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SPORTS PERFORMANCE

Running economy, mechanics, and marathon racing shoes

Iain Hunter ⬥, Aubree McLeod, Dru Valentine, Tyler Low, Jared Ward and Ron Hager

Exercise Sciences, Brigham Young University, Provo, UT, USA

ABSTRACT

The choice of marathon racing shoes can greatly affect performance. The purpose of this study is to metabolically and mechanically compare the consumer version of the Nike Vaporfly 4% shoe to two other popular marathon shoes, and determine differences in running economy. Nineteen subjects performed two 5-minute trials at 4.44m/s wearing the Adidas Adios Boost (AB), Nike Zoom Streak (ZS), and Nike Vaporfly 4% (VP) in random order. Oxygen uptake was recorded during minutes 3–5 and averaged across both shoe trials. On a second day, subjects wore reflective markers, and performed a 3-minute trial in each shoe. Motion and force data were collected over the final 30 seconds of each trial. VP oxygen uptake was 2.8% and 1.9% lower than the AB and ZS. Stride length, plantar flexion velocity, and center of mass vertical oscillation were significantly different in the VP. The percent benefit of the VP over AB shoe was predicted by subject ground time. These results indicate that use of the VP shoe results in improved running economy, partially due to differences in running mechanics. Subject variation in running economy improvement is only partially explained by variation in ground time.

Introduction

In an effort to design ideal running shoes for improved marathon performance, changes in various shoe properties have resulted in improved running economy (Fuller, Bellenger, Thewlis, Tsiros, & Buckley, 2015; Hoogkamer et al., 2018; Hoogkamer, Kipp, Spiering, & Kram, 2016; Hoogkamer, Kram, & Arellano, 2017). Running economy is inversely related to metabolic costs. As running economy improves, metabolic costs decrease, resulting in improved performance times (Hoogkamer et al., 2016). Modifications to running shoes over the years have included changes in shoe mass, energy return and cushioning through foam properties, and shoe bending stiffness. Shoes that are lower in mass, provide external cushioning, and/or carbon fiber insoles are beneficial when running economy is a primary concern (Franz, Wierzbinski, & Kram, 2012; Frederick, 1984; Frederick EC & SK, 1980; Fuller et al., 2015; Kram & Franz, 2012; Oh & Park, 2017; Tung, Franz, & Kram, 2014). Because of continual advancement in technology, materials, and research assessment capabilities the creation of the ideal running shoe is likely a never-ending pursuit.

Nike recently released a shoe called the Nike Vaporfly 4% (VP). They believed it would significantly improve running economy by providing minimal weight with excellent energy return and optimal stiffness (Hoogkamer et al., 2017). The shoe design includes a lightweight responsive midsole with a full-length carbon fiber plate that adds stiffness with little added weight. Measurements on a prototype shoe showed a 4% improvement in running economy at 14, 16, and 18 km/hr running scenarios compared with two of the most popular elite marathoning shoes (Hoogkamer et al., 2018). Eliud Kipchoge ran 2:00:25 with pacers and drafting during an attempt to break 2:00:00 in the marathon, then went on to

break the official world record in 2:01:39 in the 2018 Berlin Marathon while wearing the VP shoes. With the VP shoe now available to the public, we wanted to replicate the prototype shoe study with some minor changes to investigate whether the consumer version of the shoe would indeed result in a 4% improvement in running economy in comparison to the Adidas Adios Boost (AB) and the Nike Zoom Streak (ZS) (Figure 1). The AB and ZS shoes were chosen because of recent success that elite marathoners have had with these shoes (Table 1).

Many physiological, anatomical, biomechanical, and external factors affect running economy (Daniels, 1985; Di Prampero, Atchou, Bruckner, & Moia, 1986; Heise & Martin, 2001; Kram & Taylor, 1990; Kyrolainen, Belli, & Komi, 2001). Since running economy is such a large component of endurance performance, even a small change in oxygen uptake is likely meaningful to a runner. If the VP shoe is effective in improving running economy, it must be associated with changes in running mechanics. Since the midsole has a higher bending stiffness and the height of the shoe is greater than traditional marathon racing shoes, we expected some differences in running mechanics due to variations in the external moment arm from center of pressure to the ankle joint. In pilot testing, we noticed an anterior shift of the center of pressure during the second half of ground contact time while wearing the VP shoe likely due to the greater shoe bending stiffness. This anterior shift will change the mechanical advantage around the hip, knee, and ankle along with the differences in energy return from the shoe, we hypothesized changes in peak force, ground time, stride length, vertical impulse, knee range of motion during ground contact, hip range of motion, plantar flexion velocity, and center of mass vertical oscillation. Finally, since runners vary in anatomy and

Figure 1. The three shoes used in this study (Nike Vaporfly 4%. Adidas Adios Boost, and Nike Zoom Streak).

