.

2.2. *Experimental set-up*

2.2.1. *Footwear conditions*

Two Newton Neutral Trainer footwear conditions were utilised for this study: (1) with actuator lugs (WL), (2) without actuator lugs (WOL) (Figure 2). The lugs are rectangular shaped, approximately 43 × 19 × 5 mm in geometry, and have 62 Shore A hardness. They are housed in separate chambers that allow them to deflect relative to the surrounding outsole. Two identical pairs of footwear were fitted and assigned to each participant. One pair had the actuator lugs removed using a commercial-grade belt sander. Removal was complete when the lug height was flush with surrounding outsole. As a result of lug removal the WOL footwear condition (mass: 240.3 ± 14.3 g) had a lower mass than the WL footwear condition (mass: 254.8 ± 18.8 g). Participants were not permitted to run in either footwear condition prior to data collection to limit any conscious gait retraining. Previous reports have demonstrated that runners can significantly alter gait patterns through an extended gait retraining programme (6–12 wks) (Dallam *et al.* 2005, Diebal *et al.* 2012). No participant reported having trained in any model of Newton running shoes.

Figure 2. Two footwear conditions were used in this study (WL, WOL). The Newton Neutral Racer (WL; mass = 254.8 ± 18.8 g) was modified by removing the forefoot actuator lugs (WOL; mass 240.3 ± 14.3 g).

2.2.2. *Procedures*

All procedures were conducted in the Human Performance Laboratory at Sacred Heart University. On the initial testing day, VO_2peak was assessed for each participant using a standard graded, incremental treadmill (TM) (Trackmaster TMX425C, Newton, KS) protocol. Indirect, open circuit calorimetry (ParvoMedics, Sandy, UT) was used to collect all metabolic data, while heart rate (HR) data were collected via telemetry (Polar Electro, Kempele, Finland). Standard experimental conditions (barometric pressure, humidity, temperature) were maintained within the laboratory during all testing sessions. The same TM was used for all participants across both testing days as alterations of TM compliance had been shown to influence running energetics (Grant *et al.* 1998). Participants wore their preferred footwear during the initial VO_2peak assessment and all were familiar with TM running. No instructions were given as to the how a participant should run and no visual/auditory cues were given throughout either collection session. Following this initial VO_2peak assessment, the same researcher fitted each subject for the Newton Neutral Trainer footwear.

Each participant completed their submaximal RE assessment between 5–7 days following the initial assessment and were instructed to refrain from running or other exercise activities on the day of their second testing session. RE was assessed for each 6 min level grade TM run across four submaximal velocities with a procedure similar to a previous RE study (Daniels and Daniels 1992). In a similar sample of highly trained runners, Brisswalter and Legros (1994) reported that the mean daily variation of RE was not significantly different and had a moderate reliability (r = 0.70). The testing protocol was partitioned into four stages with two 6 min submaximal level-grade TM runs separated by a 5 min passive recovery per stage. Trial duration was chosen to ensure that steady-state was attained during the first 4 min and data collection from the last 2 min. A 4 min period has also been reported to be necessary to stabilise shoe properties (Divert *et al.* 2005). Additionally, it has been reported that alterations to leg stiffness during running are made almost instantaneously when encountering an altered surface condition (Ferris *et al.* 1999). Thus, each participant would total 48 min of running split into eight trials with four trials per footwear condition. The four submaximal TM velocities were individually determined based on the peak aerobic capacity test to ensure similar physiological intensities across participants. Utilising the peak aerobic capacity value, velocities corresponding to 60%, 70%, 80% and 90% intensity were estimated from the following regression equation (Davies and Thompson 1979).

$$\text{SubmaximalVel.}(\text{m}\cdot\text{min}^{-1}) = (xVO_2 + 7.736)^{*}4.202 \tag{1}$$

Averaged across all subjects, submaximal velocities were 3.72 $\text{m}\cdot\text{s}^{-1}$, 4.25 $\text{m}\cdot\text{s}^{-1}$, 4.66 $\text{m}\cdot\text{s}^{-1}$ and 5.03 $\text{m}\cdot\text{s}^{-1}$ respectively.

For each stage, the velocity was randomised and footwear condition order was counterbalanced (Figure 3). Following each trial the participant was re-weighed without shoes. All participants performed a brief TM warm-up run (10–15 min) prior to their first trial, but they were not permitted to wear either of the footwear conditions used in the study.