Table 1. Successes of the three shoes used in this study. Masses are of men's size 10 shoes.

Shoe	Stats
Adios Boost (230 gm)	Three of four most recent World Records (Berlin 2011, 2013, 2014)
Zoom Streak (192 gm)	3 different athletes 2:04:00 or faster
Vaporfly 4% (184 gm)	Out of the six 2017 World Majors marathons, 19 of the 38 top 3 finishes were in the Vaporfly 4%. Most recent world record (2018 Berlin).

physiology, there may be differences in how someone would benefit from a different shoe in comparison with another runner (Ferber, Davis, & Williams, 2003; Nicola & Jewison, 2012; Williams, 2007). Given the previous research findings with the prototype VP shoe and the consumer availability of the VP shoe now, the primary purpose of this study was to determine if running in the consumer VP shoe would improve running economy compared to AB and ZS. Thus, we expected that running in the VP show would be associated with decreased oxygen uptake (ml/kg/min) compared to running in both the AB and ZS shoe conditions. We also expected some mechanical differences between individuals would lead to greater benefits while wearing the VP shoe. Thus, we also assessed kinetic and kinematic variables to identify the biomechanical mechanisms associated with the expected improvement in running economy.

Methods

Nineteen men participated in two days of testing (Age (yrs): 23.3 ± 6.1, height (m): 1.80 ± 0.07, mass (kg): 66.5 ± 6.6). A previous study (Hoogkamer et al., 2018) and a power analysis focused on oxygen uptake as a way to define running economy differences led to 18 subjects as the goal. Due to high interest, we ended up with an extra subject desiring to complete the study. Inclusion to the study required subjects over 18 years old and having completed a 10 km run in less than 32:00 within the past year. No runners were accepted if they required orthotic use. Sizes US 8–12 were available for the study which limited us to runners fitting into those shoes. Anyone with injury that limited their training at any time during the previous three months was excluded from the study. The choice of shoes was due to the success of top marathon times completed in these shoes and not due to

any connections with any company. All costs were provided with internal research funds. The University's Institutional Review Board approved the study. Prior to participating, study personnel explained the study to each potential subject, and each enrolled subject then provided written informed consent to participate.

On day one, subjects performed a warm up on a treadmill at 3.53 m/s for five min. Following the warm up, they were fitted with equipment for measuring oxygen uptake (TrueOne 2400, Parvo Medics, UT). After trying on shoes for a good fit, testing continued using one of three shoe models in random order. While wearing the first shoe in each subject's order, runners completed a three-minute run at 4.44 m/s while oxygen uptake was measured to ensure equipment was measuring correctly and subjects were near an equilibrium of oxygen uptake prior to beginning the measured intervals. The speed of 4.44 m/s was chosen since it matched one of the speeds used in the previous study and provided an intensity well-below each subject's anaerobic threshold (Hoogkamer et al., 2018). Subjects completed five-minute runs at 4.44 m/s on an instrumented treadmill (AMTI Force Sensing Tandem Treadmill, MA) followed by five-minute breaks to change shoes until they had worn all three shoe models twice. The random order for the first three runs was repeated providing two runs in each shoe. Oxygen uptake was recorded every 15 s, then averaged over the final two minutes of each interval. This provided four minutes of oxygen uptake data for each subject in each shoe with adequate time to reach an equilibrium of oxygen uptake prior to each measurement used in the statistical model. This measurement allowed us to define running economy as the sub-maximal oxygen uptake in ml/kg/min while running at 4.44 m/s. All costs were provided with internal research funds.