2.2.3. *Measurements*

RE for each trial was assessed as the number of metres run per millilitre of oxygen consumed per kilogram of body weight (Turner *et al.* 2003). A high-speed camera (Casio EXILIM EX-FS10, CASIO AMERICA, INC, Dover, NJ) (210 Hz) recorded sagittal-plane video during the last 45 seconds of each 6 min trial. Stance duration (ST), stride rate (SR), and foot strike pattern (FS) were determined from frame-by-frame analysis of five random gait cycles

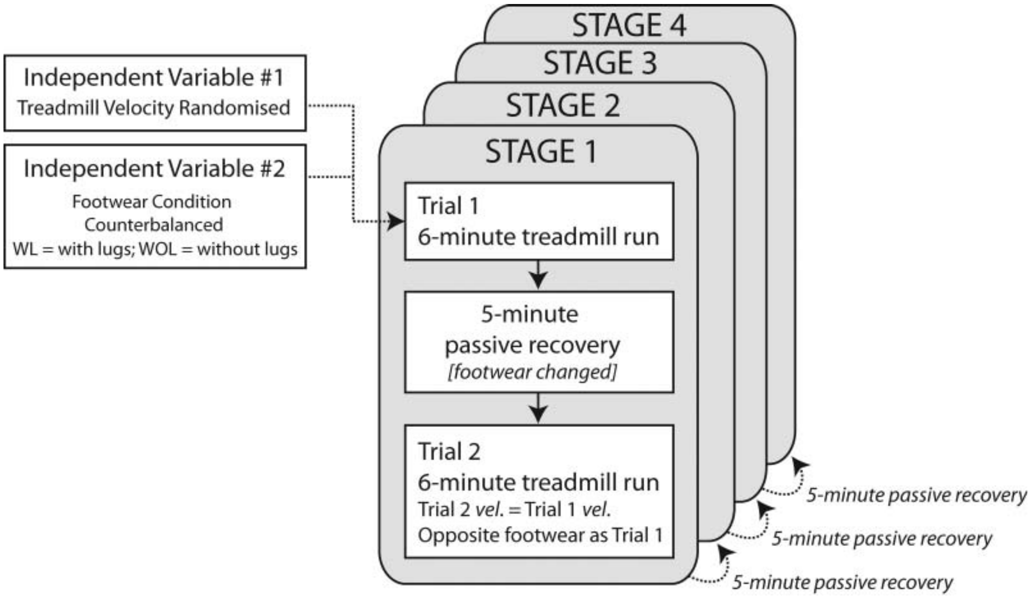

Figure 3. Day two running economy testing protocol.

per trial via video processing software (VirtualDub 1.9.11). FS, determined through visual observation of high-speed video, was classified as rearfoot (RFS), midfoot (MFS), and forefoot (FFS) (Cavanagh and Lafortune 1980, Hasegawa *et al.* 2007). Consistency of TM belt speed was assessed by counting the number of frames required to complete 10 random revolutions from each trial. A small white rectangle (5.72 × 1.27 cm) painted on the TM belt was used to accurately determine each revolution. TM belt speed varied by less than 0.02 $m{\cdot}s^{-1}$ for all paired trials. Ratings of perceived effort (RPE) on a 6–20 scale were self-reported at the conclusion of each trial (Borg *et al.* 1970). HR was continuously recorded during the data collection.

Running economy aggregate curves (oxygen consumption versus running velocity) were plotted for each participant and footwear condition, respectively. Two linear regression equations, one for each footwear condition, were subsequently fit to each curve for each participant (Figure 4) (Daniels and Daniels 1992). These individual regression equations permitted the exact computation of running velocity corresponding to 60%, 70%, 80%, and