On Day 2, subjects had 36 retro-reflective markers placed on various landmarks according to the Vicon Plugin Gait Model (Vicon Corp, Oxford, UK). Ten cameras were sampling at 250 Hz with force plates sampling at 1000 Hz synchronized in one collection system. While running on the same force-instrumented treadmill as Day 1, subjects ran for three minutes in each shoe one time. Motion data and force data were collected during the final 30 seconds of running in each shoe. Ground contact time (s), stride rate (Hz), peak vertical force (BW), vertical impulse (Ns), center of mass vertical oscillation (mm), knee flexion range of motion during stance (deg) while in contact with the ground, hip flexion range of motion during

swing (deg), and plantar flexion velocity (deg/s) from maximum dorsiflexion until toe-off were all determined using customized software created with Microsoft Visual Basic (Seattle, WA). Each characteristic was averaged over the 30-s measurement. Ground contact time was computed from the moment vertical force rose above 30N until it returned to below 30N. A stride was counted as the right foot hitting the ground until the right foot hit the ground again with the rate being measured in strides per second. Center of mass vertical oscillation was measured from the lowest point of center of mass to the highest within each step. These measures were included due to the expected differences in moment arms around the hip, knee, and ankle due to the decreased bending stiffness and greater height of the VP shoes.

Statistical analysis

A repeated-measures mixed model was used for determining differences in running economy and running characteristics between shoe conditions. This model used maximum likelihood to estimate fixed effects. Correlation matrices on each subject were calculated based on a compound symmetry structure, and Tukey HSD adjustments were made for post-hoc comparisons between shoes. A second repeated-measures mixed model tested for correlations between the mechanical measures and the effectiveness of the VP shoes compared to

the average of the AB and ZS shoes based upon the differences in running economy between shoes. Alpha was set at 0.05 for all analyses.

Results

Running economy differences

Significant differences in the oxygen uptake at 4.44 m/s in the VP shoe showed on average a 2.8% improved running economy than the AB shoe ($p < 0.001$, Cohen's D = 2.52) and 1.9% improved running economy than the ZS shoe ($p < 0.001$, Cohen's D = 1.73). The ZS shoe was 0.9% more economical than the AB shoe ($p = 0.022$, Cohen's D = 0.79) (Table 2 & Figure 2). Running economy in the VP compared to AB and ZS shoes ranged from 0.0 to 6.4% for individual subjects. No increase in oxygen uptake was observed between first and second runs in each shoe ($p = 0.507$) demonstrating no cardiovascular drift across trials. All respiratory exchanges ratios values stayed below 0.90 indicating sub-lactate threshold efforts (Dittrich, de Lucas, Beneke, & Guglielmo, 2014; Helge, Watt, Richter, Rennie, & Kiens, 2001).

Running technique

Stride length, plantar flexion velocity, and center of mass vertical oscillation were all significantly different between all shoes. No other mechanical variables were significantly different between any combination of shoes (Table 3).

Greatest benefit

The percent benefit of the VP shoe over the average of ZS and AB shoes was predicted only by individual subject ground time (F = 7.990, $p = 0.011$, R^2 = 0.330). Ground time was the

Table 2. Results of metabolic testing on each shoe.

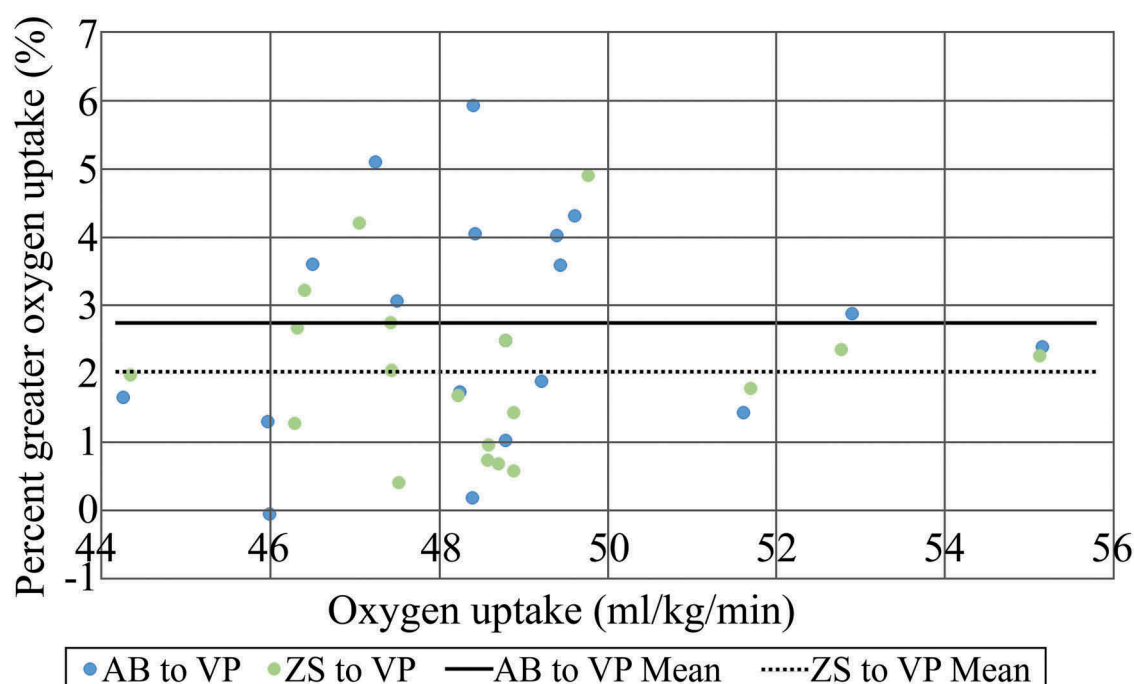| Shoe	Running Economy ± SD (ml/kg/min)	95% Conf LB	95% Conf UB	p-value to VP	p-value to AB
Adidas Boost	49.48 ± 2.60	48.30	50.60	<0.001	NA
Zoom Streak	49.05 ± 2.55	47.84	50.15	<0.001	0.022
Vaporfly	48.11 ± 2.49	46.86	49.17	NA	<0.001

Figure 2. Plot of degree of benefit for each subject. The lines represent the means for each comparison.

Table 3. Differences in running mechanics across shoes with mean and standard errors. Superscripts show which shoes were statistically different than others.

	AB	ZS	VP
Peak Force (BW)	2.997 ± .076	3.048 ± .073	2.942 ± .052
Ground time (s)	.190 ± .004	.190 ± .004	.190 ± .005
Stride Length (m)	3.03 ± .03 [NS, VP]	3.05 ± .03 [AB, VP]	3.07 ± .03 [AB, NS]
Vertical Impulse (Ns)	97.4 ± 4.8	100.7 ± 3.9	97.1 ± 3.0
Knee Range (degrees)	23.0 ± 1.0	22.8 ± .9	22.6 ± 1.3
Hip Range (degrees)	70.0 ± .8	70.0 ± .8	70.0 ± .8
Plantar Flexion Velocity (deg/sec)	222.3 ± 9.7 [NS, VP]	233.3 ± 7.9 [AB, VP]	208.4 ± 8.0 [AB, NS]
CM Vertical Oscillation (mm)	98.0 ± 6.8 [NS, VP]	98.5 ± 6.6 [AB, VP]	103.2 ± 7.3 [AB, NS]

only measure correlated with the amount of running economy benefit from the VP shoe (Figure 3 & Table 4). The prediction equation for the percent benefit to running economy by ground time was "running economy benefit (%) = −0.542 x GT + 0.131". Peak force, stride length, vertical impulse, knee range, hip range, plantar flexion velocity and vertical oscillation were not significantly correlated with which runners received the greatest benefits in running economy from the VP shoe ($p > 0.05$).

Discussion

Metabolic differences

As expected, running in VP shoes provided a benefit to running economy over both the ZS and AB shoes. This agrees with previous research showing an economical benefit to the VP shoe (Hoogkamer et al., 2018). The percent improvement in running economy of the VP shoe over the AB happens to be the same as Frederick found between traditional shoes and air cushion shoes (Frederick EC & SK, 1980). Hoogkamer et al. found 4% running economy benefits across a range of speeds (14–18 km/hr, 2:20:39 to 3:00:50 marathon finish times). Our study tested 16 km/hr finding 2.8% improvements in running economy. The benefits demonstrated from the VP shoe found in this study should provide meaningful improvements in performance times among the typical subject in our study (Hoogkamer et al., 2016). However, some showed much greater benefits in running economy while others showed no benefit from the VP shoes.