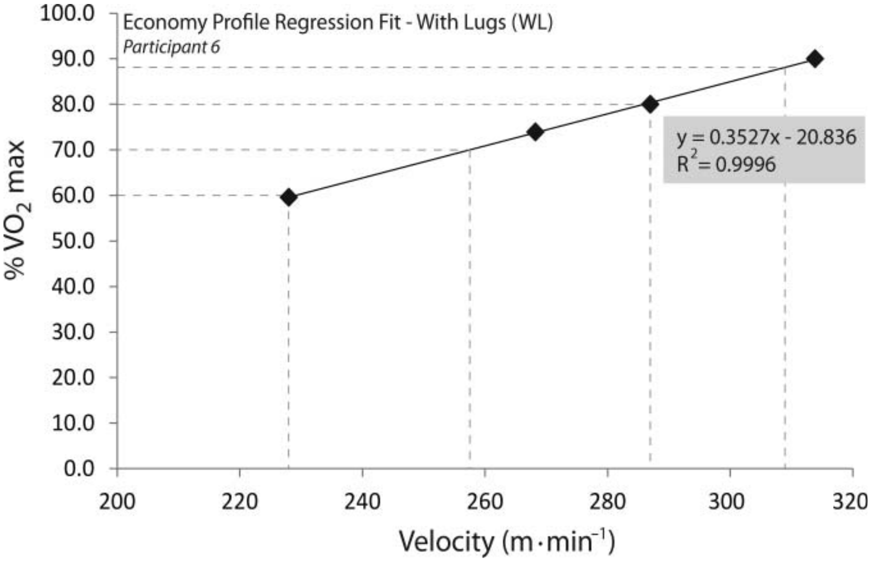

Figure 4. Economy profile regressions were computed for each participant for each footwear condition. Subsequent running velocities were computed for 60%, 70%, 80%, and 90% $\dot{V}O_2$peak.

90% $\dot{V}O_{2peak}$. This additional analysis was only conducted so differences in footwear condition could be reported in terms of running pace (min per kilometre) rather than consumed oxygen.

2.3. Statistical analysis

Experimental design included two independent variables and five dependent variables (RE, HR, RPE, ST, SR). Factorial repeated-measures analyses of variance (ANOVA) were performed to test for statistical significance with a significance level of $\alpha = 0.05$ (PASW Statistics 18; Chicago, IL).

3. Results

3.1. Running economy (RE)

When averaged across all submaximal velocity conditions, RE in the WL condition was 4.96 ± 0.12 m·ml^{-1}·kg^{-1} as compared to 4.91 ± 0.10 m·ml^{-1}·kg^{-1} in the WOL condition (Table 1). In statistically analysing RE, Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of footwear condition and running velocity, $\chi^2 = 23.572$, $p < 0.001$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.429$ for the main effect of footwear). There was a significant main effect of footwear condition ($F_{1,\ 11} = 10.707$; $p < 0.05$) and running velocity ($F_{1.287,\ 14.154} = 9.465$; $p < 0.05$) on RE. Despite the significant effect of footwear condition on RE, the effect sizes (0.22, 0.19, 0.04, and 0.09) were small for each of the respective velocities (60%, 70%, 80%, 90%). There was no significant interaction between footwear condition and running velocity ($p = 0.202$). This indicated that the effect of footwear condition was not influenced by running velocity.

When averaged across all four submaximal velocities and all participants, the WL condition resulted in a −0.95 ± 0.98% improvement in economy (Table 2). Specifically, 10 of the 12 participants were more economical in the WL condition, one participant experienced no change and one participant was more economical in the WOL condition. On average, three participants experienced more than 2% improvement in RE during the WL trials.

3.2. Heart rate (HR) and ratings of perceived effort (RPE)

All participants' HR was below 120 bpm at the beginning of every trial. An ANOVA revealed that there was not a significant main effect of footwear condition on HR ($p > 0.05$), but there was a significant main effect on RPE ($F_{1,\ 11} = 6.557$; $p < 0.05$). This suggests that runners perceived less effort during the WL condition, however, while the finding was significant the effect sizes (0.28, 0.31, 0.07, and 0.07) were small for each of the respective velocities (60%, 70%, 80%, 90%).

3.3. Spatiotemporal variables (ST, SR, FS)

An ANOVA revealed that there was not a significant main effect of footwear condition on ST ($p > 0.05$) or SR ($p > 0.05$). There was a significant main effect of running velocity on ST ($F_{2.408,26.484} = 75.682$; $p < 0.05$) and SR ($F_{1.544,16.982} = 79.642$; $p < 0.05$). This indicated, regardless of footwear condition, that the percentage of time spent in stance phase decreased as running velocity increased and the frequency of strides was

Table 1. Descriptive statistics for running economy (RE), heart rate (HR), rating of perceived effort (RPE), stride rate (SR), and stance cycle% (ST) from 12 participants for 2 levels of footwear condition (WL = with lugs; WOL = without lugs) and 4 levels of running intensity (60, 70, 80, 90%). [Mean ± SD]

Dependent Variable	Footwear	60%	70%	80%	90%	Mean ± SD
RE$_{a,b}$ (m · ml^{-1} · kg^{-1})	**WL**	5.09 ± 0.40	5.01 ± 0.36	4.91 ± 0.41	4.81 ± 0.39	**4.96 ± 0.12**
	WOL	5.01 ± 0.36	4.94 ± 0.35	4.90 ± 0.41	4.78 ± 0.38	**4.91 ± 0.10**
HR (bpm)	**WL**	142 ± 10	160 ± 8	174 ± 7	184 ± 9	**165 ± 18**
	WOL	144 ± 9	161 ± 10	171 ± 10	184 ± 8	**165 ± 17**
RPE (6–20)	**WL**	9.7 ± 1.5	12.3 ± 0.9	14.3 ± 1.2	16.1 ± 1.4	**13.1 ± 2.8**
	WOL	10.1 ± 1.6	12.6 ± 1.2	14.3 ± 1.1	16.2 ± 1.2	**13.3 ± 2.6**
SR (strides·s^{-1})	**WL**	1.45 ± 0.06	1.49 ± 0.06	1.53 ± 0.06	1.56 ± 0.06	**1.51 ± 0.00**
	WOL	1.46 ± 0.07	1.49 ± 0.06	1.53 ± 0.06	1.57 ± 0.06	**1.51 ± 0.00**
ST (%)	**WL**	33.7 ± 3.6	33.3 ± 3.8	32.1 ± 3.5	31.6 ± 3.8	**32.7 ± 1.0**
	WOL	34.0 ± 4.0	33.1 ± 3.7	32.5 ± 4.0	31.6 ± 3.9	**32.8 ± 1.0**

$_a$ = significant main effect for footwear
$_b$ = significant main effect for intensity

Table 2. Running economy, expressed as metres run per millilitre of oxygen consumed per kilogram of body mass ($m\cdot ml^{-1}\cdot kg^{-1}$), averaged across all running velocities for each participant. Ten of the 12 participants were more economical in the with lug (WL) footwear condition. Mass is reported in kg and FS (foot strike) was classified as rearfoot (RFS), midfoot (MFS) and forefoot (FFS). [Mean ± SD]

			Running Economy (RE) ($m\cdot ml^{-1}\cdot kg^{-1}$)		RE Difference	
Part.	Mass	FS	WL	WOL	Absolute	%
1	73.8	MFS	5.94 ± 0.13	5.81 ± 0.10	−0.13	−2.27
2	65.1	RFS	4.74 ± 0.10	4.72 ± 0.13	−0.03	−0.59
3	70.9	RFS	4.37 ± 0.13	4.32 ± 0.11	−0.04	−0.94
4	67.1	RFS	4.80 ± 0.32	4.76 ± 0.31	−0.03	−0.66
5	76.2	RFS	5.04 ± 0.05	5.06 ± 0.10	0.02	0.44
6	80.3	RFS	4.70 ± 0.04	4.56 ± 0.13	−0.14	−2.91
7	68.0	RFS	4.92 ± 0.19	4.88 ± 0.21	−0.05	−0.94
8	55.8	MFS	4.97 ± 0.07	4.93 ± 0.09	−0.04	−0.73
9	62.6	MFS	4.86 ± 0.06	4.83 ± 0.05	−0.03	−0.54
10	68.0	RFS	4.93 ± 0.11	4.93 ± 0.13	0.00	0.00
11	55.2	MFS	4.99 ± 0.31	4.97 ± 0.24	−0.01	−0.29
12	60.1	MFS	5.22 ± 0.11	5.11 ± 0.14	−0.11	−2.03
			4.96 ± 0.12	4.91 ± 0.10	−0.05 ± 0.05	−0.95 ± 0.98

greater as running velocity was increased. Foot strike pattern was invariant due to running velocity or footwear condition. Five participants (42%) demonstrated MFS while the remaining seven (58%) demonstrated RFS. These percentages are similar to foot strike patterns of elite half marathon runners as reported by Hasegawa *et al.* (2007).

3.4. *Running economy aggregate curves*

Individual linear regression equations fit to $VO_{2\text{peak}}$% versus running velocity data were utilised to compute corresponding running velocities at 60, 70, 80, and 90% $VO_{2\text{peak}}$ for each footwear condition. Averaged across all subjects, the WL condition resulted in a faster running velocity by 0.11, 0.07, 0.05, 0.03 $m\cdot s^{-1}$ for 60, 70, 80, and 90% $VO_{2\text{peak}}$ respectively (Table 3).