All respiratory exchange ratios were below 0.9 and there was no difference between first and second trials in each shoe, indicating the runs were below subject's anaerobic thresholds. With that confidence in the metabolic data, we wondered why our results showed a smaller benefit than Hoogkamer's. The models of shoes used in this study affected each athlete differently. Our data showed a range of 0.0 to 6.4% among our 19 subjects while Hoogkamer found 2 to 6% for his 18 subjects. This wide range may be explained by different optimal shoe stiffnesses for different runners. Other studies that tested multiple levels of shoe stiffness found a large variety in the stiffness levels that provided optimal economy for each individual runner (Fuller et al., 2015; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Willwacher, Konig, Braunstein, Goldmann, & Bruggemann, 2014; Willwacher, Konig, Potthast, & Bruggemann, 2013). Perhaps the bending stiffness of the VP shoe due to its carbon fiber plate was not ideal for running economy for some of our subjects. This may partially explain why our study did not find the 4% that Hoogkamer measured with two of our subjects showing nearly
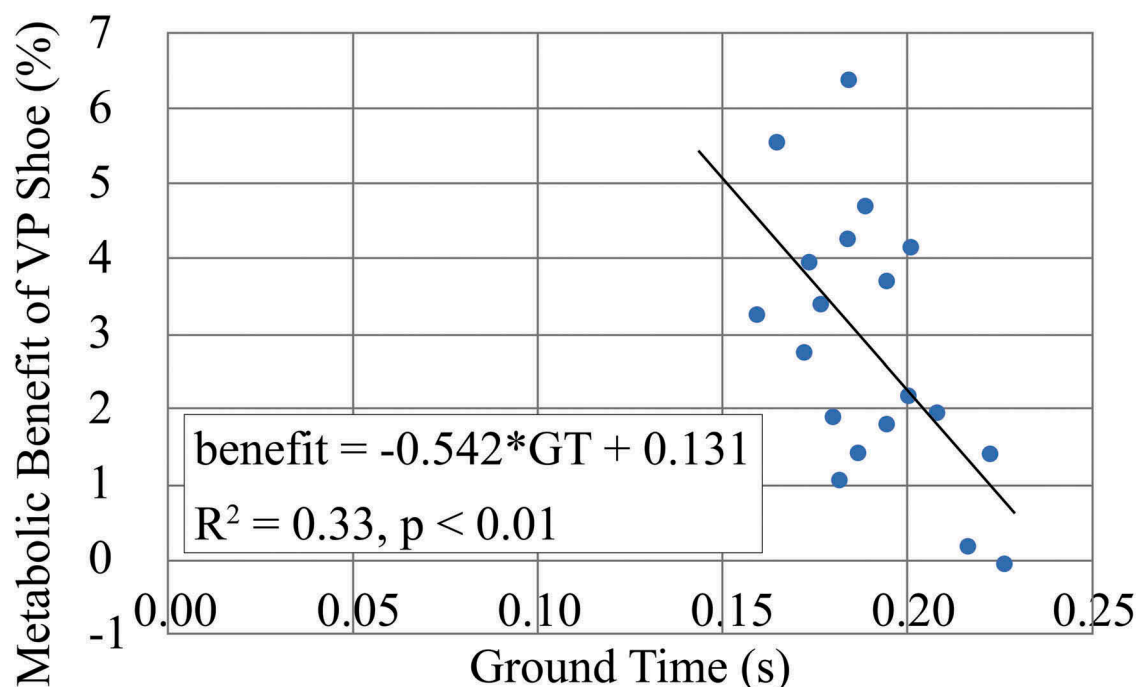
Figure 3. The observed benefit of the VP over the average of the other two shoes versus ground time.

Table 4. Factors tested to determine which type of running mechanics receive the greatest improvement in running economy from wearing the VP shoe.