4. Discussion

The purpose of this study was to determine if forefoot actuator lugs would improve RE as compared to an identical shoe without forefoot actuator lugs during initial exposure to the footwear condition. It was hypothesised that the presence of forefoot actuator lugs would have a negligible influence on both RE and spatiotemporal gait characteristics in trained distance runners across four submaximal velocities. The first hypothesis was rejected as forefoot actuator lugs produced a significant improvement in RE (0.95%) across a range of submaximal velocities. The magnitude of improvement is comparable to previous studies investigating alterations to shoe mass, midsole hardness, bending stiffness, and comfort. There was a small but significant reduction in the perception of effort while wearing the WL shoes, however, no significant differences were noted for HR response or any measured gait characteristic (ST, SR, FS). As it was beyond the scope of this investigation, it is not possible to elicit mechanistic reasons for the reported RE improvement, but it is probable some combination of alteration(s) in (a) lower extremity kinematics, (b) muscle activations and/or (c) increased midsole energy return resulted in the runners' improved efficiency.

Several investigators have explored the alteration of running kinematics in the presence of altered midsole

Table 3. Linear regression equations fit to $VO_{2\text{peak}}$% versus running velocity data were utilised to predict corresponding running velocities at 60, 70, 80, and 90% $VO_{2\text{peak}}$ for each footwear condition. The WL condition resulted in faster running velocities at each intensity.

Intensity ($VO_{2\text{peak}\%}$)	Footwear	Predicted Running Vel. ($m\cdot s^{-1}$)	Mean Pace ($min\cdot km^{-1}$)
60	**WL**	3.70 ± 0.24	4.51
	WOL	3.61 ± 0.29	4.61
70	**WL**	4.20 ± 0.20	3.97
	WOL	4.13 ± 0.25	4.03
80	**WL**	4.71 ± 0.26	3.54
	WOL	4.66 ± 0.23	3.58
90	**WL**	5.21 ± 0.28	3.20
	WOL	5.18 ± 0.25	3.22

properties (McNair and Marshall 1994; Hardin *et al.* 2004; Kersting and Brüggemann 2006). Harder midsoles absorb less impact force causing an increase in maximum knee flexion velocity (Clark *et al.* 1983) and dorsiflexion velocity (Hardin *et al.* 2004) immediately following foot strike. Therefore, it is possible that alterations in the shoe-ground interaction in the current study caused lower extremity kinematic changes that reduced muscular demands and lowered oxygen consumption. Increased joint angular velocities require larger eccentric muscular contractions to control this motion, thus increasing the energy demands for every foot strike. It is possible that the runners in the current study altered their sagittal plane lower extremity kinematics during the actuator lugs condition and this subsequently resulted in decreased oxygen consumption. Although ST and SR were invariant across all speeds and footwear conditions, it is possible that their knee and/or ankle kinematics were influenced by the presence of the actuator lugs. Hardin *et al.* (2004), investigating the influence of midsole stiffness in running, reported a similar finding as their participants had a significant kinematic change (ankle dorsiflexion velocity) with no alterations of ST and SR.

Alteration of lower extremity muscle activity as a factor of midsole stiffness has received conflicting reports. Wakeling *et al.* (2002) reported that six runners altered their muscle activations in a subject-specific manner while completing a 30 min run in two different midsole conditions (61 Shore C, 41 Shore C). Variation of the electromyography (EMG) frequency ratio suggested that muscle fibre type recruitment pattern was sensitive to midsole stiffness. These findings were corroborated in a later study that reported subject-specific muscle activity alterations while running in two shoes only differing in their heel midsole properties (Nigg *et al.* 2003). Although these runners demonstrated an altered muscle response, their oxygen consumption was invariant between shoe conditions. Nigg and Gérin-Lajoie (2011) more recently reported that both pre- and post-heel strike lower extremity muscle activities were unaltered during a 30-m run with three different midsole conditions in a large sample of recreational runners. The investigators speculated on whether increased habituation to a footwear condition may cause long-term muscle activation alterations. As the present study allocated increased trial duration (6 min) versus a 30-m run, it is possible that muscle activity was altered, consistent with Nigg *et al.* (2003), which could have contributed to the reported improved energetics.

Although the aggregate results across all participants and submaximal velocities reveal only a small percentage RE improvement during the WL condition, three participants experienced a RE improved by more than 2% (Table 2; participants 1, 6, 12). It is hard to ascertain mechanistic reasons as to why these participants appeared to 'respond' better to the WL treatment. Roy and Stefanyshyn (2006) reported a negative relationship between body mass and midsole bending stiffness in eliciting an improved RE. In the current study, body mass and RE improvement had a non-significant correlation ($p = 0.349$). Since the actuator lugs are positioned under the forefoot, it could be hypothesised that a MFS pattern may alter the amount of lug deformation during impact and thus influence energy return. Utilising a mathematical midsole model, Shorten (1993) concluded that a MFS pattern would elicit peak midsole deflections of 14 mm beneath the forefoot while a RFS pattern would undergo peak deflection beneath the heel. Theoretically, this would allow a MFS pattern to potentially store more strain energy within the actuator lugs than a RFS pattern. Two of the responders demonstrated a MFS, however, three other participants displaying a MFS pattern had a muted response ($-0.29\% \leq x \leq -0.73\%$). It is possible that even with a similar foot strike classification (*e.g.* MFS) both the magnitude and timing of load deformations across the lugs could be varied; however, an in-shoe pressure measurement device would be required to confirm this assertion.

Coaches and runners may be interested in whether these RE improvements would be expected across the full range of submaximal velocities or if there is some interaction between the expected RE improvement and running velocity. In other words, are these RE improvements relegated to certain submaximal training pace ranges or are they consistent across a range of paces including typical race intensities ($> 80\%\ V\text{O}_{2\text{peak}}$)? In an attempt to contextualise RE improvements to actual training paces, a regression analysis was utilised to compute training paces for equivalent intensities of the WL and WOL condition (Table 3). On average, at 60% $V\text{O}_{2\text{peak}}$ the presence of actuator lugs produced a six seconds per km faster pace than without actuator lugs. While at 90% $V\text{O}_{2\text{peak}}$ this advantage was reduced to only one second per km. Based on these results, one might conclude that as running intensity increased the influence of actuator lugs produced less of an effect. While these results are intriguing, statistical analysis of RE data revealed that the footwear condition and velocity interaction was not statistically significant ($p = 0.234$). RE is influenced by surface stiffness, shoe properties and the body's response to the interaction of the surface-shoe collision. Although the current study controlled for surface stiffness, caution should be heeded when applying these results to other running surfaces (*i.e.* overground).

Shoe mass was not controlled in this study as the removal of lugs for the WOL condition resulted in a lighter shoe by 5.7% (~15 g per shoe). The relationship between shoe mass and energy cost is intuitive; energy demands during running are greater as shoe mass is increased (Frederick *et al.* 1982). Since the WL condition was slightly heavier than the WOL condition, the RE improvements reported for the WL condition were slighter diminished by the heavier shoe. Frederick *et al.* (1982) reported that 135 g shoe mass reduction equated to approximately a 0.7% energy savings. Since the shoe mass differential was small compared to this previous report, it is unlikely that a 30 g combined difference had a substantial influence on the study's results.

In summary, the current investigation produced similar energy savings (~1%) during running, across a range of training paces, as previous investigations that have altered either midsole or shoe properties (Frederick *et al.* 1982, Frederick *et al.* 1986, Roy and Stefanyshyn 2006, Luo *et al.* 2009). Although the alterations to midsole properties were localised to only the forefoot region, energy savings seemed to be independent of foot strike classification and did not produce a significant variance in the runners' spatiotemporal gait mechanics (stance duration, stride rate). The introduction of the lug condition did not change the foot strike classification of RFS runners suggesting that any initial alterations to foot strike may be subtle. Three-dimensional kinematics were not collected in this study so the influence of the lug design feature on lower extremity joint angles is still unknown. Although the underlying mechanisms explaining these energy savings were not uncovered, these results may still be useful to coaches and athletes from a performance context. This study was designed to only investigate the initial effect of a novel midsole design feature on running energetics, and the potential long-term gait and muscle activity adaptations are still unknown. Based on the results of the current investigation, future studies investigating this midsole design feature should specifically (1) measure lower extremity kinematics during RE trials, and (2) provide a longer footwear adaptation period to investigate any potential long-term alterations in gait mechanics and muscle activation patterns.

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Conflict of interest

None.

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