Variable	*p*-value
Ground Time (s)	0.010
Stride length (m)	0.261
Vertical Impulse (Ns)	0.639
Knee flexion range of motion during ground contact (deg)	0.282
Hip flexion range of motion through full stride (deg)	0.446
Plantar flexion velocity from maximum flexion to toe off (deg)	0.446
Vertical oscillation of center of mass (cm)	0.126

zero benefit in running economy with the VP shoes. However, the differences between the two studies might also simply be a function of the subject sample size in each study. As future research adds more subjects and investigates the effects of different foams and stiffnesses of footwear, a better understanding will come of how shoes can be customized to the athletes for optimizing performance.

Increased shoe mass is a disadvantage to running economy (Hoogkamer et al., 2016, 2017). We expected greater benefits from the VP shoe since we did not add any mass to the VP shoe to equalize mass to the AB and ZS shoes. While the VP showed the greatest improvement in running economy, the difference between shoes was smaller in this study compared with Hoogkamer (Hoogkamer et al., 2018). The VP prototype shoes used in the previous study had a different sole than the consumer version. Some of our subjects complained of slipping on the treadmill surface in the consumer VP shoe. The surface of these shoes is relatively smooth compared with the AB and ZS. This could take away from some of the potential metabolic benefit of the VP. This may not be a problem when used on roads which would have a different coefficient of friction with the VP compared with the treadmill surface. Some post-collection subjective testing showed no visible slipping with high speed video. Consequently, we conclude that if slipping was occurring in the VP shoe, it is very minimal. The previous study also only used US size 10 shoes. We used a range of shoes, but did not have large enough numbers in each shoe size to determine with any confidence whether shoe size had any effect upon running economy differences.

The midsole of the VP shoe includes a relatively stiff carbon fiber plate inside a thick midsole made with a lightweight responsive foam. This leads to a greater standing height with the shoes on compared with the other two used in this study (approximately 1 cm taller in the VP to ZS and AB). These shoe properties change the mechanical advantage of the foot and leg. The stiff midsole should bring the center of pressure more anterior during toe off, leading to a greater external moment arm from the ankle (Stefanyshyn & Fusco, 2004; Willwacher et al., 2014, 2013). The greater shoe height will lead to a greater moment arm from the ground to the knee and hip. These changes in moment arms lead to an altered mechanical advantage around the lower body joints that appear to change running mechanics in a way that has the body more mechanically optimized for better economy. With the center of pressure further forward and the shoe not allowing as much MTP joint range of motion, the foot is effectively longer creating a greater vertical oscillation. The range of plantar flexion may also be limited. With no change in ground time, this explains why plantar flexion velocity would be decreased.

With this greater vertical oscillation and no change in hip and knee range of motion, the body is vaulted slightly higher in the air such that there is a slight increase in the distance from peak vertical oscillation to when the foot contacts the ground. This results in an increased stride length, contributing to a better overall running performance.

Muscles contract to aide tendons in absorbing and returning energy during gait (Shorten, 1993). If the sole of an energy efficient shoe can do this instead, less muscle work is required, which improves running economy. With the greater height of the midsole in the VP shoe, we expected greater knee flexion during stance without an increase in center of mass vertical oscillation (Ferris, Liang, & Farley, 1999). In contrast, we observed unaltered knee flexion, and an increase in center of mass vertical oscillation in the VP shoe. The increased vertical oscillation may be explained by the greater stride lengths observed among the subjects in our study wearing the VP shoe. The VP shoe has some beneficial properties of energy return leading to greater stride lengths with greater vertical oscillation without requiring greater metabolic effort.

The changes in running economy are encouraging, but athletes need to know how that translates to performance times. For every 100g of added mass to shoes, there is a 0.8% increase in metabolic cost, which leads to an increase of 0.78% in performance time (Hoogkamer et al., 2016, 2017). Although the differences we observed were due to shoe type rather than shoe mass (Table 1), we expect the same relationship between metabolic cost differences and performance time. Whether these differences can be extrapolated through a full marathon remains to be determined, but even small percent differences in performance times can be very meaningful to the runners.

Running mechanics differences

In order to understand why the VP shoe improves running economy, we measured various temporal, kinetic, and kinematic running characteristics. While wearing the VP shoes, runners utilized a 0.9% longer stride, 5.0% greater vertical oscillation, and 8.5% lower plantar flexion velocity from maximum dorsiflexion to toe-off. Although a 0.9% longer stride may not sound like much, if it were to translate to a 0.9% faster race, the finish time of the speed used in this study of 16 km/hr marathon (2:38:14) would be dropped by 0:01:25 which is a considerable amount for many marathoners. These changes in mechanics occurred with no significant increase in peak vertical force ($p = 0.137$). A similar study actually found a decrease in peak force while wearing the VP compared with the AB and ZS (Hoogkamer et al., 2018). This collection of differences could explain the benefit to running economy. The longer stride with no increase in peak force and a lower plantar flexion velocity are likely associated with the main differences of the VP shoe, which are the sole height, type of foam, and the greater bending stiffness. The compression and relaxation of the foam returns energy differently than the AB and ZS. The longitudinal stiffness of the shoe changes the mechanical advantage (ratio of internal moment arms to external) about the ankle by limiting the amount of metatarsal-phalangeal hyperextension. This stiffness that restricts

bending of the shoe and foot increases the moment arm from the center of pressure to the ankle by shifting the center of pressure more anterior as the heel comes off the ground leading to changes in running mechanics. The height of the shoe (39mm at the heel) also changes mechanical advantages about the hip and knee compared with shorter shoes (AB = 23mm, ZS = 26mm) by increasing the height of the knee and hip from ground level. This may have very little effect during mid-stance, but early and late in the stance phase, the ground reaction force vector would be directed further away from the lower body joints creating meaningful differences in external moment arms. These differences in shoe design explain why some aspects of running mechanics vary between shoes, but further investigations will need to be completed to fully explain where the benefits to running economy exist.

We expected a lengthening of the moment arm from the ground to the ankle due to the stiffer VP shoes. This was not measured during the study. However, while running over fixed force plates, we observed a 0.01 m anterior shift of center of pressure during the pushoff phase when the vertical force went from 800 N down to 100N. Though not measured in this study, the foam of the shoe likely made a difference in some of the mechanics also. Hoogkamer measured deformations of foam in 6.1 mm, 5.9 mm, and 11.9 mm and energy returns of 65.5%, 75.9%, and 87.0% in the ZS, AB, and VP respectively (Hoogkamer et al., 2018). While the publicly available shoe might be slightly different than the prototype VP shoes from Hoogkamer's study, we expected the currently available shoe would have similar foam properties.

Which type of runner gets a greater benefit?

Shorter ground contact time is related to better running economy (Chapman et al., 2012). While the VP shoe did not change ground contact time in our study, this characteristic did come across when comparing how effective the shoe was for one individual over another. Runners that spent less time on the ground received a greater benefit in running economy while wearing the VP shoe ($p = 0.010$) (Figure 3). This was compared with the average ground time measurements from the AB and ZS combined. The mechanical advantage changes described above along with anatomical differences between runners may explain why some runners received a greater metabolic benefit. Foot size, leg stiffness, rigidness of foot, foot type, and perhaps other characteristics go into determining an individual's preferred ground time (Baxter, Novack, Van Werkhoven, Pennell, & Piazza, 2012; Di Michele & Merni, 2014; Morin, Samozino, Zameziati, & Belli, 2007). Since the benefit to running economy from wearing the VP shoe varied between people, future studies could look at customizing shoe properties to characteristics of individual runners.

We did not account for shoe mass in this study which prevents us from isolating the effect of shoe mass. We chose this approach intentionally to determine how the shoes would affect runners that purchase the shoes included in this study. We also only tested one running speed which makes this applicable only to that pace. However, Hoogkamer et al. (2018) showed similar findings in the running economy

component of this study across speeds ranging from 14–18 km/hr. One benefit we had of only choosing one speed to run is that we were able to obtain more trials in each shoe with less visits to the lab.

Conclusions

Use of the VP shoe resulted in improved running economy when compared with the AB and ZS at 4.44 m/s. The benefits in metabolic cost from the VP shoes is enough to improve performance times in a meaningful way, although a placebo effect cannot be ruled out. Improvements in performance times are expected in the VP shoe. These differences are partly explained by alterations in running technique that seem to be due to shoe differences. Some people responded to the shoes differently than others. Future research will look at determining what leads one runner to find more or less benefit from given footwear.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Iain Hunter 🆔 http://orcid.org/0000-0002-3942-9811

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